Waterhole ecology in the Flinders and Gilbert catchments

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

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TropWATER

Centre for Tropical Water and Aquatic Ecosystem Research

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The Strategy was guided by two committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater, during the first part of the Strategy) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; and the Queensland Government.

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government.

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Director's foreword

Northern Australia comprises approximately 20% of Australia's land mass but remains relatively undeveloped. It contributes about 2% to the nation's gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation's south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural opportunities
- assess potential environmental, social and economic impacts and risks.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to 'join the dots'. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader's values and their aspirations for themselves and the region.

Dr Peter Stone, Deputy Director, CSIRO Sustainable Agricultural Flagship

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Shortened forms

a.i.	active ingredient
ANZECC	Australian and New Zealand Environment Conservation Council
APHA	American Public Health Association
AWD	alternate wetting and drying
BOD	Biological Oxygen Demand
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEHP	Department of Environment and Heritage Protection (Queensland Government)
DIN	Dissolved Inorganic Nitrogen
DON	Dissolved Organic Nitrogen
DIP	Dissolved Inorganic Phosphorus
EBPC Act	Environmental Protection and Biodiversity Conservation Act 1999
ECM	Export Coefficient Model
EPP Water	Environmental Protection (Water) Policy 2009, Queensland
EST	Eastern Standard Time
EU	European Union
EV	Environmental Values as stated under the EPP Water Policy
FHA	Fish Habitat Area declared under the Queensland Fisheries Act (1994)
GAB	Great Artesian Basin
GCM	global climate model
GCM-ES	global climate model output empirically scaled to provide catchment-scale variables
GM	genetically modified
IUCN	International Union for the Conservation of Nature
IR	infrared
IWD	intermittent wet-and-dry rice
Landsat TM	Landsat Thematic Mapper
MRL	maximum residue limit
N	Nitrogen
NHT	Natural Heritage Trust
NMDS	non-metric multidimensional scaling
NRM	natural resource management
NTU	nephalometric turbidity units
P	Phosphorus
PN	particulate nitrogen

PS-II	photosystem II
RE	Regional Ecosystem
RE_N	Nitrogen fertiliser recovery efficiency
SIGNAL	Stream Invertebrate Grade Number Average Level
SSNM	site-specific nutrient management
TN	Total Nitrogen
TP	Total Phosphorus
TRaCK	Tropical Rivers and Coastal Knowledge
TRARC	Tropical Rapid Appraisal of Riparian Condition
TropWATER	Centre for Tropical Water and Aquatic Ecosystem Research
TSS	Total Suspended Solids
WQO	Water Quality Objectives (as stated under the Queensland EPP Water Policy (2009))

Units

MEASUREMENT UNITS	DESCRIPTION
°C	degrees Celsius
cm	centimetres, 10 millimetres
d^{-1}	day
g	grams
GL	gigalitres, 1,000,000,000 litres
ha	hectares
hrs	hours
kg	kilograms
km	kilometres, 1000 metres
L	litres
m	metres
mm	millimetres
mg	milligrams
min	minutes
µm	micrometres
NTU	neolithic turbidity units
t	tonnes, 1000 kilograms
yr	year

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

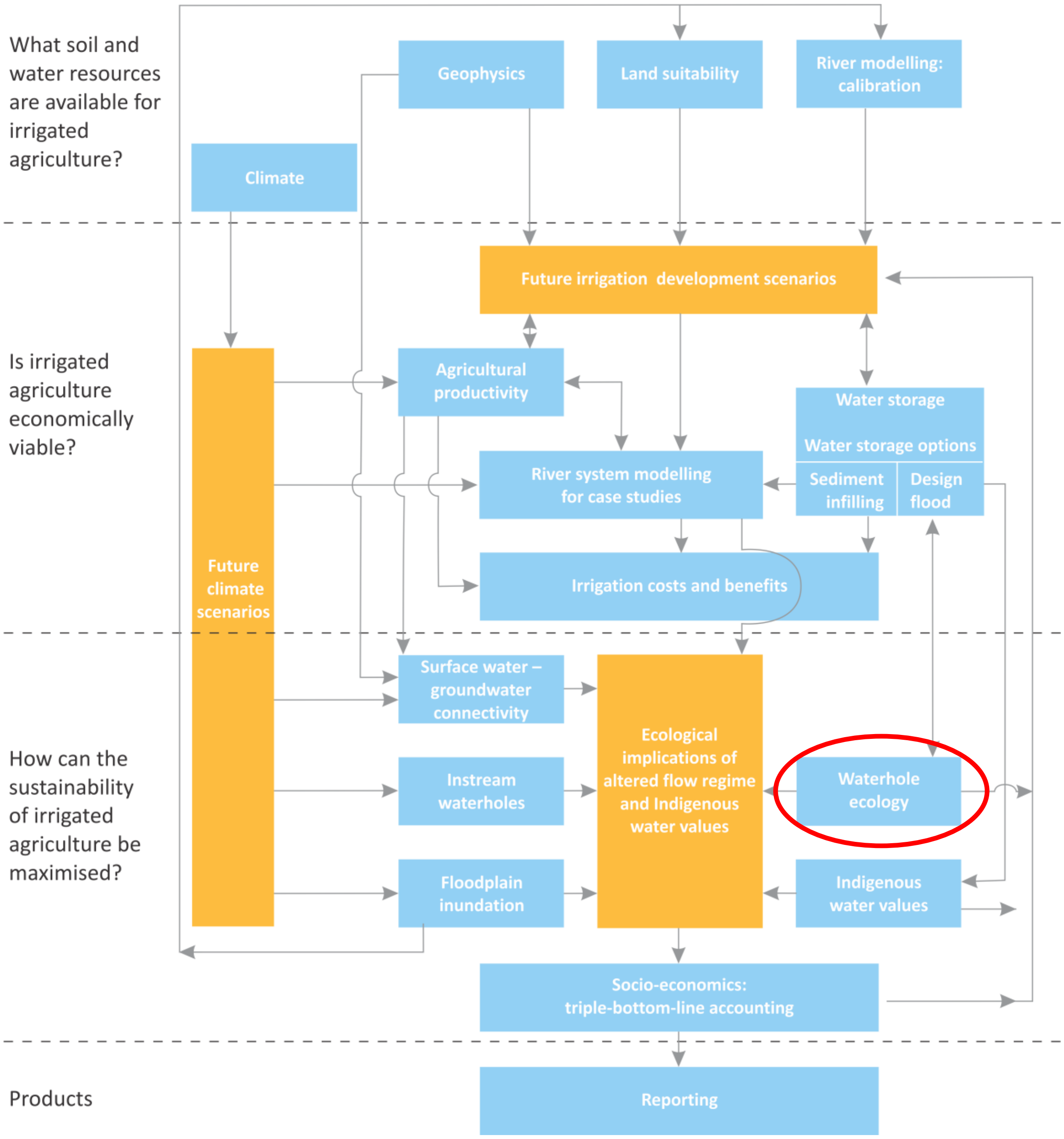
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an 'activity box' links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

The Flinders and Gilbert catchments in north Queensland have been investigated as potential areas for further agricultural development. This report forms part of the Flinders and Gilbert Agricultural Resource Assessment (the Assessment), an integrative evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments. The current study addresses aspects of the potential impacts of irrigation development upon the aquatic habitats and resources of the Flinders and Gilbert catchments.

This component of the Assessment comprised the following elements:

1) A brief desktop review outlining current knowledge of freshwater assets in the study area (Chapter 2);
2) Assessment of the water quality and limnology of ten waterholes in each catchment (Chapter 3);
3) Detailed examination of instream temperature regimes, and modelling to estimate how these might vary under climate change scenarios (Chapter 4);
4) Survey of aquatic biota at ten waterholes in each catchment, review and collation of existing ecological data available for both catchments (Chapter 5);
5) Modelled estimates of nutrient, sediment and pesticide pollutant export loads for a range of potential development scenarios for both catchments (Chapter 6); and,
6) An overall synthesis discussing the underlying risks and challenges that require consideration in a potential irrigation development drawing on knowledge and data from other irrigation schemes in northern Queensland (Chapter 7).

The field components of this work have resulted in the collection of baseline data indicative of pre-development conditions. It is important to note that the field work component of the study only covered less than one year, and climatic conditions prevailing at the time were atypical. Additional monitoring would be required, under a variety of different climate and weather conditions, in order to obtain a baseline data set suitable for use in assessments of potential future impact. Nevertheless, analysis of the existing data has significantly enhanced our understanding of the status of waterways in the Assessment area. The key findings, conclusions and recommendations are summarised below.

The Flinders is the drier of the two catchments with mean rainfall as low as 350 mm in the upper catchment, hence freshwater ecosystems are heavily constrained by water availability. Stream flow is seasonal in the sense that most precipitation occurs during summer months, however, rain events large enough to generate runoff to rivers occur only 4 to 7 days per year on average. The section of the river system that has been assessed in this study receives no significant inputs of groundwater, so flows are highly episodic, and most of the time the aquatic ecosystem is constrained to a disconnected series of relatively stagnant waterholes. In order for the aquatic ecosystem to persist, at least some waterholes in each subcatchment must be capable of retaining sufficient quantities of good quality water to sustain biological communities even during the most prolonged droughts.

Although the Gilbert catchment has more rainfall than the Flinders, with runoff potentially occurring about 8 to 16 days per year, the above comments are still relevant to most sections of that river system. However, the Gilbert catchment hosts a number of tributary streams that receive sufficient groundwater inputs to sustain permanent flows of clear water. Perennial streams of this sort are rare in northern Australia and are ecologically important enough to suggest that they are worthy of special protection, as are the springs and groundwater formations which drive their baseflow, along with the associated groundwater recharge areas. Accordingly, study to identify and characterise the sources of the perennial baseflows in these streams is recommended, to help devise a management plan to ensure that the groundwater formations which drive the baseflow are adequately protected from excessive water extraction and any agricultural developments with the potential to contaminate the aquifers.

The brief pulses of swift flow (i.e. stormwater flow) that occur at some stage during most wet seasons are known to play a number of critical roles in maintaining the river ecosystems. They allow aquatic organisms to escape the confines of discrete waterholes and access habitats necessary for completing their life cycles; they flush out, replenish and rejuvenate instream waterholes and off-stream wetlands, and stimulate productivity within the river system and the estuarine and marine fisheries further downstream. A certain amount of flow may also potentially be needed to recharge riparian groundwater reserves contained within the river bed and adjacent alluvium. Observations conducted during this Assessment indicate that some waterholes can only retain water if there has been sufficient sustained flow and/or local rainfall during the preceding wet season to replenish the subsurface water reserves associated with the river.

The quantity and duration of flow required to achieve the above-mentioned outcomes is poorly understood, and because the current investigation coincided with the onset of a prolonged drought, there was virtually no opportunity to gather quantitative data indicative of the effects of flow events. Accordingly, this Assessment was mainly constrained to evaluating the condition and ecological significance of waterholes, with an emphasis on their capacity to serve as effective drought refugia. It is nevertheless apparent that the small quantities of flow that occurred during the Assessment were insufficient to fully flush and replenish waterholes. In fact it is noteworthy that there was no stage during the 2012-2013 hydrological year when water could have been extracted from either river system without incurring significant risk of adverse impacts on the size, permanency and ecological condition of waterholes.

Data collected in this Assessment indicate that drought-related stresses were already beginning to develop at a number of waterholes during the early stages of the drought (for example water temperatures often approached or exceeded the physiological limits of local fish species, and dissolved oxygen availability was becoming limited). However, the ultimate ecological impacts of the drought cannot be assessed until it has run its course. Data indicative of the immediate and long term effects of such a severe drought would provide an extremely valuable basis for assessing the capacity of the ecosystem to cope with water deprivation, and hence for predicting the effects of water extraction. Accordingly, there would be benefits from further monitoring and assessment of waterhole condition occurring as soon as possible. Such a study would ideally be linked to a hydrological investigation to determine the extent to which the persistence of waterholes is reliant upon subsurface water reserves, and ascertain how much flow and/or rainfall is required to recharge them.

Note that some of the waterholes that serve as vital drought refugia in the drier subcatchments are small enough to be adversely affected if even modest volumes of water were to be extracted either directly from the waterhole or (more likely) from spears and bores situated within the streambed or adjacent alluvium.

The 20 waterholes examined during this Assessment have been classified into three distinctive types, as follows:

1) Type 1 – Persistently turbid, highly ephemeral flow (includes all Flinders catchment waterholes, but only a few Gilbert catchment waterholes).
2) Type 2 – Seasonally clear, seasonally intermittent flow (includes the majority of non-perennial Gilbert catchment waterholes).
3) Type 3 – Persistently clear, perennial flow (comprises three tributary streams in the Gilbert catchment; Elizabeth, Bundock and Junction Creeks).

Each of the three waterhole types share some characteristic limnological and ecological traits that influence their inherent vulnerability to different anthropogenic pressures and govern the ways in which they will potentially respond to hydrological alterations and/or agricultural contaminant inputs. These factors, which are detailed in Chapter 3, should be taken into consideration in water management and planning activities.

For example, the existing turbidity levels at Type 1 waterholes are already high enough to constrain primary production to the near-surface water layer, and as a consequence, moderate increases in turbidity will only subtly affect their productivity. In contrast, Type 2 waterholes are clear enough to support significant levels of productivity all through the water column to the bottom, and consequently even subtle increases in turbidity would be enough to significantly impair productivity. In fact, because they are generally stagnant these waterholes rely heavily on plant photosynthetic production to maintain adequate oxygen levels. Hence a pulse input of turbid water late in the dry season (when there is a high biomass of benthic plants present) could result in a significant oxygen sag (because the benthic plants would be unable to get enough light to produce oxygen and would begin consuming oxygen instead). Type 3 waterholes are also clear enough to support significant benthic productivity but, because they flow constantly, surface inputs of turbid water will be dispersed rapidly and are likely to be too transient to have such a significant effect. The baseflows at Type 3 waterholes also provide aeration and mixing, so they are less likely to suffer from deoxygenation effects. However, this resilience is contingent on the baseflow waters being of good quality, hence the importance of protecting the groundwater formations that sustain the baseflow. There were major differences between fish and invertebrate communities in the Flinders and Gilbert catchments, primarily driven by differences in water clarity and the absence of submerged macrophytes at Type 1 waterholes in the Flinders catchment.

All Assessment waterholes developed thermal stratification at times (i.e. water near the surface warmed sufficiently to form a discrete layer that could not intermix with the cooler waters closer to the bottom). Type 1 waterholes are particularly prone to stratification because turbid water absorbs heat more efficiently than clear water. Hence, all Type 1 waterholes were stratified for most of the time during this study and several maintained stable stratification for weeks at a time. Type 2 waterholes are less prone to stratify because sunlight is absorbed deeper in the water column, but most of the waterholes in this Assessment still exhibited pronounced diurnal stratification (i.e. discrete surface layers of warm water formed during the heat of the day but mixing occurred when the surface water cooled down overnight). Type 3 waterholes are the least likely to stratify because the constant flow promotes water circulation. However, even these waterholes exhibited measurable diurnal stratification for most of the duration of the study.

Stratification creates complex microhabitats which aquatic animals must exploit in order to survive in these waterholes. For example, the surface temperatures recorded during this study frequently exceeded the optimal thresholds of local fish (in several cases by more than 5°C) and at times lethal thresholds were exceeded. Maximum bottom temperatures on the other hand seldom exceeded the threshold indicating that bottom waters can act as a cool water refuge for biota during the heat of the day, on the proviso that other water quality conditions, and especially oxygen levels, are suitable near the bottom. Modelling conducted as part of this study indicates that, under a global warming scenario of a 2°C increase in air temperature, waterholes are likely to experience a 1°C increase in water temperature, which markedly increases the amount of time water temperatures exceed optimal and lethal thresholds for fish. Increased water temperatures will also greatly increase oxygen consumption rates, creating a situation of increased respiratory oxygen demand but reduced oxygen availability.

All of the waterholes monitored during the Assessment exhibited diel oxygen and pH cycling in the surface water layer (i.e. levels fluctuated over the course of each day), and in most cases, oxygen and pH levels also declined with increasing depth through the water column. These effects were most evident at Type 1 waterholes. Type 2 waterholes generally exhibited more moderate fluctuations, however, the Type 3 waterholes (which benefit from the aeration and mixing provided by constant flow) were the only waterholes where variations were subtle enough to suggest that they would be inconsequential to biological communities. Notably, oxygen values low enough to asphyxiate sensitive fish species were reported on a number of occasions, and suboptimal levels were encountered frequently, at Type 1 and 2 waterholes.

The above observations indicate that temperature and hypoxia stresses were beginning to develop during the early stages of the 2013 drought, and there is little doubt that conditions would have continued to deteriorate through the year, and especially during the hot months of the pre-wet season. Natural reduction in water levels (due to evaporation and seepage losses) would be sufficient to significantly increase daily temperature maxima and would decrease the likelihood of a cool bottom layer forming (which would mean that fish would be unable to escape the heat). Depth reductions due to water extraction would have the same effect.

Quantitative modelling reported in Chapter 6 shows that agricultural development has the potential to elevate sediment (i.e. turbidity), nutrient and pesticide inputs into streams of the Assessment area, and also has the potential to impact on the productivity of ecosystems far removed from the developed areas (i.e. estuaries and near shore coastal systems).

The productivity of riverine waters in the Assessment area is governed by numerous factors, the most significant being water clarity. However, the results obtained during this Assessment indicate that phytoplankton productivity was also nutrient-limited and there were clear indications of increased growth in response to inflows of nutrient rich stormwater. Because they are not light-limited, Type 2 waterholes are likely to respond most vigorously to nutrient inputs, nevertheless, the effects of increased phytoplankton productivity in the near-surface layer of Type 1 waterholes can still be substantial. The adverse effects of excessive growth of plants and algae in response to increased nutrient inputs (termed eutrophication) are well established and are a ubiquitous problem in most developed catchments.

It is salient to note that, under the conditions prevailing during this study, waters in the Assessment area were quite alkaline, with pH above 8.8 being reported in more than 20% of cases. Eutrophication would almost certainly increase this already high pH. One of the consequences of this is that the waterholes will be highly vulnerable to acute impacts such as fish kills should they receive inputs of ammonia; the toxicity of which increases dramatically with increasing pH. This is significant, given that most nitrogen fertilisers contain either ammonia or chemicals that can be converted to ammonia in water.

There are a myriad of other impacts that could potentially result from agricultural water resource development in the Assessment area, depending on the type of proposed development and how it is operated as well as its geographic and biological context. As a guide, Chapter 7 briefly discusses some examples of the kinds of impacts that have been reported in other irrigation areas, but without very specific information regarding the precise nature of any development, a more detailed risk assessment is not possible.

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1 Objectives

1.1 Introduction

River systems in northern Australia have extremely seasonal streamflow (Kennard et al., 2010). For many rivers, including the Flinders and Gilbert catchments, the vast majority (greater than 90%) of total annual streamflow occurs during the wet season (November to April) and often during a short timeframe (e.g. over a few weeks; CSIRO, 2009a). Wet season flow is important in the longitudinal, lateral and vertical connection of river systems and wetlands, especially on floodplains, and also to allow aquatic species (e.g. fish) to move to suitable areas for spawning and feeding (Balcombe et al., 2007; Boulton, 2007; Bunn et al., 2006; Medeiros and Arthington, 2008). The wet season delivers productivity-boosting freshwater and nutrients to estuarine and coastal waters which support economically important fisheries (Buckworth et al., 2013). The flow also recharges groundwater aquifers (Boulton, 2007), which support riparian and floodplain vegetation communities, and contribute important dry season baseflow to downstream waterholes, and in some cases long after the flow from floodwater returning to river channels has ceased (Butler et al., 2009).

In contrast, flows during the dry season are very limited or more usually, completely non-existent and aquatic habitats in the catchment often exist as a series of discrete waterholes. As the dry season unfolds, waterholes begin a process of drying out. Waterholes that are connected to groundwater reserves typically do not change greatly in size. Any waterholes that persist throughout the year provide critical habitat for aquatic biota and ecological processes (Arthington et al., 2010; Bunn and Arthington, 2002; DERM, 2011; Hamilton et al., 2005; Kennard, 2010; Pahl-Wostl et al., 2013; Pearson et al., 2013; Sheldon et al., 2010).

Water resource developments have the potential to cause major environmental disturbances, resulting from changes in the hydrology and limnology of river basins. Reductions in peak and wet season flows, for example, can affect downstream habitats, including estuarine and coastal habitats, as well as riverine geomorphology, aquifer recharge and riverine flushing. Reductions in aquifer recharge and/or water extraction during the dry season can impact upon the ecology of persisting water bodies (i.e. waterholes) through reductions in their volume. Furthermore, agricultural activity associated with water resource developments result in increased sediment, nutrient and agricultural chemicals (pesticides) loads to aquatic habitats.

In other north Queensland streams affected by irrigation development (e.g. in the Burdekin and Walsh irrigated districts), a reduction in water quality has been the dominant factor affecting poor faunal health and driving negative ecosystem outcomes (Burrows, 2004a; Butler, 2008; Butler et al., 2007; Pearson et al., 2003). Significant extractions of water associated with agricultural developments may result in smaller pools with less seasonal persistence (Butler et al., 2009; Leigh, 2012). Water quality becomes more limiting for aquatic fauna and ecological processes in such waterholes, especially in relation to increased temperature and turbidity and decreased dissolved oxygen (Butler et al., 2007; Butler et al., 2009). Irrigation developments that cause a loss of shading via clearing of riparian vegetation or increase weed invasion and sediment and nutrient loading to streams as runoff from irrigated farms, exacerbate these water quality issues particularly so for temperature and dissolved oxygen (Butler and Burrows, 2007; DNRMW, 2006).

1.2 Objectives

This investigation is closely aligned with other activities undertaken as part of the Assessment (see Preface Figure 1). Specifically this investigation has five tasks:

1) Summarise existing knowledge on the status and condition of ecological communities and natural assets in the Assessment area;

2) Examine water quality, limnology and habitat suitability of waterholes in the Assessment area;
3) Explore waterhole thermal regime, in particular, frequency of time when waterholes approach or exceed thresholds;
4) Study the fish and aquatic invertebrate communities of waterholes in the Assessment area; and
5) Evaluate potential sediment, nutrient and pesticide export from farms to aquatic environments.

The Assessment occurred over one seasonal cycle in which fieldwork could be conducted. Within the available time, the intention was to focus on examining the ecology of waterholes very late in the dry season, where conditions are hot, and water levels are very low. A second aspect was to examine the first flush inflows upon waterholes where at the end of the dry season, remaining waterholes are often in a vulnerable state, having low volumes and poor water quality conditions. The first inflows of the wet season are critical in flushing out the waterhole, and 'resetting' them for the year ahead. In situations where the first inflows merely fill the waterhole with localised runoff containing, for example, sediment and nutrients from the riverbank and nearby areas, and do not create enough streamflow to flush the waterhole out, the ecological outcomes will be poor. Irrigators in dry catchments often require access to the first inflows of the wet season in order to set about establishing their crops before the wet season proper starts. Access to the first inflow therefore creates a conflict of needs between environmental ecosystem services and farming outcomes. The failure of the 2012-13 wet season during the Assessment precluded examination of the responses to first flushing. Instead, this circumstance afforded the opportunity to research water quality and the fate of aquatic communities during this extended dry season and by proxy, increased abstraction of water from the aquatic ecosystems.

1.3 Report structure

This report has four main components:

1) Assessment of water quality and limnology of ten waterholes in each catchment;
2) A more detailed examination of instream temperature regimes and modelling to estimate how these might vary under climate change scenarios;
3) Survey of aquatic biota at ten waterholes in each catchment, review and collation of the available data for both catchments; and
4) Calculation of nutrient, sediment and pesticide pollutant export loads for a range of proposed development scenarios for both catchments.

The final chapter provides an overall synthesis discussing the underlying risks and challenges that require consideration in a proposed irrigation development drawing on knowledge and data from similar irrigation schemes in northern Queensland. This section also includes a brief desktop consideration of relevant issues that could not be covered in fieldwork undertaken for this Assessment.

2 Flinders and Gilbert catchments - Assessment area

2.1 Pre-colonial

The landscape of both catchments today must be considered against a background of significant historical climate variation and shifting landmasses which provide a key to understanding contemporary distributions of species and communities. For much of the Pleistocene age (approximately 2.6 million years before present to 10,000 years ago) Australia was part of the Sahul landmass which comprised the Australian mainland, Tasmania and New Guinea. During this period a series of ice ages reduced sea levels and exposed land bridges across the globe including the Australia–New Guinea continental shelf and putatively connected many rivers across northern Australia. During the last glacial episode the Gulf of Carpentaria was dominated by a large inland lake, Lake Carpentaria (Torgersen et al., 1985). Evidence for the existence of this large inland lake from studies of sediments and organic matter trapped within them, suggest that this lake oscillated between brackish and freshwater before the final incursion of marine waters into the lake at around 10,800 years before present (Reeves et al., 2007).

The current day fragmented distributions and low endemicity of many freshwater fish and crustaceans throughout the Gulf region probably reflects this historical hydrological connectivity with Lake Carpentaria acting as a conduit that periodically allowed species to move between the rivers of the Gulf. This pattern of periodic connection and movement is supported by genetic research on a variety of freshwater fauna in the Gulf rivers including pennyfish (*Denariusa bandata*), redclaw crayfish (*Cherax quadricarinatus*), giant freshwater prawn (*Macrobrachium spinipes*; formally *Macrobrachium rosenbergii* until Ng and Wowor (2011)), spangled perch (*Leiopotherapon unicolor*) (Baker et al., 2008; Bostock et al., 2006; Cook and Hughes, 2010; de Bruyn et al., 2004). However, the timing for when freshwater faunas across northern Australia became disjunct and fragmented into the distributions found today is unclear. The Pleistocene age was characterised by drier periods of lower rainfall which may have played a part in limiting the exchange of species across northern Australia and further afield (Unmack, 2001). Some evidence suggests therefore that distributions of freshwater fauna in the region originated much earlier in the late Miocene age (5.3 to 23 million years before present), when the climate was much wetter (Cook and Hughes, 2010). However, this is a complicated story as even today, large floods may establish connectivity between adjacent river systems, facilitating dispersal of freshwater biota and mixing of gene pools.

The coastal floodplains and deltaic regions of both catchments represent a relatively recent geological environment. Work on nearby river systems, in particular the Mitchell River suggest that extension of river deltas in the region into the sea has been occurring since around 5,700 years before present (Brooks et al., 2010; Chappell et al., 1982; Nanson et al., 2013). This is associated with a fall in relative sea levels attributed to hydro-static adjustment or the rebounding of the landmass following its depression by the weight of water (Lewis et al., 2013; Nanson et al., 2013). Substantial shifts in coastal vegetation occurred throughout the Holocene with extensive mangrove forests, termed the “Big Swamp”, developing around 6800 – 5300 years before present followed by successional changes towards freshwater wetlands dominated by grasses and sedges and the reestablishment of a distinct meandering river channel (Finlayson, 2005; Woodroffe et al., 1986; Woodroffe et al., 1985). Further inland, today the landscape is predominantly tussock grasslands on the floodplain with eucalypt woodlands at higher elevations (DEWR, 2005). The broad landscape vegetation communities of the catchment seen today had probably developed by the start of the Pleistocene (Kershaw et al., 1994) although shifts in the distribution and extent of these communities occurred throughout the Pleistocene and Holocene (10,000 years ago to present) and continue up to the present day. Anthropogenic influences over thousands of years prior to European settlement are likely to have impacted upon the vegetation of the region particularly through aboriginal burning practices (Bird et al., 2013) although their influence on broader scale vegetation patterns and consequences for the regional tropical climate are the subject of some debate in the published literature.

The journals of early explorers and archaeological evidence of aboriginal activities in the region provide information on the ecology of the catchments prior to pastoralism. These records are however generally an inventory with only occasional references to species being abundant or plentiful. The course of early explorers through the region frequently followed streams and rivers. Botanical records for the eastern Gulf of Carpentaria reconstructed through the 1845 journals of Ludwig Leichhardt include a diverse array of riparian and in stream vegetation species with reference to reeds, *Nymphaea* spp., *Pandanus sprialis*, *Damasonium* spp., *Utricularia* spp., Villarsia (*Nymphoides* spp.), *Melaleuca* spp., stravadium (*Barringtonia acutangula*), *Polygonum* spp., nonda trees (*Parinari nonda*), flooded-gum (*Eucalyptus camaldulensis*), raspberry-jam trees (*Excoecaria parvifolia*) amongst others (Fensham et al., 2006). The journals of William Landsborough (Landsborough, 1862) from later expeditions along the Flinders River in search of the explorers Burke and Wills, make frequent reference to creeks lined with Tea trees and box which are probably *Melaleuca* spp. or *Asteromyrtus* spp., and *Eucalyptus* spp. although the exact species are not known. The journals also make reference to other freshwater biota particularly those that were eaten (as in the case of mussels, small fish and ducks).

2.2 Contemporary

2.2.1 NATURAL ASSETS AND PROTECTION AREAS

The upper region of the Assessment lies within the Einasleigh and Desert Uplands biodiversity hotspot, which is recognised for the mix of ecologically and geologically important features and habitats provided (http://www.environment.gov.au/biodiversity/hotspots/national-hotspots.html#hotspot1). A series of ecologically important nature reserves, wetland systems, and regionally important vegetation ecosystems extend across the Flinders and Gilbert catchments that collectively provide important terrestrial and aquatic habitat for a broad range of common, rare and threatened species (Kingsford, 2000). A recent examination of the non-riverine and riverine areas of both catchments concluded that their aquatic values were moderate to high, with respect to the extent of naturalness, special features, diversity and richness of flora and fauna, and threatened species (Rollason and Howell, 2010). A major conclusion of the Rollason and Howell study was that the Flinders catchment has a less established network of protection and conservation areas compared to the Gilbert catchment. This may hinder achieving species protection and conservation outcomes with respect to proposed development pressure more broadly in the Flinders compared to Gilbert catchment (Rollason and Howell, 2010).

A summary of important habitats has been prepared by searching databases of Ramsar listed wetlands, the Directory of Important Wetlands in Australia (Blackman et al., 1999), the Register of National Estate, nature reserves/protection areas, wetlands and springs and Regional Ecosystem (V7) data from the Queensland Government, assisted by discussion with local community members and Northern Gulf NRM Group, published reports and other local expert knowledge (Figure 2.1).

The Directory of Important Wetlands provides a list and description of wetlands that represent natural functioning, important habitat for animal taxa for lifecycle stages and refuge, contain native plants and animals which are considered endangered or vulnerable at the national level, or wetlands that have historical or cultural significance (Blackman et al., 1999). The Assessment area intersects several wetlands that are included in the national directory, particularly on the coastal plains, and one in the upper Gilbert catchment (Undara larva tubes), and at least one is located entirely within the Assessment area, near Julia Creek (Figure 2.1a). A corresponding summary table for each wetland, size, criteria of importance, and a list of identified threats is provided in Table 2.1.

The Register of National Estate is compiled by the Australian Heritage Commission and recognises sites of environmental, cultural, social or historical significance. Locations relevant to aquatic values are shown in Figure 2.1b, and those important to the Assessment are listed in Table 2.2.

Fish Habitat Areas (FHAs) declared throughout coastal Queensland under the Fisheries Act (1994) are intended to enhance current and future fishing activities, and to protect important habitat for fish and other aquatic fauna (Beumer et al., 1997). Designation of these marine areas is essential in protecting critical wetland habitats which sustain fish and invertebrate (including prawn, crab, worm, shellfish) stocks upon which recreational, commercial and indigenous fishing sectors depend. Sea turtles, dugongs and many shore birds also benefit from these coastal intertidal protection areas. There are two declared Fish Habitat Areas located along the coastal zone within the region (Figure 2.1c). The first is the Staaten-Gilbert Fish Habitat Area (10,175 ha) located between 1 km south of the Gilbert River mouth to 8 km north of the Staaten River mouth. In the Gilbert catchment, the declared Fish Habitat Area extends a short distance upstream, while in the Staaten River it extends up the lower reach of the Staaten River main channel, Staaten North Branch and Vanrook Creek. The second is the Morning Inlet-Boyne River Fish Habitat Area (18,336 ha) located over intertidal regions of the Gulf of Carpentaria and its tributaries between Morning Inlet and Bynoe River, and extending into the lower Flinders River estuary. A third Fish Habitat Area (Nassau River Fish Habitat Area) is located to the north of the Assessment region.

A series of marine reserves and coastal protection zones are present within the Gulf of Carpentaria, declared as part of the Commonwealth's marine reserve network (Figure 2.1c). The designation of these marine reserves is in response to the need to maintain the long-term health and productivity of Australia's coastal marine environment (SEWPaC, 2012a). The Gulf of Carpentaria Marine Reserve is characterised by submerged patches, platform and barrier reefs that form a broken margin around the perimeter of the Gulf of Carpentaria. The offshore waters of the Gulf of Carpentaria region are generally well mixed though heavily influenced by freshwater flows during the monsoon period (Burford and Rothlisberg, 1999). Along the coastal line, the Gulf of Carpentaria coastal zone provides key protection for the ecological functioning, integrity, and biodiversity values for a range of marine flora and fauna, including a number of commercially and recreationally targeted species (Blaber et al., 2010; Brewer et al., 1995; Stobutzki et al., 2001). While many fish and crustacean species utilise the Gulf of Carpentaria waters, from a conservation perspective the most significant and vulnerable species in freshwater and estuarine areas is the freshwater sawfish (*Pristis pristis*; formerly *P. microdon*; Faria et al., 2013)) which is listed as Vulnerable under the Commonwealth EPBC Act, Endangered on the 2000 IUCN Red List of Threatened Species and Critically Endangered in SE Asia (SEWPaC, 2012a). A second fish species in the Assessment area also of high conservation importance is the giant freshwater whipray (*Himantura dalyensis*) (Chin et al., 2010), which was recently split from *H. chaophraya* which is listed as Vulnerable under the 2000 IUCN Red List and Critically Endangered in Thailand (Pogonoski et al., 2002).

There are a number of wetland and springs located across the region, and while small in size, at times, each provide permanent aquatic habitat in an otherwise dry region. These landscape features generally contain specialist plants and animals and often hold high cultural values. The Great Artesian Basin (GAB) underlies most of the northern Gulf region and the Queensland Government has mapped the wetlands and springs it forms at the surface (Fensham and Fairfax, 2003). Additional springs not associated with the GAB occur in the region, namely around the McBride Plateau (draining into the Einasleigh River), the granite springs near Georgetown, Tallaroo hot springs and the upper parts of the Norman, Gilbert, Staaten and Lynd rivers (Burrows, 2004a). In the case of springs, the mapped data include both permanent discharge features and those that have become inactive since European settlement (Ponder, 2002). Many of the springs have probably become inactive across the GAB, while the remaining springs are particularly vulnerable to disturbance from livestock, feral pigs (*Sus scrofa*), ponded pastures, bore-drain construction and cane toads (Burrows, 2004a). The Flinders and Gilbert catchments support a series of national parks, forest reserves and state forests shown as Nature Refuges and Protection Areas (Figure 2.1d). These features provide protection of important terrestrial habitat and areas of high regional ecosystem value. A summary of the refuges and protection areas is provided in Table 2.2.

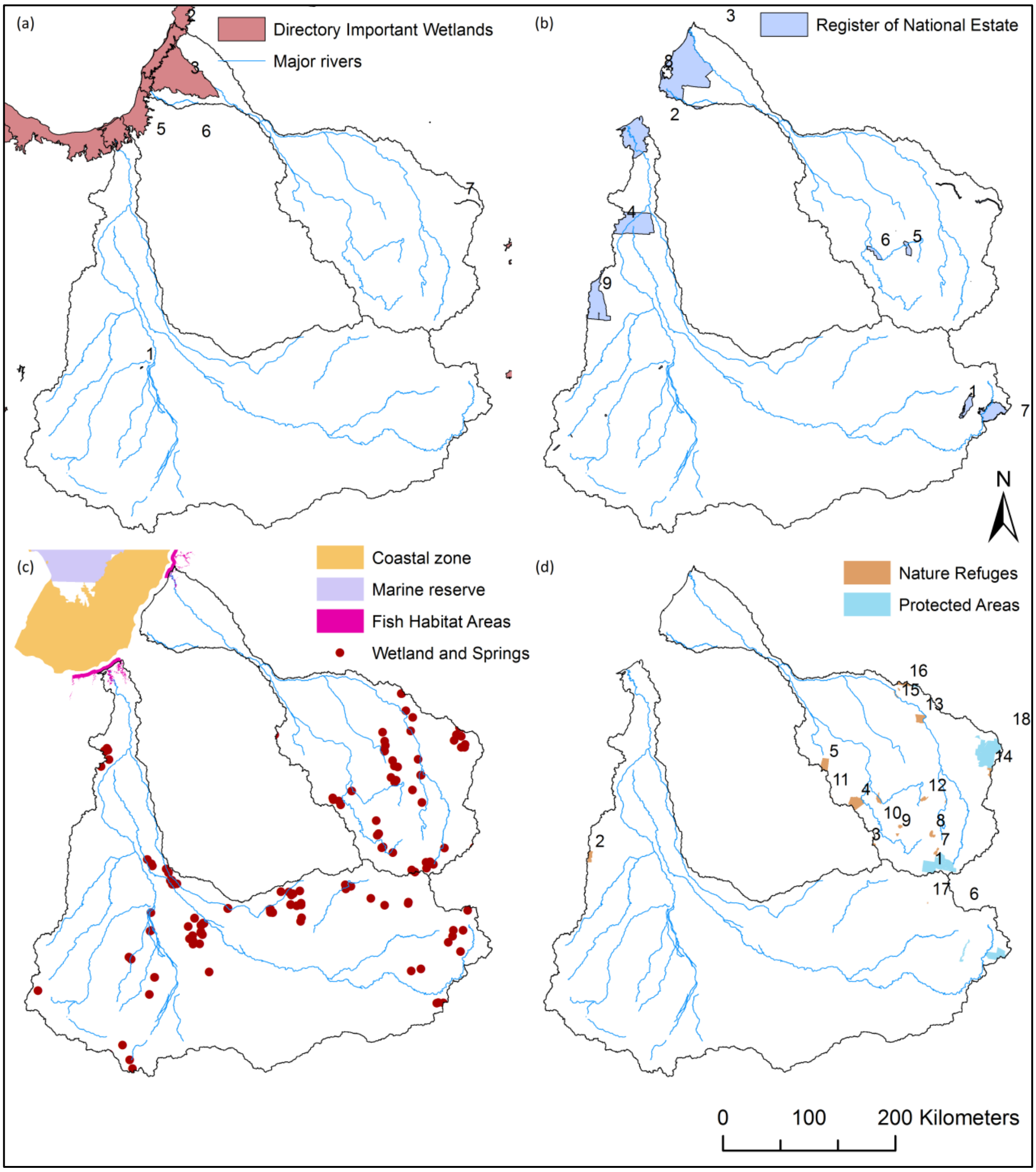


Figure 2.1 Spatial representation of important ecological assets across the Assessment region. a) directory of important wetlands (see Table 2.1); b) register of national estate (Table 2.2); c) marine conservation and coastal protection zones, described wetlands and springs; and d) nature refuges and protection areas (Table 2.3)

Table 2.1 Summary of classified Directory of Important Wetlands in the Southern Gulf Plains (see Figure 2.1a)

WETLAND NUMBER	WETLAND NAME	AREA (HA)	WETLAND TYPE	CRITERIA FOR IMPORTANCE	IDENTIFIED THREATS (BLACKMAN ET AL., 1999)
1	Lignum Swamp	282	• Seasonal and irregular river/stream • Permanent freshwater pond (< 8ha), marshes and swamps on inorganic soils, with emergent vegetation waterlogged for at least most of the growing season • Seasonal/intermittent freshwater ponds and marshes on inorganic soils, includes sloughs, potholes, seasonally flooded meadows, sedge marshes • Shrub swamps, shrub-dominated freshwater marsh, shrub, alder thicket on inorganic soils	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role • Wetland provides important habitat for animal taxa at vulnerable stage of their lifecycle, provides important refuge during adverse drought conditions	Cattle grazing
2	Macaroni Swamp	258	• Seasonal/intermittent freshwater lake (> 8ha), floodplain lake	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role • Wetland provides important habitat for animal taxa at vulnerable stage of their lifecycle, provides important refuge during adverse drought conditions	None evident
3	Smithburne-Gilbert Fan Aggregation	250,320	• Permanent river, stream • Seasonal and irregular river, stream • Riverine floodplain, river flats, flooded river basin, seasonally flooded grassland, savannah and palm savannah • Permanent freshwater lake (> 8ha), including large oxbow lake • Seasonal/intermittent freshwater lake (> 8ha), floodplain lake • Seasonal/intermittent freshwater ponds and marshes on inorganic soils, includes sloughs, potholes, seasonally flooded meadows, sedge marshes • Shrub swamps, shrub-dominated freshwater	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role • Wetland provides important habitat for animal taxon at vulnerable stage of their lifecycle, provides important refuge during adverse drought conditions	Moderate to high cattle grazing, feral pigs, infestation of rubber vine (*Cryptostegia grandiflora*)

WETLAND NUMBER	WETLAND NAME	AREA (HA)	WETLAND TYPE	CRITERIA FOR IMPORTANCE	IDENTIFIED THREATS (BLACKMAN ET AL., 1999)
			marsh, shrub carr, alder thicket on inorganic soils • Freshwater swamp forest, seasonally flooded forest, wooded swamps on inorganic soils		
4	Southeast Karumba Plain Aggregation	336,233	• Marine waters – permanent shallow, < 6m at low tide, includes sea bay and straits • Sand, shingle or pebble beaches, sand bars, spits and sandy islets • Estuarine waters, permanent waters of estuaries and estuarine delta • Intertidal mud, sand or salt flats • Intertidal marshes, including saltmarsh, raised salt marsh, tidal brackish and freshwater marshes • Intertidal forested wetland, includes mangrove swamps, *Nypa* swamps, tidal freshwater swamp forest • Brackish to saline lagoon and marsh with one or more narrow sea connection • Freshwater lagoon and marsh in coastal zone • Non-tidal freshwater forest wetland • Water storage area, reservoirs, barrages, impoundment (> 8ha)	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role • Wetland provides important habitat for animal taxa at vulnerable stage of their lifecycle, provides important refuge during adverse drought conditions • Wetland supports < 1% of national population of any native plant or animal taxa • Supports native plant, animal taxa or communities considered endangered or vulnerable at national level • Outstanding historical or cultural significance	Moderate cattle grazing, feral pigs, infestation of rubber vine
5	Southern Gulf Aggregation	545,353	• Marine waters – permanent shallow, less than 6m at low tide, includes sea bay and straits • Subtidal aquatic beds including kelp, seagrass, tropical marine meadows • Sand, shingle or pebble beaches, sand bars, spits and sandy islets • Estuarine waters, permanent waters of estuaries and estuarine delta • Intertidal mud, sand or salt flats • Intertidal marshes, including saltmarsh, saltings, raised salt marsh, tidal brackish and freshwater	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role • Wetland provides important habitat for animal taxa at vulnerable stage of their lifecycle, provides important refuge during adverse drought conditions • Wetland supports < 1% of national population of any native plant or animal taxa • Supports native plant, animal taxa or communities considered endangered or	Low cattle grazing, feral pigs (*Sus scrofa*), horses, large infestation rubber vine, dredging for Karumba Port development, mining runoff

WETLAND NUMBER	WETLAND NAME	AREA (HA)	WETLAND TYPE	CRITERIA FOR IMPORTANCE	IDENTIFIED THREATS (BLACKMAN ET AL., 1999)
			marshes • Intertidal forested wetland, includes mangrove swamps, *Nypa* swamps, tidal freshwater swamp forest • Brackish to saline lagoon and marsh with one or more narrow sea connections	vulnerable at national level • Outstanding historical or cultural significance	
6	Stranded Fish Lake	67	• Brackish to saline lagoon and marsh with one or more narrow sea connections	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role	None evident
7	Undara Lava Tubes	1254	• Inland, subterranean karst wetland	• Good example of a wetland type occurring within this bioregion • Wetland plays important ecological and hydrological role • Wetland provides important habitat for animal tax at vulnerable stage of their lifecycle, provides important refuge during adverse drought conditions • Supports native plant, animal taxa or communities considered endangered or vulnerable at national level • Outstanding historical or cultural significance	Minimal disturbance, active conservation management as national park

Table 2.2 List of the Register of National Estate lands within the Southern Gulf Plains (Figure 2.1b)

ESTATE NUMBER	SITE	AREA (HA)	STATEMENT OF SIGNIFICANCE	IDENTIFIED THREATS
1	Porcupine Gorge National Park	282	• Sheer walls in gorge rise approximately 120 m above creek bed • Gorge supports permanent waterholes	• Cattle grazing
2	Mutton Hole Wetlands	545,000	• Largest continuous estuarine wetland aggregation in northern Australia • Supported by a complex system of mangroves, samphire flats, grassland, woodland, closed forest, sedge land and freshwater waterholes • Important wet and dry season habitat for migratory and local waterbird and terrestrial bird species, including many rare species • Freshwater waterhole fringes support many fish, turtles and crustacean species, along with many important vegetation species	• Natural vegetation community considered in good condition • Erosion due to grazing has caused damage to permanent water holes and riparian vegetation • Woody weed invasion occurs through much of the wetland • Some pressure from vehicle tracks contributing to erosion
3	Inkerman-Galbraith Area	178,900	• Comprises a mix of estuarine/sub tidal channel environments with extensive mangrove wetlands, samphire and grasses. Numerous tidal channels are narrow and poorly defined in terms of flow. Sections of tidal channels and mud flats are also devoid of vegetation, though support abundant wader bird species • Saline flats occur which are overlain by a series of discontinuous secondary dunes. Ephemeral brackish lakes form between secondary dunes • Seasonal brackish and freshwater swamps with sedges and mixed grasses occur amongst the grass dominated plains. These grasslands support many terrestrial fauna species, including reptiles and birds • South-western region supports a network of semi-permanent and permanent freshwater levees, channels, swamps, lakes, and lagoons. This network is dominated by tea tree, grasses and waterlilies species. Estuarine crocodiles are known to occur throughout freshwater extent, along with freshwater crocodiles. Fish community is expected to include common species within the region	• Some evidence of impact from grazing cattle, though low • Invasive woody weeds • Feral pig population high, contributing pressure to local vegetation and fauna

ESTATE NUMBER	SITE	AREA (HA)	STATEMENT OF SIGNIFICANCE	IDENTIFIED THREATS
			• Little is known about terrestrial and aquatic vertebrate fauna, in particular, reptiles and freshwater turtles	
4	Donors Hills Gulf Plain	178,000	• High diversity of land systems and high wilderness qualities • River channel contains seasonal and permanent water bodies • Vegetation community includes various grassland species, eucalypt, acacias, and melaleuca species	• Grazing pressure • Weed infestation • Feral pig infestation
5	Fish Hole Area, Forsayth	8500	• Diverse and rugged area with a landscape formed by volcanic activity • Includes Robertson River Gorge, permanent waterholes, with numerous other waterholes and waterfalls fed by underground springs • Vegetation community dominated by open eucalypt forest and woodland, lancewood, rocky area vegetation (spinifex and shrubs), river red gums, melaleucas • Waterholes support abundant freshwater fish and turtle species, and also freshwater crocodiles	• Some evidence of impact from grazing cattle, though low • Invasive wood weeds
6	Cobbold Gorge	8900	• High scenic value containing landscape of sandstone cliffs and gorge • Permanent water supports abundant freshwater fish, turtles and freshwater crocodiles • Vegetation communities include pandanus and melaleuca along water course, with spinifex, shrubs, eucalypts, acacias, and woodland with a range of grasses • Both terrestrial and water birds are abundance	• Considered to be in a relative natural state due to remoteness and limited access • Managed stock grazing probably contributes to low impact • Some invasive wood weeds and feral pigs
7	White Mountains National Park Area	42,000	• Very significant area due to location in an area with high wilderness quality values • High number of plant species endemic to this region, with several species newly described. A number of plant species are rare and threatened at state, national and international level • Rare species of butterfly, and pebble-mound mouse, known to occur in this region • Fish species include many widespread species from the	• Invasive wood weeds and feral pigs • Limited vehicle access • Minor impacts from grazing land

ESTATE NUMBER	SITE	AREA (HA)	STATEMENT OF SIGNIFICANCE	IDENTIFIED THREATS
			region	
8	Point Austin Little Tern Site, Point Austin	~ 150	• Sandy Island where the little tern (*Sterna albifrons*) nests each year • Little Tern is on the Commonwealth endangered species list	• Visitor impacts • Vehicles driving through nesting areas • Feral dogs, foxes, pigs
9	Landsborough Gulf Plains	No data available	• No data available	• No data available

Table 2.3 Summary of designated nature refuges and protection areas within the Southern Gulf Plains (Figure 2.1d)

PROTECTION AREA NUMBER	SITE	AREA (HA)	SIGNIFICANCE	POTENTIAL THREATS
1	Blackbraes National Park	52,000	• Creeks dissect the plains and wetlands. Swamps, dams and springs support a variety of waterbirds including ducks, egrets, herons, cormorants and grebes • Allied rock-wallabies *Petrogale assimilis* and monitors *Varanus sp.* are found among the boulders	• Weeds, exotic plants, human disturbances
2	Bullen Bullen Nature Refuge	4615	• Dominated by arid tropical savannas of native grasses • Provides habitat for critically endangered species including the throughton's sheathtail-bat (*Taphozous troughtoni*) and the purple-necked rock-wallaby (*Petrogale pupureicolls*)	• Weeds, exotic plants, human disturbances • Managed stock grazing probably contributes a low impact
3	Bellfield Nature Refuge	28,049	• No data available	• No data available
4	North Head Nature Refuge	18,510	• Sandstone bluffs above eucalypt woodlands • An 11 km reach of the Gilbert River is included, along with several smaller creeks and five permanent springs.	• No data available
5	Torrlinger Nature Refuge	11,450	• No data available	• No data available
6	Clarke Hills Nature Refuge	10,488	• No data available	• No data available
7	Werrington Nature Refuge	2444	• No data available	• No data available
8	Eagles View Nature Refuge	3522	• No data available	• No data available
9	Gilberton	569	• Mainly granite country with grassy eucalypt woodland and black spear grass (*Heteropogon*	• Weeds, exotic plants, human disturbances

PROTECTION AREA NUMBER	SITE	AREA (HA)	SIGNIFICANCE	POTENTIAL THREATS
	Nature Refuge		*contortus)*	• Managed stock grazing probably contributes a low impact
10	Stuarts Spring Nature Refuge	1713	• No data available	• No data available
11	Esmeralda Nature Refuge	23,488	• Includes part of the Gregory Range with deep gorges and permanent waterholes • A recharge area for the Great Artesian Basin • Provides suitable habitat for a number of endangered and near threatened species including the Gouldian finch (*Erythrura gouldiae*), the black-throated finch (*Poephila cincta atropygialis)*, and the pictorella manikin (*Heteromunia pectoralis*)	• Managed stock grazing probably contributes a low impact
12	Newcastle Range - The Oaks Nature Refuge	2946	• No data available	• No data available
13	Tallaroo Springs Nature Refuge	9175	• No data available	• No data available
14	Goanna Spring Nature Refuge	3700	• A geographically significant landscape due to the intrusion of lava flows • Regional ecosystems include dry rainforest and a high diversity of plant species • Provides habitat for rare and threatened plant species	• No data available
15	Dingo Spring Nature Refuge	1786	• Deep permanent waterholes in this 5 km section of the Einasleigh River and Dingo Spring provide important drought refuge for fauna	• No data available
16	Torwood Nature Refuge	44,648	• No data available	• No data available

PROTECTION AREA NUMBER	SITE	AREA (HA)	SIGNIFICANCE	POTENTIAL THREATS
17	Maiden Springs Nature Refuge	172	• No data available	• No data available
18	Forty Mile Scrub National Park	6330	• Features geologically recent basalt lava flows • Fertile basalt soils support semi-evergreen vine-thicket • Near threatened and vulnerable species in the park include the common death adder (*Acanthophis antarcticus),* rainforest habernaria (*Habenaria hymenophylla*), *Ipomoea eriocarpa, Desmodium macrocarpum* and *Lepturus minutus*	• No data available

2.2.2 REGIONAL ECOSYSTEMS

Queensland is divided into 13 bioregions based on similar landscape patterns and features such as geology, climate, and groupings of plants and animals. Across these bioregions, the Queensland Herbarium has mapped the remnant extent of regional vegetation communities using a combination of satellite imagery, aerial photography and on-ground studies. Each ecosystem has an assigned conservation status which reflects the current status within the bioregion. Importantly, these ecosystems are declared in the Vegetation Management Regulation 2000 and classified as either endangered, of concern or, least concern, with intermediate categories also included. These mapping data are crucial in the preparation of development applications that propose land clearing or some other disturbance to Queensland vegetation communities.

Regional vegetation communities in the Flinders and Gilbert catchments consist mostly of a mix of *not of concern dominant* communities across both catchments (Figure 2.2). There are extensive areas that hold *of concern sub-dominant* and *dominant* communities, particularly over much of the south west region of the Cloncurry, upper north east Flinders (Hughenden/Richmond), and the upper Einasleigh and most of the Gilbert River coastal plains. Small areas support *endangered sub-dominant* and *dominant* communities, particularly in the upper Cloncurry and Corella catchment, Hughenden and upper Einasleigh catchment. Much of the regional ecosystems of elevated significance in both catchments are either located along drainage lines or on floodplains thus indicating some form or extent of water dependence. A more detailed examination of vegetation communities within the vicinity of proposed water storage facilities in both catchments is covered in a companion report (Petheram et al., 2013). An updated version of the regional ecosystem mapping will be available in late 2013. Dominant communities are defined as having greater than 50% within a mapped polygon while sub-dominant has less than 50% of the community within the polygon.

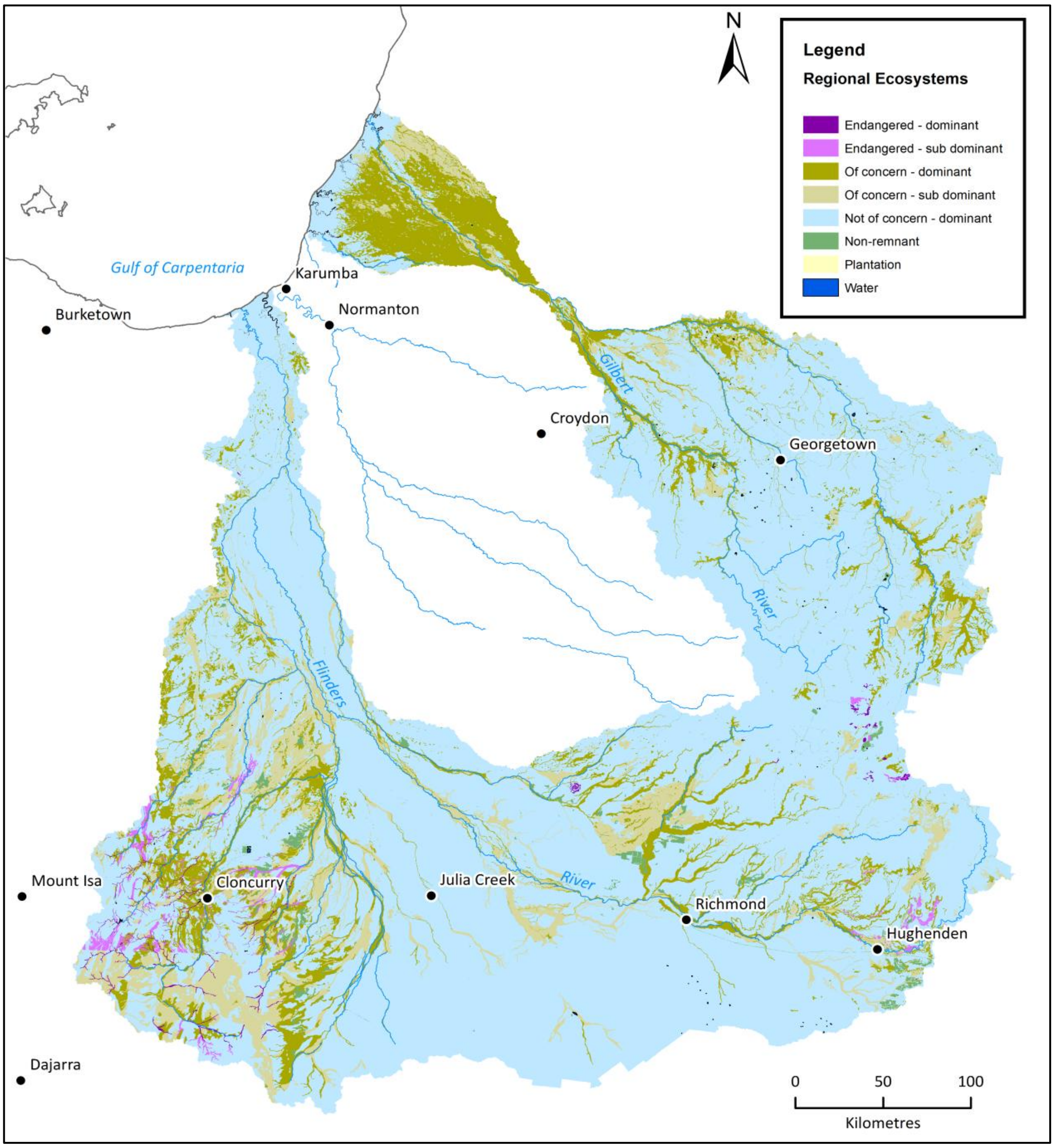


Figure 2.2 Extent of Regional Ecosystems (v7.0) across the Flinders and Gilbert catchments. Data sourced from Queensland Government. Definitions in Vegetation Management Act 1999

2.2.3 COMMUNITY ENVIRONMENTAL VALUES

In Queensland, the Environmental Protection (Water) Policy 2009 (EPP Water) provides the framework for development of Environmental Values (EVs), and management goals and Water Quality Objectives (WQOs) for Queensland waters. These EVs and WQOs once established and agreed to by community, industry and government in a local region, are then featured in Schedule 1 of the EPP Water 2009, thereby becoming part of the legislation (DEHP, 2013). It is these community aspirations and values that are considered by planners and resources managers when making land use development decisions that will affect the utility of waters or water quality for human and ecosystems (Waltham, 2002). The WQOs are the measures, levels or narrative statements necessary to protect or enhance the EVs. The WQOs need not only be numerical (i.e. nutrient concentrations or dissolved oxygen concentrations), but can include biological indictors (e.g. macroinvertebrates and fish), pathogens, and measures of waterway condition (e.g. riparian vegetation condition) (DEHP, 2013).

The process of determining EVs for waterways in the Southern Gulf Plains has been recently completed in collaborative project between Department of Environment, Heritage and Protection (DEHP) and Southern Gulf Catchments NRM (DERM, 2013). The survey focused on the upper and mid Flinders catchment, and the associated tributaries overlaying the Galilee basin. A survey was posted to catchment stakeholders, combined with follow-up discussions. However, unfortunately a limited response rate suggests that the report would under represent the full cross-section of stakeholders, so some caution is needed in interpreting the results, in particular when comparing the relative importance of one identified EV with another (DERM, 2013). This document sets an important framework for further engagement with additional stakeholder in future iterations of this process. A similar process of community engagement has not been completed in the Gilbert catchment. As part of the Assessment, a socioeconomic analysis has been completed for both the Flinders and Gilbert catchments and a full account of the results can be found in Crossman et al. (2013). Water in the context of the Assessment also has specific values, rights and interest in relation to development potential by local Indigenous groups, and is examined in a companion report (see Barber, 2013).

2.3 Flinders catchment

The Flinders catchment has an area of 109,000 km^2 and a population of about 6000 people (Figure 2.3). The Flinders catchment has a semi-arid tropical climate. The mean and median annual rainfall, spatially averaged across the catchment, are 492 mm and 454 mm, respectively (Petheram and Yang, 2013). However, the historical annual rainfall series for the Flinders catchments shows considerable variation between years (Figure 2.4). The highest mean annual rainfall (1310 mm) for the catchment occurred in 1974, and was nearly three times the median annual rainfall value. Spatially, mean annual rainfall varies from about 800 mm on the coast in the north of the catchment to about 350 mm in the south.

A defining characteristic of the climate of the Flinders catchment is the seasonality of rainfall, with 88% of rainfall occurring during the wet season (November to April inclusive) (Figure 2.5). The highest median monthly rainfall in the Flinders catchment occurs during the months of January and February (~100 mm). The months with the lowest median rainfall are July and August (~ 0.5 mm). The Flinders catchment has a mean annual areal potential evaporation of 1862 mm. Mean wet and dry season potential areal evaporation are 1115 mm and 762 mm respectively. The majority of the Flinders catchment experiences a mean annual rainfall deficit of greater than 600 mm. The climate of the Flinders catchment is described in more detail in a companion technical report by the climate activity (Petheram and Yang, 2013).

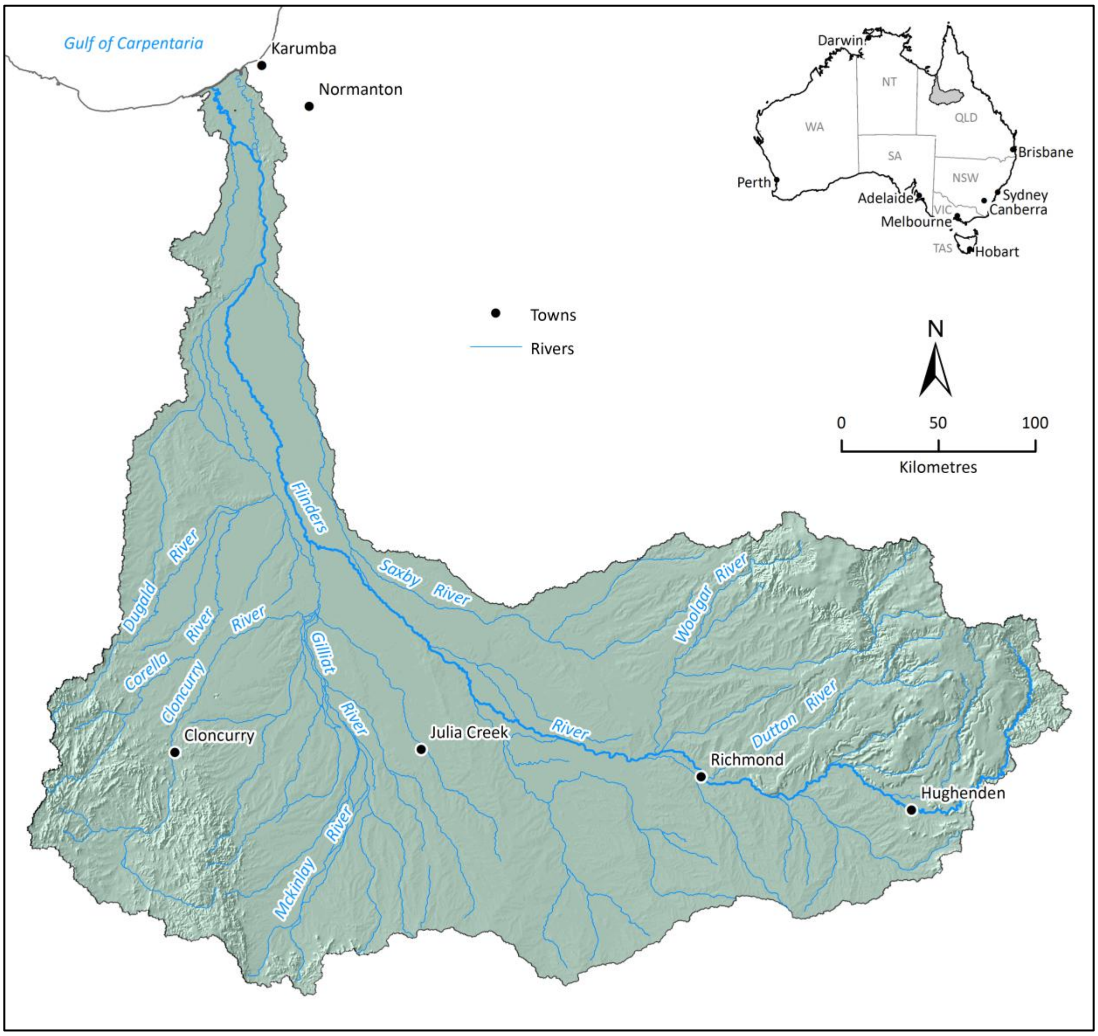


Figure 2.3 Relief map of the Flinders catchment showing main rivers and townships

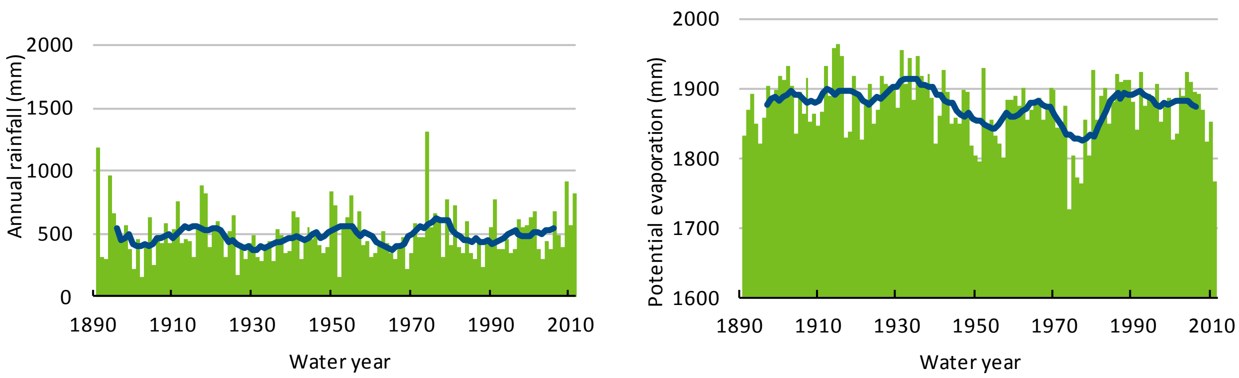


Figure 2.4 Historical mean annual rainfall and areal potential evaporation in the Flinders catchment (Petheram and Yang, 2013)

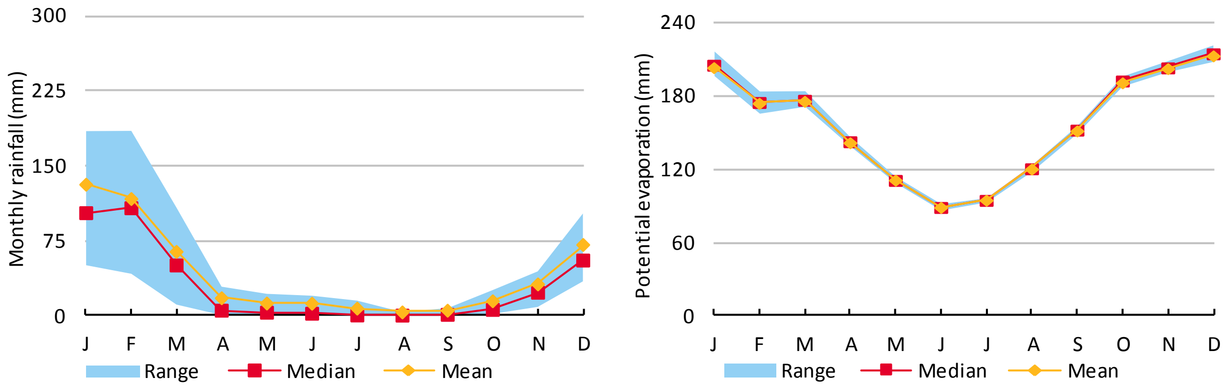


Figure 2.5 Monthly rainfall and areal potential evaporation averaged over the Flinders catchment (the range is the 20th to 80th percentile monthly rainfall) (Petheram and Yang, 2013)

2.4 Gilbert catchment

The Gilbert catchment is located in the Gulf region of north west Queensland (Figure 2.6) and covers an area of 46,200 km^2. It has a population of approximately 1200 with one urban centre in Georgetown (population of 243; Petheram and Yang, 2013). It has a semi-arid tropical climate, with a mean and median annual rainfall spatially averaged across the catchment are 775 mm and 739 mm respectively (Petheram and Yang, 2013). The historical annual rainfall series for the Gilbert catchment shows considerable variation between years. The highest catchment mean annual rainfall (2187 mm) occurred in 1974, and was nearly three times the median annual rainfall value (Figure 2.7). Spatially, mean annual rainfall varies from about 1050 mm on the coast in the north of the catchment to about 650 mm in the south-east of the catchment.

A defining climate characteristic of the Gilbert catchment is the seasonality of rainfall (Figure 2.8), with 93% of rainfall occurring during the wet season (November to April inclusive). The highest median monthly rainfall in the Flinders catchment occurs during the months of January and February (~200 mm). The months with the lowest median rainfall are July and August (~0.5 mm). The Gilbert catchment has a mean annual areal potential evaporation of 1868 mm. Mean wet and dry season areal potential evaporation is 1067 mm and 815 mm respectively. The majority of the Gilbert catchment experiences a mean annual rainfall deficit of greater than 600 mm.

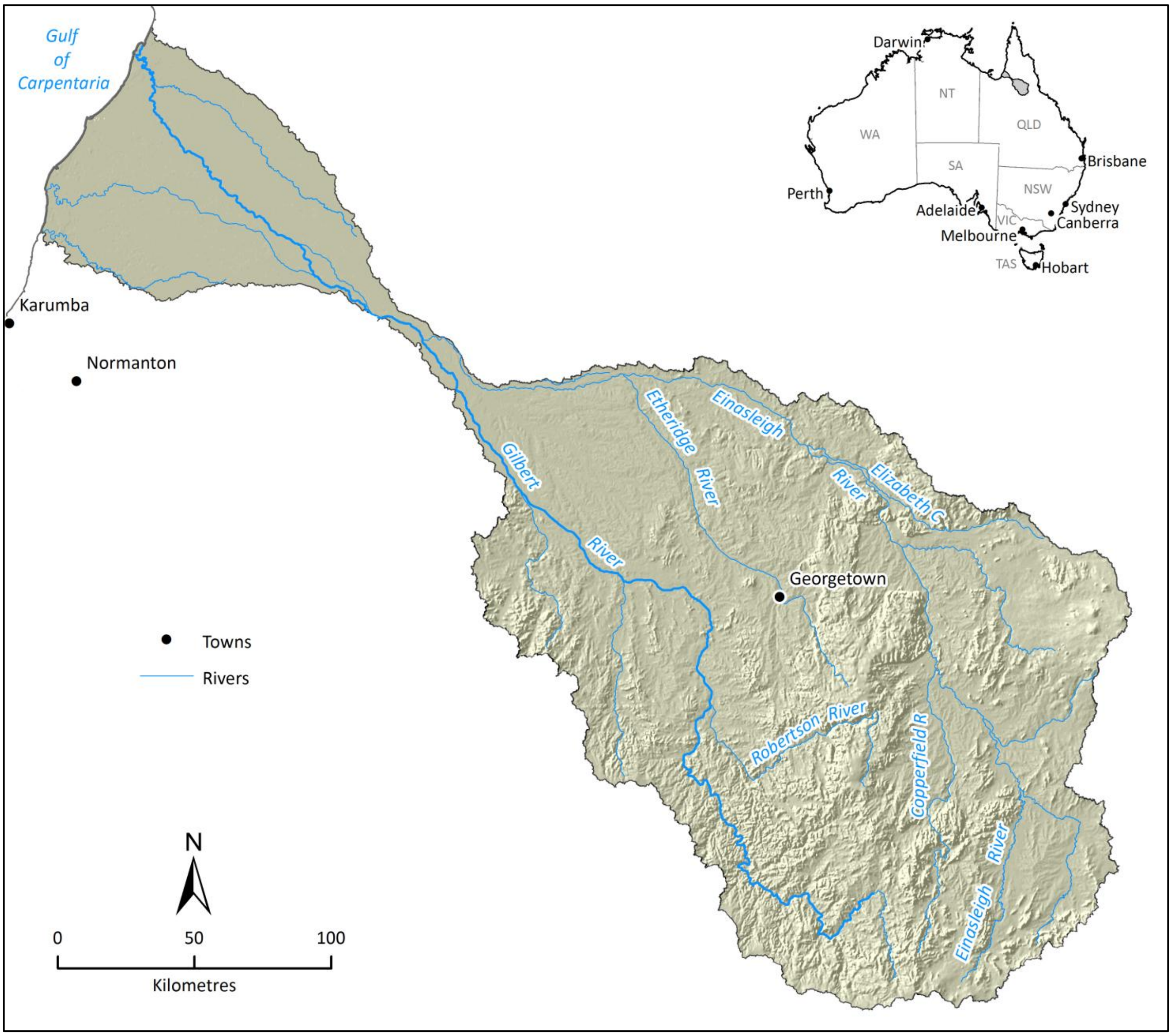


Figure 2.6 Relief map of the Gilbert catchment showing main rivers and townships

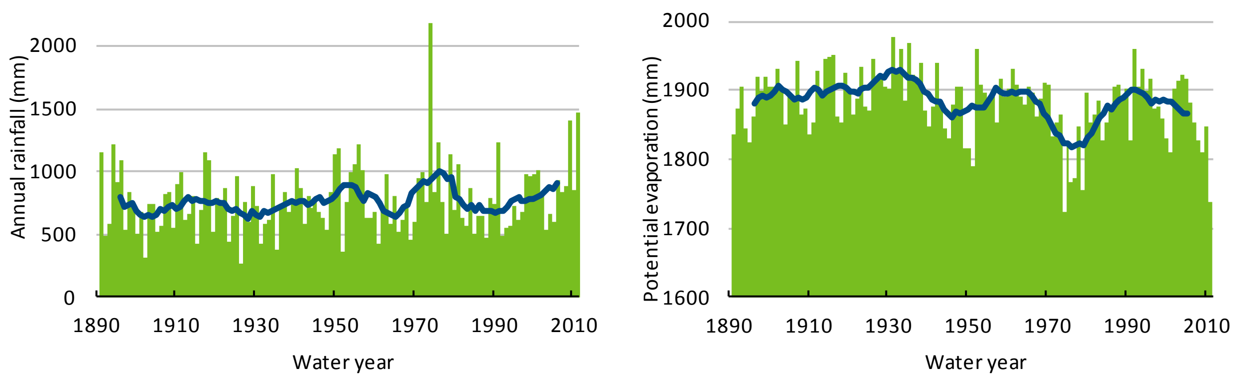


Figure 2.7 Historical mean annual rainfall and areal potential evaporation in the Gilbert catchment (Petheram and Yang, 2013)

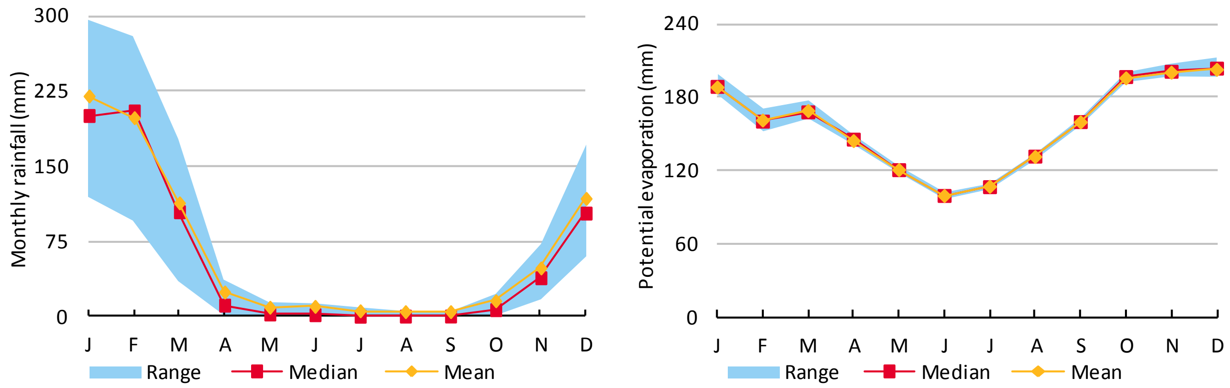


Figure 2.8 Monthly rainfall and areal potential evaporation averaged over the Gilbert catchment (the range is the 20th to 80th percentile monthly rainfall) (Petheram and Yang, 2013)

2.5 Rainfall and streamflow during the Assessment

In a review and classification of the hydrology of northern Australian river systems Kennard et al. (2010) revealed that the upper and middle reaches of the Flinders catchment followed either class 12 (variable summer; extremely intermittent) or class 11 (unpredictable summer; highly intermittent) streamflow patterns, while the downstream reaches of the catchment have a more predictable streamflow pattern (class 10). For the Gilbert catchment the majority of the gauged sites were grouped into class 10 (predictable summer; highly intermittent flow), although a stable summer base flow (class 3) was also identified. An extensive appraisal of the river hydrology in both catchments has been completed in a companion report as part of the Assessment (Lerat et al., 2013), wetland connectivity in lower catchment regions and coastal floodplains is presented in another companion report (Dutta et al., 2013), while river system flows under climate change and proposed development scenarios is in another companion report (Petheram et al. unpublished report). During the Assessment, McJannet et al. (2013) examined the persistence of dry season waterholes and determined that the duration of zero flow is typically much longer in the Flinders catchment, particularly in the Cloncurry and mid-Flinders, compared to the Assessment areas in the upper Gilbert catchment.

The Flinders study area lies within one of the driest areas of northern Australia. The Gilbert is somewhat wetter and more likely to receive wet season rain (Figure 2.9). Rain events large enough to generate significant run off occur almost exclusively during wet season months and even then are relatively rare (4 to 7 days per year in the Flinders and 8 to 16 days per year in the Gilbert; Figure 2.10). Rainfall heavy enough to generate significant stream flow is even less frequent, and is generally associated with brief but intense rain events associated with tropical lows and cyclones. Rain events large enough to generate significant runoff occur almost exclusively during wet season months and even then are relatively rare (4 to 7 days per year in the Flinders and 8 to 16 days per year in the Gilbert). Rainfall heavy enough to generate significant stream flow is even less frequent, and is generally associated with brief but intense rain events associated with tropical lows and cyclones. The upper catchment areas (where the Assessment area is situated) have limited water retention capacity hence storm water residence times are relatively low and hydrographs are quite peaky. Hence the vast majority of storm waters and accompanying contaminants generated pass through the river system rapidly, within a few days of rainfall, in the smaller upstream streams and tributaries, and within a few weeks in the main river channels (Butler, 2008). The quantities of water that are discharged from the river at other times of the year (i.e. for most of the year) are negligible compared to the event flows, especially in the Flinders catchment (Lerat et al., 2013).

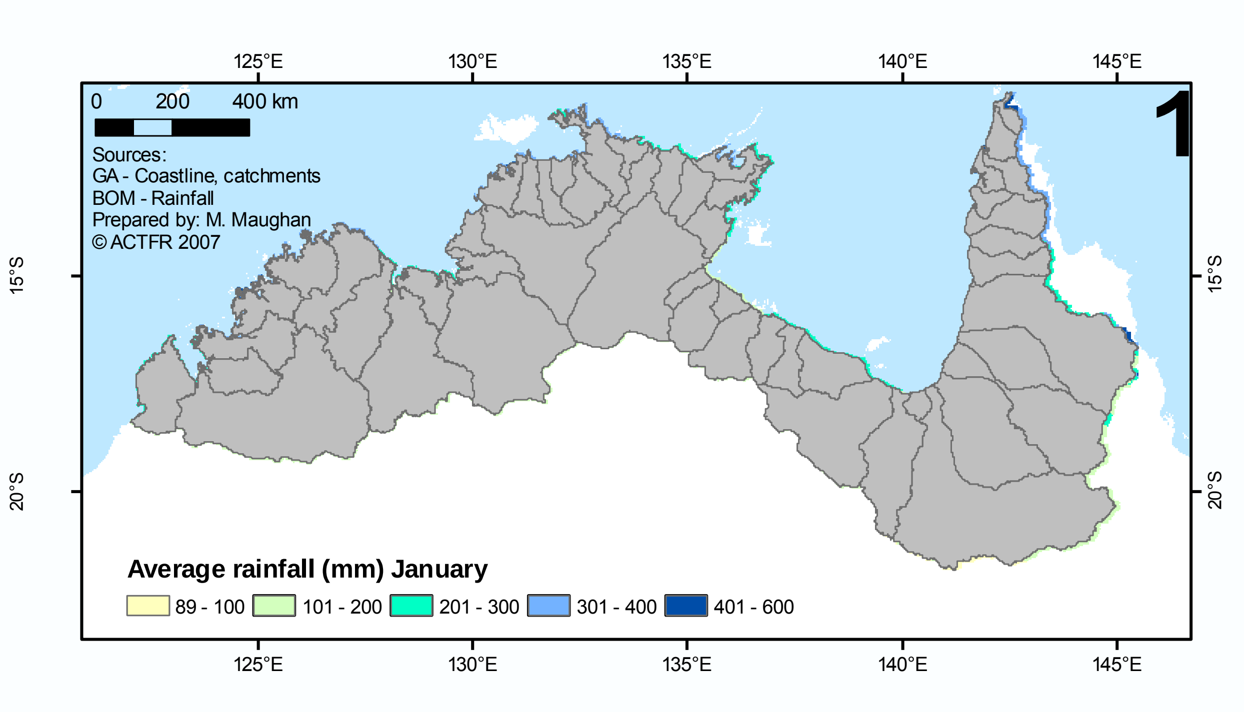


Figure 2.9 Mean (average) rainfall (mm) for January mapped for northern Australia (Butler, 2008)

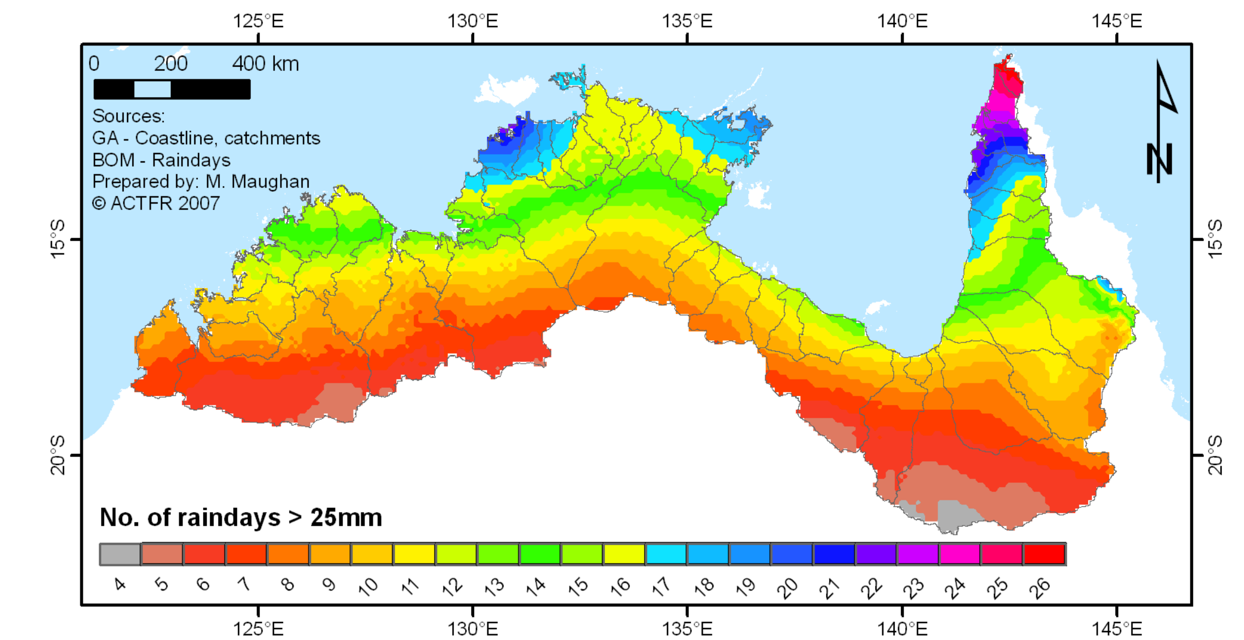


Figure 2.10 Number of rain days > 25mm across northern Australia (Butler, 2008)

During the Assessment, flow was much lower than compared to the previous five years for the region (Figure 2.11). The failed wet season rainfall and flow during the 2013 wet season and thereby extended dry season (drought) has been a major limiting factor in the collection of adequate data during the Assessment to strictly examine the ecological and water quality conditions across the hydrograph. Many waterholes received no inflow. Some minor flow was recorded in the Flinders catchment at the Cloncurry and

Richmond gauging station, and also in the Gilbert catchment at Mt Surprise and Rockfields gauging station, though this was not nearly sufficient to fully examine the hypotheses set initially. Additional focus was therefore placed on collecting water quality samples, and not on ecological sampling. Post flush data were subsequently not collected, however, water sampling continued over the Assessment, concluding May 2013, in order provide an extended baseline water quality database in both catchments. This should be considered in the interpretation of the data presented.

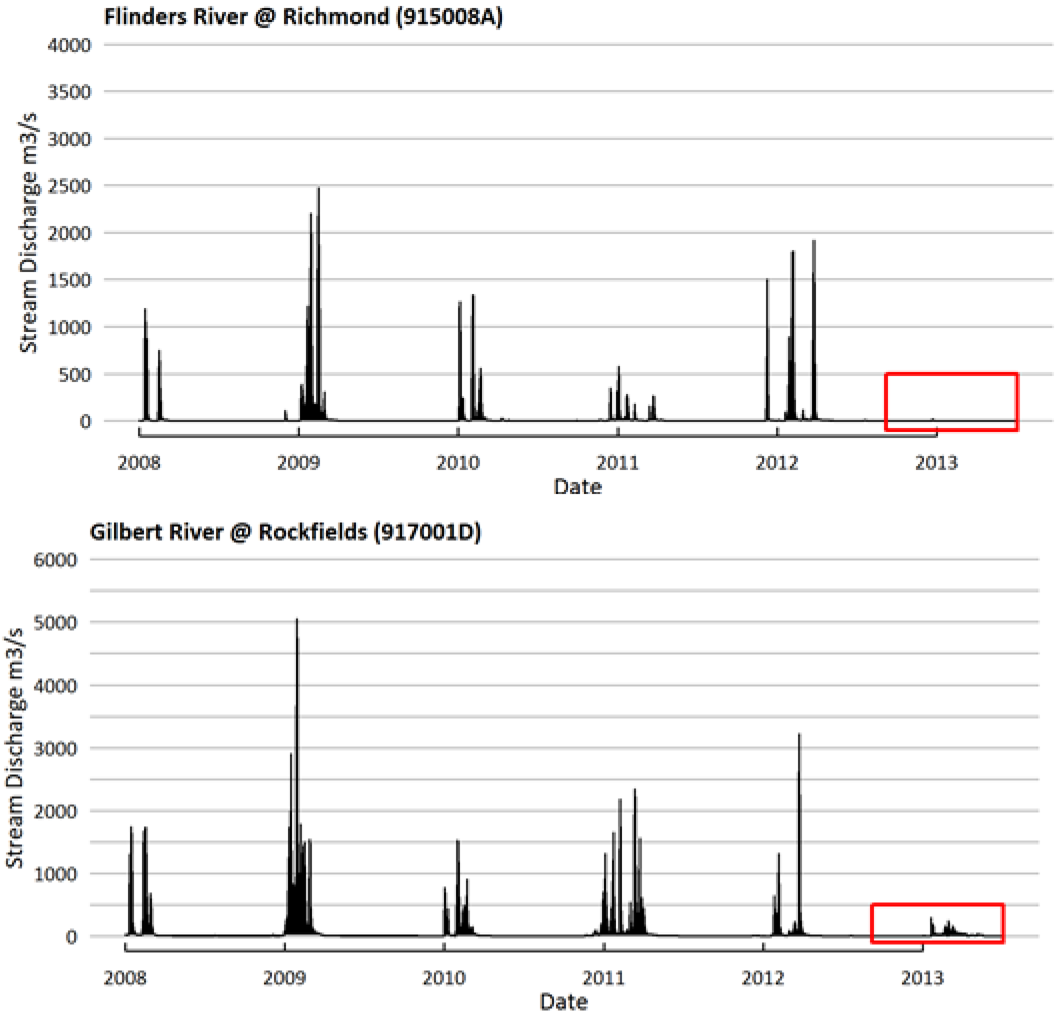


Figure 2.11 Rainfall records over the past few years at selected stations in Flinders and Gilbert catchments. Red box is flow recorded over the course of the Assessment

2.6 Waterholes investigated in the Assessment

Twenty waterholes were included in this investigation, ten in each catchment (Figure 2.12). A comprehensive description of each waterhole is provided in Appendix E (Flinders catchment) and Appendix F (Gilbert catchment). The waterholes investigated here did not always match the refugia identified by McJannet et al. (2013) (see Figure 2.13 and Figure 2.14). This was due in part to the remote nature and difficulties accessing some waterholes, particularly during anticipated wet season flush sampling, but was also a function of the fact that both investigations were run concurrently. Hence the information on waterhole distribution and permanency was not available during the final selection of waterhole sites in this investigation. A summary of the level of field work effort in the Flinders and Gilbert catchments is provided in Table 2.4 and Table 2.5 respectively. Waterholes were visited during each survey, though several waterholes were visited more frequently to achieve a more explicit temporal assessment.

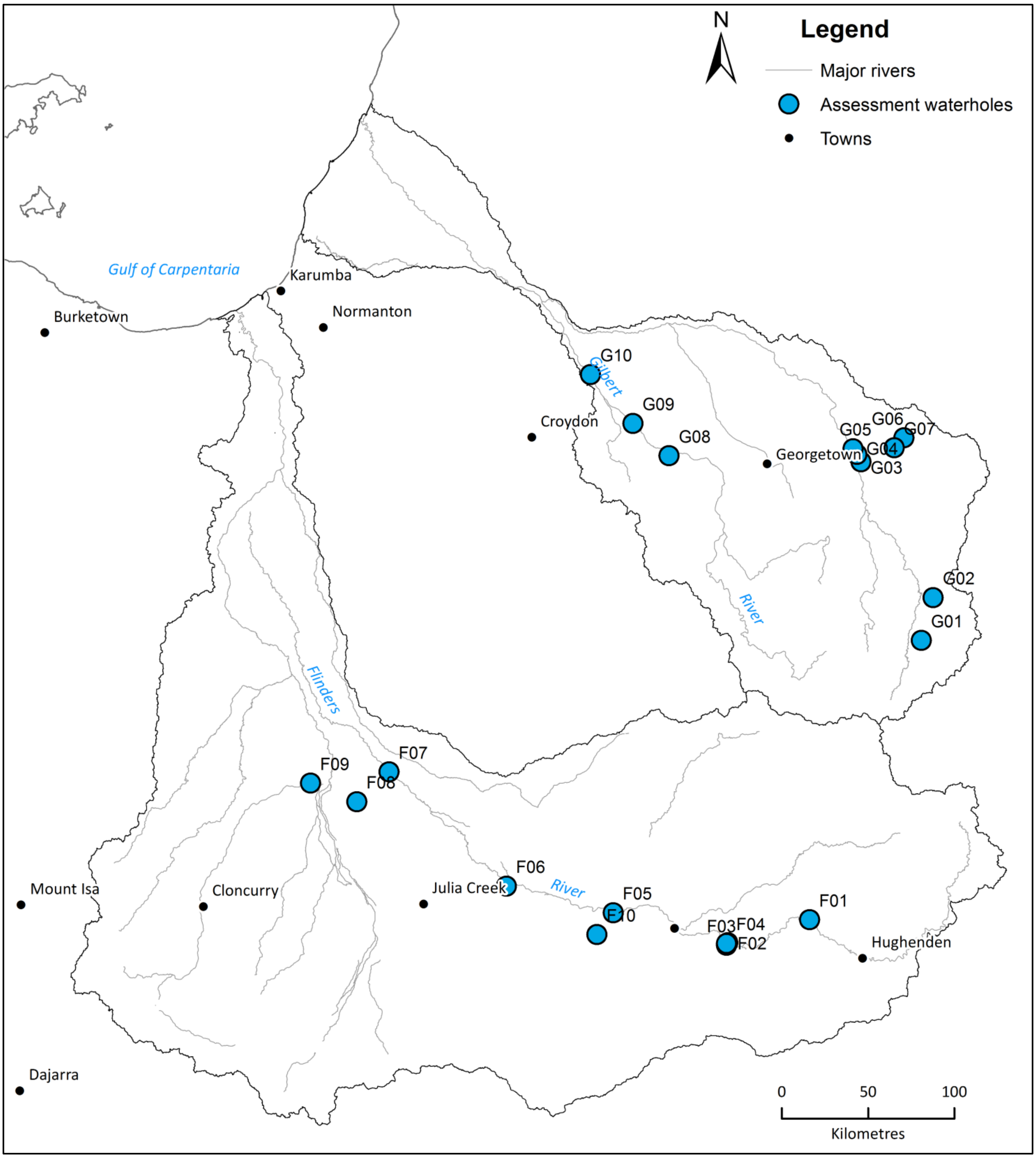


Figure 2.12 Location of waterholes investigated in the Flinders and Gilbert catchments during the Assessment

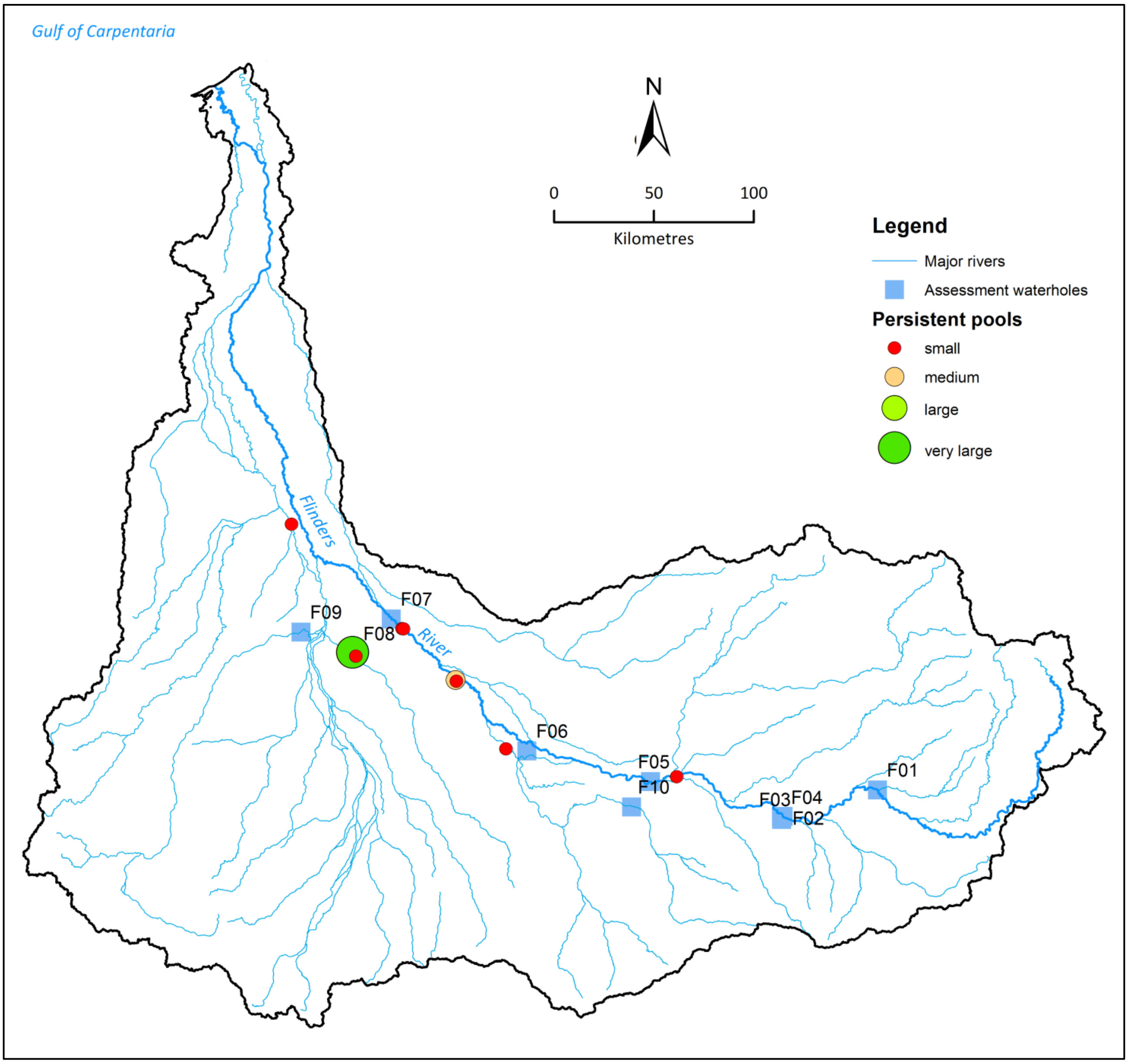


Figure 2.13 Location of key refugia identified in the Flinders catchment (McJannet et al., 2013) relative to the waterholes in the Assessment

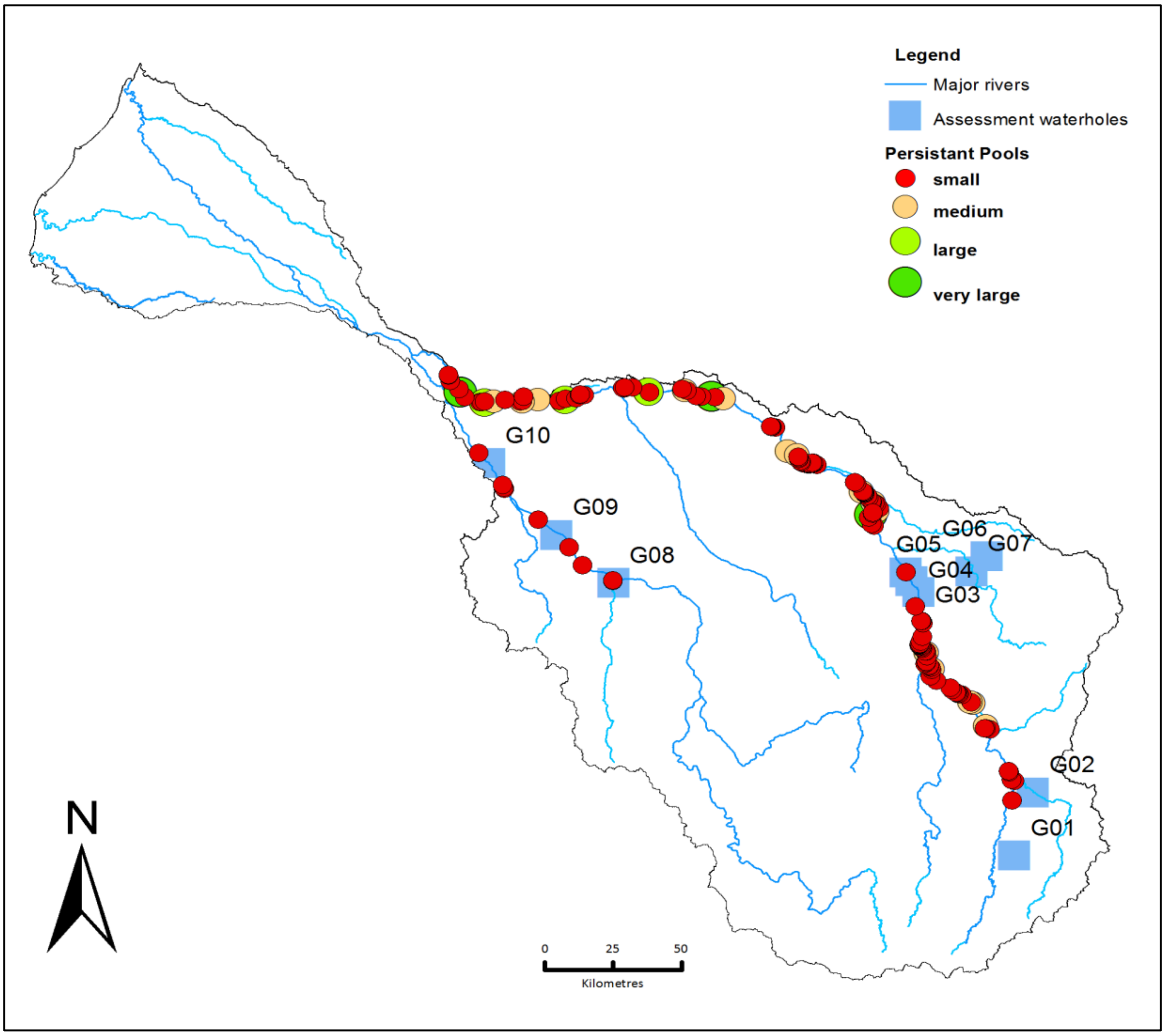


Figure 2.14 Location of key refugia identified in the Gilbert catchment (McJannet et al., 2013) relative to the waterholes in the Assessment

Table 2.4 Flinders catchment sampling schedule

WATERHOLE	SURVEY	DATE SAMPLED	TIME SAMPLED	HYDROLOGY STAGE	PROFILING/ WATERHOLE ASSESSMENT	WATER SAMPLE	HYDROLAB DATA COLLECTED	FISH ASSEMBLAGE	SEDIMENT SAMPLE	AQUATIC INVERTEBRATES
F01	Survey 1	18.09.12	13:35	No flow	ò	ò				
	Survey 2	29.10.12	08:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 5	07.12.12	12:00	No flow	ò	ò		ò	ò	ò
	Survey 6	19.12.12	13:45	Swift flow	ò	ò				
	Survey 7	17.01.13	09:30	Base flow	ò	ò				
	Survey 9	01.06.13	08:30	No flow	ò					
F02	Survey 1	07.09.12	15:30	No flow	ò	ò				
	Survey 2	28.10.12	15:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 6	19.12.12	17:30	Swift flow	ò	ò				
	Survey 7	14.01.13	13:00	Base flow	ò	ò				
	Survey 8	23.02.13	12:50	No flow	ò	ò				
	Survey 9	31.05.13	14:45	No flow						
F03	Survey 1	07.09.12	12:30	No flow	ò	ò				
	Survey 2	28.10.12	12:30	No flow	ò	ò	ò	ò	ò	ò
	Survey 5	08.12.12	16:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	14.01.13	15:00	No flow	ò	ò				
	Survey 9	31.05.13	14:50	Dry						
F04	Survey 1	18.09.12	08:00	No flow	ò	ò				
	Survey 2	28.10.12	09:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 5	08.12.12	09:00	No flow	ò	ò	ò		ò	ò
	Survey 6	19.12.12	17:00	Dry						
	Survey 7	14.01.13	14:45	Dry						
	Survey 9	31.05.13	15:30	Dry						
F05	Survey 1	08.09.12	09:00	No flow	ò	ò				
	Survey 2	27.10.12	12:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 5	09.12.12	10:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 6	20.12.12	07:00	Swift flow	ò	ò				
	Survey 8	23.02.13	13:00	No flow	ò	ò				
	Survey 9	31.05.13	10:00	No flow	ò					
F06	Survey 1	08.09.12	09:00	Dry						
	Survey 6	20.12.12	08:00	Dry						
	Survey 9	31.05.13	08:00	Dry						
F07*	Survey 1	09.09.12	11:00	No flow	ò	ò				
	Survey 2	25.10.12	15:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 5	11.12.12	12:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 6	20.12.12	11:00	No flow	ò	ò	ò			
	Survey 7	15.01.13	13:30	No flow	ò	ò	ò			
	Survey 8	22.02.13	09:00	No flow	ò	ò				
					ò					

WATERHOLE	SURVEY	DATE SAMPLED	TIME SAMPLED	HYDROLOGY STAGE	PROFILING/ WATERHOLE ASSESSMENT	WATER SAMPLE	HYDROLAB DATA COLLECTED	FISH ASSEMBLAGE	SEDIMENT SAMPLE	AQUATIC INVERTEBRATES
F07*	Survey 9	30.05.13	15:00	No flow						
F08*	Survey 1	09.09.12	13:30	No flow	ò	ò				
	Survey 2	25.10.12	09:00	No flow	ò	ò		ò	ò	ò
	Survey 5	11.12.12	10:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 6	20.12.12	08:35	No flow	ò	ò				
	Survey 7	15.01.13	15:30	No flow	ò	ò	ò			
	Survey 8	22.02.13	12:00	No flow	ò	ò				
	Survey 9	30.05.13	17:30	No flow	ò					
F09	Survey 1	10.09.12	08:00	No flow	ò	ò				
	Survey 2	26.10.12	11:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 5	10.12.12	10:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 6	20.12.12	10:00	No flow	ò	ò				
	Survey 7	15.01.13	09:00	Recent flow	ò	ò				
	Survey 9	30.05.13	11:30	No flow	ò					
F10	Survey 1	08.09.12	11:30	No flow	ò	ò				
	Survey 2	27.10.12	09:00	No flow	ò	ò	ò			ò
	Survey 3	15.11.12	06:30	Dry						
	Survey 5	01.12.12	16:00	Dry						
	Survey 7	20.01.13	10:30	Dry						
	Survey 9	27.05.13	10:30	Dry						

* Hydrolab deployed for extended period; F7 – 11/12/12 to 22/12/12, 16/1/13 to 04/02/13; F8 – 11/12/12 to 29/12/12, 16/1/13 to 5/2/13

Table 2.5 Gilbert catchment sampling schedule

WATERHOLE	SURVEY	DATE SAMPLED	TIME SAMPLED	HYDROLOGY STAGE	PROFILING/ WATERHOLE ASSESSMENT	WATER SAMPLES	HYDROLAB DATA COLLECTED	FISH ASSEMBLAGE	SEDIMENT SAMPLES	AQUATIC INVERTEBRATES
G01	Survey 2	08.10.12	12:00	Base flow	ò	ò	ò		ò	ò
	Survey 3	15.11.12	06:45	Base flow	ò	ò		ò		
	Survey 5	01.12.12	16:15	Base flow	ò	ò	ò	ò	ò	ò
	Survey 7	20.01.13	10:00	Base flow	ò	ò				
	Survey 9	27.05.13	10:30	Base flow	ò					
G02	Survey 2	09.10.12	07:35	No flow	ò	ò	ò		ò	ò
	Survey 3	14.11.12	14:30	No flow	ò	ò	ò	ò		
	Survey 5	01.12.12	12:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	20.01.13	12:00	Recent flow	ò	ò				
	Survey 9	27.05.13	12:50	No flow	ò					
G03	Survey 2	09.10.12	15:30	No flow	ò	ò	ò		ò	ò
	Survey 3	14.11.12	07:30	No flow	ò	ò	ò	ò		
	Survey 4	28.11.12	11:20	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	18.01.13	10:00	Recent flow	ò	ò				
	Survey 8	19.02.13	12:00	No flow	ò	ò				
	Survey 9	28.05.13	08:30	No flow	ò					
G04*	Survey 2	10.10.12	10:00	No flow	ò	ò			ò	ò
	Survey 3	13.11.12	10:30	No flow	ò	ò	ò	ò		
	Survey 4	28.11.12	07:55	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	18.01.13	11:20	Recent flow	ò	ò	ò			
	Survey 9	28.05.13	10:00	No flow	ò					
G05	Survey 2	10.10.12	15:30	No flow	ò	ò	ò		ò	ò
	Survey 3	13.11.12	15:00	No flow	ò	ò	ò	ò		
	Survey 4	27.11.12	16:20	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	18.01.13	14:30	Recent flow	ò	ò				
	Survey 8	19.02.13	07:00	No flow	ò	ò				
	Survey 9	28.05.13	11:30	No flow	ò					
G06*	Survey 2	11.10.12	07:30	Base flow	ò	ò	ò		ò	ò
	Survey 3	10.11.12	09:00	Base flow	ò	ò	ò			
	Survey 4	27.11.12	06:30	Base flow	ò	ò	ò	ò	ò	ò
	Survey 7	18.01.13	07:00	Base flow	ò	ò	ò			
	Survey 8	18.02.13	14:30	Recent flow	ò	ò				
	Survey 9	27.05.13	16:00	Base flow	ò					
G07	Survey 2	11.10.12	14:10	Base flow	ò	ò	ò		ò	ò
	Survey 3	10.11.12	06:00	Base flow	ò	ò	ò	ò		
	Survey 4	27.11.12	12:45	Base flow	ò	ò	ò	ò	ò	ò
	Survey 7	20.01.13	07:00	Base flow	ò	ò				
	Survey 9	28.05.13	06:30	Base flow	ò					

WATERHOLE	SURVEY	DATE SAMPLED	TIME SAMPLED	HYDROLOGY STAGE	PROFILING/ WATERHOLE ASSESSMENT	WATER SAMPLES	HYDROLAB DATA COLLECTED	FISH ASSEMBLAGE	SEDIMENT SAMPLES	AQUATIC INVERTEBRATES
G08	Survey 2	14.10.12	11:00	No flow	ò	ò	ò		ò	ò
	Survey 3	12.11.12	12:30	No flow	ò	ò	ò	ò		
	Survey 4	30.11.21	12:05	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	19.01.13	14:00	Recent flow	ò	ò				
	Survey 8	20.02.13	12:30	Recent flow	ò	ò				
	Survey 9	29.05.13	08:30	No flow	ò					
G09	Survey 2	13.10.12	16:10	No flow	ò	ò	ò		ò	ò
	Survey 3	12.11.12	06:45	No flow	ò	ò		ò		
	Survey 4	30.11.12	07:00	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	19.01.13	10:30	Recent flow	ò	ò				
	Survey 8	20.02.13	15:00	No flow	ò	ò				
	Survey 9	29.05.13	11:00	No flow	ò					
G10	Survey 2	13.10.12	09:00	No flow	ò	ò	ò		ò	ò
	Survey 3	11.11.12	16:30	No flow	ò	ò	ò	ò		
	Survey 4	29.11.12	15:40	No flow	ò	ò	ò	ò	ò	ò
	Survey 7	19.01.13	08:45	Swift flow	ò	ò				
	Survey 8	20.02.13	09:30	Swift flow	ò	ò				
	Survey 9	29.05.13	14:00	No flow	ò					

* Hydrolab deployed for extended period; G4 – 18/1/13 to 9/2/13; G6 – 18/1/13 to 18/2/13

3 Waterhole water and sediments

3.1 Summary points

- Waterholes in the Flinders catchment were more turbid than waterholes in the Gilbert catchment;
- The euphotic depths in Flinders catchment waterholes were low enough to support the hypothesis that most of the primary productivity occurs in the surface waters with little light and primary productivity occurring in benthic waters. Euphotic depth values in the Gilbert catchment waterholes generally exceeded the total water depth suggesting that the light climate allows benthic primary production;
- Many stream reaches in the Flinders catchment, and a number in the Gilbert catchment did not receive sufficient groundwater inputs to sustain baseflow. However, study sites located on Bundock Creek, Elizabeth Creek and Junction Creek catchment (all in the upper Gilbert catchment investigation area) sustained perennial baseflow which is critical in maintaining good water quality conditions;
- Most waterholes in the Flinders catchment were thermally stratified, by several degrees Celsius, due to the turbid surface waters retaining heat compared to the Gilbert catchment waterholes which were well mixed, though this fluctuated between day and night;
- Diel dissolved oxygen cycling was detected in all waterholes, with minimum concentrations falling to below 30% saturation on a number of occasions, particularly so in the stratified Flinders catchment waterholes where circulation was minimal. Following a small flow event, a single waterhole (F09) had dissolved oxygen concentrations that fell promptly to below conditions that would cause acute stress on fish and aquatic invertebrates – whether this same pattern occurs in other waterholes more broadly was not specifically examined due to the low wet seasonal rainfall experienced during the Assessment;
- pH was quite high in most waterholes though this is likely in response to the time of day when profiling was completed. On several occasions the measured pH was approaching 9.0 which is the point where ammonia toxicity increases substantially;
- A significant proportion of nitrogen and phosphorus was in dissolved form which is typical for grazed catchments. The availability of dissolved nutrients, particularly in the Flinders catchment waterholes, allows for rapid uptake by primary producers; and
- Chlorophyll-*a* (sum of the active chlorophyll-*a* and inactive phaeophytin-*a*) was higher in waterholes in the Flinders catchment than those in the Gilbert catchment. The small inflow in several sites was not large enough to flush waterholes, with concentrations increasing rapidly following flow. Lowest concentrations were recorded in waterholes with highest groundwater flow (i.e. Gilbert River sites; G06 and G07). A strong positive correction was found between diel dissolved oxygen amplitude and chlorophyll-*a* indicating that much of the cycling is attributed exclusively to phytoplankton, at least under no flow conditions.

3.2 Introduction

The seasonal conditions experienced across tropical northern Australia typically consist of brief (sometimes over two weeks) wet season rainfall followed by months of dry conditions (CSIRO, 2009b). Consequently surface flow is often episodic and most riverine waterholes experience prolonged periods of seasonal stagnation and are frequently at risk of drying out. Low water levels can result in the development of poor and sometimes critically limiting water quality in the remnant waterholes. These waterholes at the same time are important refugia for many aquatic species during the dry season until the next significant rainfall reinstates flow through the system (Butler and Burrows, 2005). Further reductions in waterhole size and volume owing to extraction for irrigation, could lead to significant negative changes in aquatic habitat quality and suitability.

On the falling limb of the hydrograph, after rainfall has ceased, flows may briefly be driven by flood water returning to the river channel after having been temporarily retained on floodplains (which is not a main contributor for the waterholes in this Assessment but potentially a more significant contributor in downstream reaches with substantial floodplain development) and delayed shallow subsurface flow (often termed through flow) of rainwater that has infiltrated land surfaces proximal to stream channels (Butler, 2008). The rapidity of flow recession on the falling limb of the hydrograph at many gauging stations in the Assessment indicates that such processes only maintain flow for a brief period (hours to a few weeks depending on the size of the stream and magnitude of the rain event) (Lerat et al., 2013). Baseflow (i.e. flow which persists during prolonged dry spells) is almost exclusively a result of subsurface inflows of groundwater. Nearly all river reaches in the Flinders catchment and most in the Gilbert catchment do not receive sufficient groundwater inputs to sustain baseflow throughout the dry season. Bundock Creek (containing waterhole G01), Elizabeth Creek (G06) and Junction Creek (G07) (all in the Gilbert catchment) are the exception receiving some level of baseflow (Jolly et al., 2013).

Research completed over the past 20 years by TropWATER (formerly Australian Centre for Tropical Freshwater Research) in the Burdekin River catchment has resulted in the development of a conceptual model for waterholes (DNRMW, 2006). This model parameterises stages of the hydrograph, specifically, relating to water quality, in particular water clarity, and underlying biological processes within waterholes. Other water quality parameters (e.g. dissolved oxygen, temperature) have also been considered in generating this model. The conceptual model underlines the importance of the first flush in determining the fate of biological processes as flows insufficient to flush water through and refresh the system can lead to life threatening water quality conditions (e.g. severe and potentially lethal oxygen sags). Timing of each stage may vary from waterhole to waterhole in response to local conditions. For example, rivers that have high groundwater inputs are known to have sharp, localised, changes in water transparency (see Ganf and Rea (2007).

The conceptual framework (Figure 3.1) is summarised below:

(a) Export phase: More than 90% of all catchment export loads (nutrients, sediments, pesticides) occurs over a few days during the flow peak. Most instream submergent vegetation, microbes and macroinvertebrates are washed away along with all sedimentary deposits lighter than sand. Mobile species such as fish take refuge in off-channel wetlands and backwaters. Instream productivity is very low and entirely heterotrophic;
(b) Limnetic heterotrophy phase: Autotrophic production is severely limited heterotrophic (microbial) utilisation of allochthonous carbon is substantial (Production/Respiration (P/R) ratios are very low). Most of this heterotrophic productivity is limnetic (planktonic) therefore biomass is exported downstream SPM is mainly colloidal and does not settle in freshwater, so retention of fine sediment and associated biomass is low. Macroinvertebrate populations are usually quite depauperate;
(c) Transitional phase: Most waterbodies thermally stratify during daylight hours resulting in the formation of a thin photic epilimnion. Water and therefore plankton residence times increase significantly. Phytoplankton and especially cyanobacteria productivity can increase dramatically. Overall productivity and P/R both increase, but most biomass is still carried away. Benthic autotrophy is confined to the very shallow margins which will soon dry out. Productivity within the benthos of the permanent waterbody is heterotrophic. Lower flows allow deposition of riparian leaf litter and debris helping macroinvertebrate populations to recover;
(d) Limnetic autotrophy phase: Improved surface mixing during cooler months and increased light availability promote phytoplankton growth residence times continue to increase but nutrient availability often becomes limiting Benthic autotrophy begins to establish in the margins of the permanent waterbody leading to retention of biomass, nutrients and bio-flocculated sediments Nonetheless overall productivity is moderate, and predominately autotrophic. Water quality is usually at its best at this time;

(e) Benthic autotrophy phase: Benthic autotroph communities (algae and/or macrophytes) are able to establish on any suitable substrata. Due to exploitation of sedimentary nutrients, growth rates can be exceptionally high. Nutrients are sequestered from the water column so efficiently that concentrations are often difficult to detect. Warmer temperatures lead to strong thermal stratification. Phytoplankton biomass declines markedly under these conditions, therefore overall productivity is often very high and mainly benthic; and

(f) Pre-flush event: Events of this kind often determine the ultimate fate of the biological communities that have developed over the course of the dry season. Pre-flush rain events deliver turbid contaminated flow (overland and/or via the river channel) without generating sufficient flows to flush them away. Benthic autotrophs can no longer photosynthesise and become oxygen consumers rather producers. A productive autotrophic system is suddenly converted into a highly heterotrophic one. Events usually occur during the very warm pre-wet season months when respiration rates are at a maximum, hence severe, life-threatening oxygen sags can develop quite rapidly. Hypoxia promotes release of nutrients and other contaminants (e.g. heavy metals, hydrogen sulphides) from benthic sediments and the decomposition of allochthonous organic matter. It also prevents nitrification, so ammonia can accumulate to dangerous levels, for fish, for example.

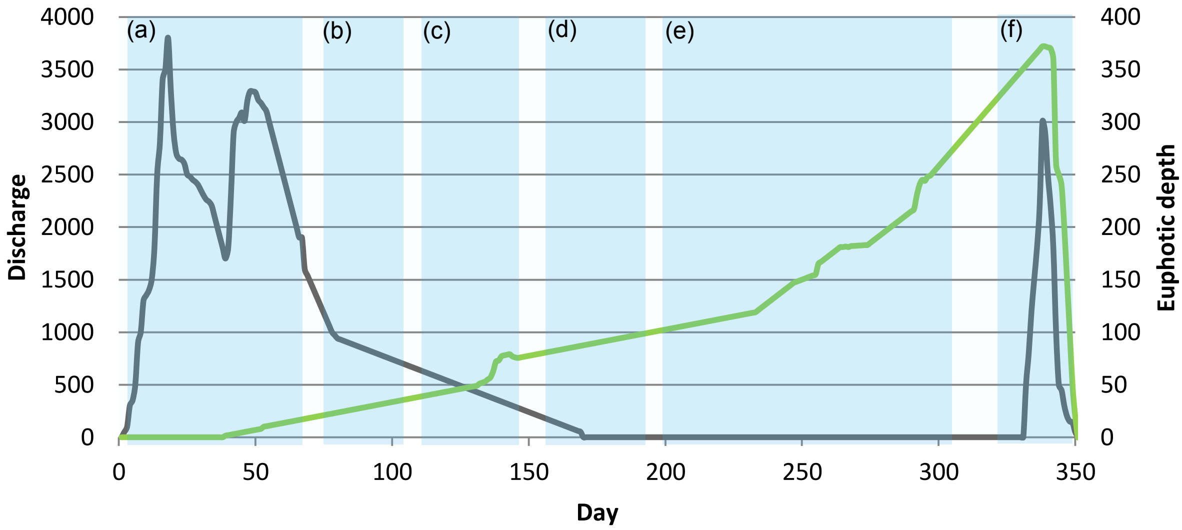


Figure 3.1 Conceptual model of dry season waterhole flow and euphotic depth conditions across the hydrocycle. (a) export phase; (b) limnetic heterotrophy phase; (c) transitional phase; (d) limnetic autotrophy phase; (e) benthic autotrophy phase; and (f) pre-flush event

It was originally planned that the above model would be used as a template to aid the identification of key differences in the relationships between streamflow, water quality and instream ecological conditions at different study sites, and provide a basis for comparison with sites located in other northern catchments. However, this did not prove to be feasible because drought conditions were maintained for the duration of the study and there was simply insufficient stream flow to be able to properly test the hydrograph-based model. Nevertheless it was evident from the data collected that there were some groups of sites that shared common water quality traits that are not consistent with the above model. This provided a basis for developing a typology to identify sites where different conceptual models would be needed to describe the relationships between flow and instream water quality conditions. For example the Flinders sites proved to be chronically turbid and would not be expected to exhibit the seasonal changes in water clarity that are depicted in Figure 3.1. It is also evident that the perennial sites in the Gilbert maintain high enough baseflow to ensure that they rapidly run clear on the falling limb of the hydrograph and as a result periods of high turbidity will be exceptionally brief. The remainder of the Gilbert sites may potentially comply with the model presented above but monitoring under more typical hydrographic conditions would be required to test that assertion.

Overall, this part of the Assessment has six main components:

- Assess key physico-chemical and nutrient water quality parameters in ten waterholes in each catchment on multiple occasions to examine trends between catchments and between different stages of flow hydrographs;
- Conduct detailed limnological surveys of ten waterholes in each catchment, especially in relation to depth, patterns of stratification and physico-chemical parameters (temperature, pH, conductivity and dissolved oxygen);
- Determine the effects of the first inflows of the wet season on water quality in remnant waterholes;
- Use assembled water quality and biological data to define a waterhole typology;
- Assess the vulnerability of defined waterhole types to water resource developments (including the expected increases in nutrient, pesticide and sediment loadings under development – Chapter 6); and
- Provide a baseline dataset against which future changes in water quality and waterhole limnology may be assessed.

This investigation occurred during the 2012/2013 wet season. However, this was one of the driest wet seasons on record and marked the beginning of a significant drought. Only 13 of the investigated waterholes received surface flow, whilst several had no flow, or dried completely over the course of the Assessment. The data indicate that the flows received were insufficient to wash away the phytoplankton biomass in the waterholes and particulate nutrient concentrations did not reach the levels expected during wet season flows in northern Australian streams. Thus no site received sufficient flow to test the effects of the kinds of hydrographic variations depicted in Figure 3.1.

At the time of this report, the region was still drought-affected and rainfall predictions for the next wet season were not particularly optimistic. If the 2013-2014 wet season fails to bring relief the drought has the potential to rank amongst the worst on record. This would present a unique opportunity to evaluate the drought resistance and resilience of the study sites, and ascertain how much water is required to sustain these river ecosystems. Field monitoring activities associated with the current investigation ceased in May 2013, ostensibly during the early stages of the drought, so there was no opportunity to monitor changes in water availability and biophysical conditions during both the later stages of the drought or during the post-drought recovery period. It would therefore be highly advisable to commission a supplementary study to carry out monitoring and assessments of that kind.

3.3 Methods

3.3.1 WATER QUALITY

Ten waterholes in the Flinders catchment and ten in Gilbert catchment were investigated during the Assessment to evaluate water and sediment quality conditions (Figure 2.12). During each survey, vertical depth profiles were conducted for pH, conductivity, temperature, dissolved oxygen, and turbidity at two random locations, plus a third location at the deepest position of the waterhole, using a hand-held Hydrolab QUANTA (multiprobe) calibrated in the laboratory before and after use on each field trip. In the case of turbidity, the sensor was not available for all trips, so the data are not as comprehensive as for other parameters. Depth profile were standardised to 0.1 m, 0.2 m, 0.5 m, 1.0 m and thereafter at each 0.5 m increment until approximately 0.1 m above the bottom. Care was needed to not disturb unconsolidated benthic sediments which can lead to erroneous recordings (Figure 3.2). A secchi disk (0.3 m diameter) was used to measure water column light attenuation. In situations where the bottom of the waterhole was visible from above, the horizontal secchi distance was measured instead. Here, a secchi disc was fixed vertically to an aluminium frame, and attached to a surveyors tape. The disc was slowly pulled away from an underwater periscope until it was no longer visible through the periscope. Light profiles through the water column were also taken using a Licor PAR light meter with a 2-pi sensor, at each of the same depth increments employed for physico-chemical profiles.

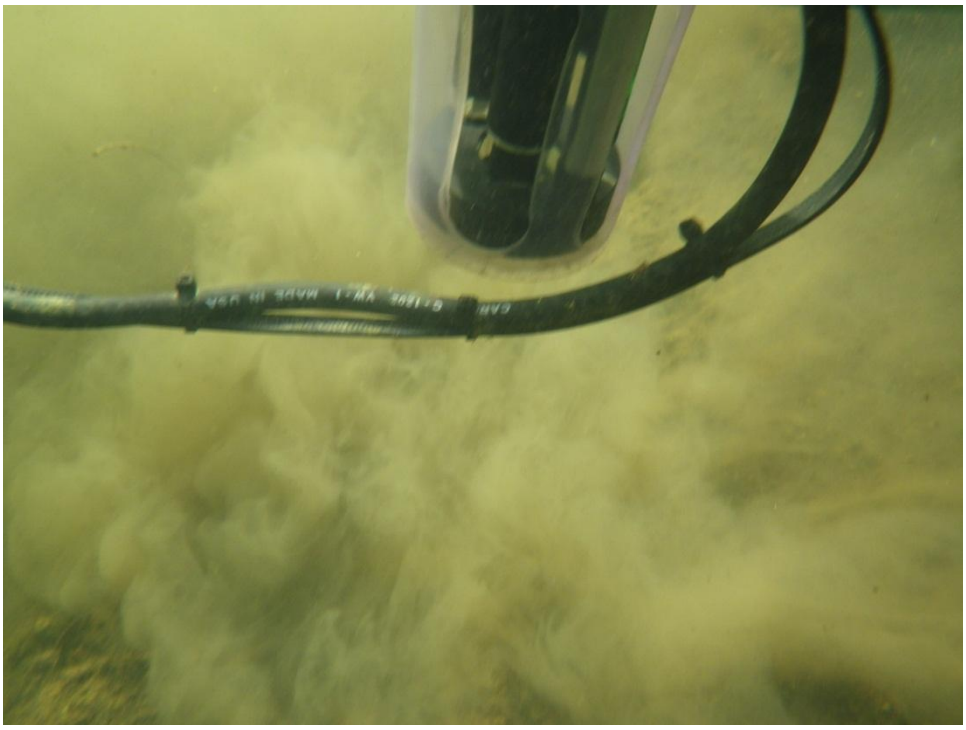


Figure 3.2 Example of fine benthic sediments displaced during profiling

On each sampling occasion, a single water sample was collected at a mid-channel position at a depth of approximately 0.3 m below the water surface. Samples were stored in portable 12V freezers (~–15 ^{o}C) until they were returned to the TropWATER Analytical Laboratory for further processing. Sampling method, sample bottles and preservation techniques, and analytical methods, were in accordance with standard methods (i.e. DERM 2009, APHA 1998).

Water samples were analysed for nutrients including nitrogen (total nitrogen, ammonia, nitrite, nitrate, oxidised nitrogen, dissolved organic nitrogen, urea, dissolved inorganic nitrogen), and phosphorus (total phosphorus, dissolved organic phosphorus, filterable reactive phosphorus, and particulate phosphorus). Samples were also examined for Total Suspended Solids (TSS), cations/anions (Ca, Mg, Na, K, Cl, SO^4), Total Organic Carbon, Dissolved Organic Carbon and Dissolved Inorganic Carbon. The parameters that were analysed on all water samples, along with the limits of detection, are listed in Table 3.1.

Table 3.1 Water quality analyses performed

WATER ANALYSIS	PARAMETER	APHA METHOD NUMBER	REPORTING LIMIT
Physical parameters	pH	4500-H^+ B	-
	Conductivity	2510 B	5 µS/cm
	Total Suspended Solids (TSS)	2540 D A 103-105°C	0.1 mg/L
	Turbidity	2130 B	0.1 NTU
	Dissolved Organic Carbon (DOC)	Aurora 1030 TC/TOC Analyser	1 mg/L
	Dissolved Inorganic Carbon (DIC)	Aurora 1030 TC/TOC Analyser	1 mg/L
	Total Organic Carbon (TOC)	Aurora 1030 TC/TOC Analyser	1 mg/L
	Alkalinity (bicarbonate, carbonate, hydroxide)	4500 CO^2-D	1mg/L
Major ion content	Calcium	3500-Ca B	0.2 mg/L
	Chloride	4500-Cl^- B	0.1 mg/L
	Magnesium	3500-Mg B	0.05 mg/L
	Potassium	35300-K B	0.02 mg/L
	Sodium	3500-Na B	0.05 mg/L
	Sulphate	4500-SO_4^{2-} E	1 mg/L
Nutrients	Total Nitrogen & Phosphorus (TNTP)	Simultaneous 4500-NO_3^- F & 4500-P F analyses after alkaline persulphate digestion	25 µg N/L 5 µg P/L
	Nitrate	4500- NO_3^- F	1 µg/L
	Ammonia	4500-NH_3 G	1 µg N/L
	Filterable Reactive Phosphorus (FRP)	4500-P F	1 µg N/L
	Chlorophyll a	10200-H	0.1 µg/L
	Total Dissolved Nutrients (TDN/TDP)	Simultaneous 4500-NO_3- F & 4500-P F analyses after alkaline persulphate digestion	25 µg N/L 5 µg P/L
	Urea	Alpkem A303-S332	25 µg N/L

As a measure of algal biomass, a known volume of water was collected from the waterhole surface (0.3 m depth) and field filtered onto glass fibre filter paper (Whatman GFF) to determine chlorophyll *a* concentrations. A second water sample was collected to measure depth integrated chlorophyll *a* concentrations. This was done by using a peristaltic pump (Solinst 410) to collect a sample of water through the entire water column. The hose was tethered to a weight and lowered to the waterhole bottom and the line flushed for approximately 2 min. The hose was slowly retrieved through the water column while pumping water into a clean (rinsed three times) bucket at the surface, until the entire water column had been evenly sampled. Speed of hose retrieval was adjusted depending on water depth. A known volume of water was decanted from the bucket and field filtered. After filtration, the glass fibre filter paper was fixed with 5 drops of magnesium carbonate, wrapped in alfoil to keep it dark, placed in a labelled envelope and frozen immediately for analysis at the TropWATER Laboratory. The samples were then freeze dried to remove all water, extracted with 90% acetone and read spectrophotometrically using APHA Method 3000B.

A calibrated Hydrolab multi-probe data logger (DS5X) was deployed in the near-surface water layer (0.2 to 0.4 m below the surface) to monitor the diel periodicity (cycling) of temperature, pH, electrical conductivity and dissolved oxygen at 20 min intervals. The loggers were deployed for between 24 hrs and 36 hrs during field trips following the schedule summary in (Table 2.4 and Table 2.5). Hydrolab data loggers were deployed for longer periods (several months) at F07 and F08, and G04 and G06 in order to collect water quality data during a flow event, should one occur.

All waterhole characteristics including percentage substrate material, percentage macrophytes and instream habitat, riparian shading, weather conditions, as well as any other important waterhole details were also recorded during each survey, as described in Chapter 5.

3.3.2 CONTINUOUS TEMPERATURE LOGGERS

To examine temperature conditions in each target waterhole, Hobo temperature loggers (Onset Corporation) were deployed in each waterhole at two depths: 1) surface – 0.2 m below water surface; and 2) bottom – 0.1 m above waterhole bottom. The surface logger was attached to the underside of a 0.15 m buoy (Figure 3.3) to shield it from the sun at all times as any direct exposure could produce erroneous results. For 13 waterholes where local air temperature data were not available from existing sources (Bureau of Meteorology), air temperature loggers were also deployed to compare ambient air temperature with stream temperature (Figure 3.4). All of these loggers (air and water) were programmed to record data every 20 min. A summary log of the instruments and the length of their data record are shown in Table 3.2 and Table 3.3. Several waterholes dried completely during the investigation with the data following this point removed from the analysis. An internal hardware problem occurred in several loggers following re-deployment of the loggers (mostly following the February 2013 survey) which resulted in an initiation malfunction and no further recording of data.

Table 3.2 Summary of logged temperature data in Flinders River catchment * indicates a waterhole which dried out during the period of observations

WATERHOLE	POSITION	DATE DEPLOYED	DATE OF LAST RECORDING
F01	Surface water	18/9/12	27/5/13
	Bottom water	18/9/12	27/5/13
F02*	Surface water	7/9/12	23/2/13
	Bottom water	7/9/12	27/5/13
F03*	Surface water	7/9/12	23/2/13
	Bottom water	7/9/12	23/2/13
	Air	7/9/12	23/2/13
F04*	Surface water	18/9/12	27/5/13
	Bottom water	7/9/12	27/5/13
F05	Surface water	8/9/12	23/2/13
	Bottom water	8/9/12	23/2/13
F06	Surface water	8/9/12	23/2/13
	Bottom water	8/9/12	23/2/13
	Air	8/9/12	23/2/13
F07	Surface water	9/9/12	27/5/13
	Bottom water	9/9/12	27/5/13
	Air	9/9/12	27/5/13
F08	Surface water	9/9/12	27/5/13
	Bottom water	9/9/12	27/5/13
	Air	9/9/12	22/2/13
F09	Surface water	10/9/12	27/5/13
	Bottom water	10/9/12	27/5/13
	Air	10/9/12	27/5/13
F10	Surface water	8/9/12	27/5/13
	Bottom water	8/9/12	27/5/13
	Air	8/9/12	8/2/13

Table 3.3 Summary of logged temperature data in Gilbert catchment

WATERHOLE	POSITION	DATE DEPLOYED	DATE OF LAST RECORDING
G01	Surface water	8/10/12	27/5/13
	Bottom water	8/10/12	27/5/13
	Air	8/10/12	27/5/13
G02	Surface water	8/10/12	27/5/13
	Bottom water	8/10/12	27/5/13
G03	Surface water	9/10/12	19/2/13
	Bottom water	9/10/12	27/5/13
	Air	9/10/12	27/5/13
G04	Surface water	10/10/12	27/5/13
	Bottom water	10/10/12	19/2/13
G05	Surface water	10/10/12	27/5/13
	Bottom water	10/10/12	27/5/13
	Air	10/10/12	27/5/13
G06	Surface water	11/10/12	27/5/13
	Bottom water	11/10/12	27/5/13
	Air	11/10/12	27/5/13
G07	Surface water	11/10/12	27/5/13
	Bottom water	11/10/12	27/5/13
	Air	11/10/12	27/5/13
G08	Surface water	14/10/12	30/11/12
	Bottom water	14/10/12	20/2/13
	Air	14/10/12	6/1/13
G09	Surface water	14/10/12	27/5/13
	Bottom water	14/10/12	27/5/13
	Air	14/10/12	27/5/13
G10	Surface water	13/10/12	27/5/13
	Bottom water	13/10/12	27/5/13

Figure 3.3 Continuous temperature rig in the Gilbert catchment. The larger float has the surface probe fixed to the bottom of the float to remain in the water column and shield from direct sunlight. The smaller float tether is a locator buoy

Figure 3.4 Continuous air temperature logger rig with probe fixed to centre of vented solar shield, located in the mid-day shade of several large trees

3.3.3 BENTHIC STREAM SEDIMENT

Benthic sediment samples were collected using a van Veen sediment grab. Sediment was collected from three locations spread across each waterhole, at a maximum depth of 1.5 m, during two surveys (see Table 2.4 and Table 2.5). These samples represent the general composition of the near-surface sediment layer at each waterhole. Near-surface sediment contains the most recently deposited material and is the microhabitat most heavily utilised by benthic and demersal biota.

A single sediment grab was able to retrieve sufficient sediment for the analysis. An aluminium disc cutter (70 mm diameter x 30 mm) was used to subsample sediment for analysis. Two replicate (approximately 500 mg) sediment samples were collected and placed in a polypropylene container, wrapped in aluminium foil to shield from light and frozen until analysis. Samples for nutrient analysis were completed at Analytical Laboratory Services. For carbon and nitrogen stable isotope analysis of sediments, this was completed using a Thermo-Finnigan Delta V Plus Isotope Ratio Mass Spectrometer interfaced with Flash EA 1112, Aurora 1030 TC/TOC Analyser and Trace GC Ultra at the Environmental Analysis Laboratory, Southern Cross University, New South Wales. Examination of the chlorophyll-*a* concentrations in samples was completed by freeze drying samples to remove water and acid extracting with 90% acetone. Samples were then read spectrophotometrically at the Marine and Freshwater Research Laboratory, Murdoch University, Western Australia. The sediment data for each parameter measured within individual waterholes, proved to be too heterogeneous for any meaningful statistical analysis (e.g. within and among waterhole examination). On this basis, the use of sediment nutrient monitoring requires close consideration given the problem of heterogeneity which would confound statistical analysis. The raw data are, however, provided in Appendix A.

3.3.4 DATA ANALYSIS

All data plots in this section are presented in a standardised fashion to assist interpretation. Waterholes within each individual watercourse or subcatchment have been grouped together and arranged in order from upstream to downstream (left to right). Groups are identified using the abbreviations listed in (Table 3.4). Each sampling survey was defined according to stage of flow on the hydrograph, with most surveys completed under no flow conditions. However, several waterholes have perennial baseflow (G01, G06, and

G07), and a small number of samples were collected under swift flow or recent flow conditions. Because of a high coincidence of sample results, the diameter of data points was adjusted. Time series plots were generated to illustrate emerging patterns in the data. Correlations among each water quality parameter combination were examined using simple scatter regression plots.

Table 3.4 Abbreviated waterway names

CATCHMENT	WATERWAY NAME	ABBREVIATION
Flinders	Julia Creek	J. Ck
	Cloncurry River	C. R.
	Flinders River	Flinders R.
	Einasleigh River	Einasleigh R.
	Elizabeth Creek	E. Ck
Gilbert	Junction Creek	J. Ck
	Langlovale Creek	L. Ck
	Pleasant Creek	P. Ck
	Gilbert River	G. R.

Data from the continuous water temperature loggers were processed by collating the data immediately preceding each survey. This allowed for the parameterisation of water column temperature conditions prior to a survey, which ranged between a few hours to 15 days where the surface and bottom conditions remained stable (see Appendix E and F).

3.4 Results

3.4.1 WATERHOLE DEPTH

The measured maximum water depth (m) for each waterhole during each survey is shown in Figure 3.5. Most waterholes were at least 2 m deep at some point during the Assessment. Five waterholes had swift flow at the time of sampling and four (all in the Flinders catchment) had no flow at all during any part of the Assessment period. In the Flinders catchment, F03, F04 and F10 dried completely, while F02 had fluctuating water depths as a result of a flow event in late December 2012 around the Hughenden region. Where waterholes were dry, data are not presented. The flow at F01 and F02 in January 2013 was classed here as bed sand baseflow, however, the results suggest that these were actually tail flows from the recent event, and not true baseflow. In the Gilbert catchment, waterholes G01, G06 and G07 had virtually the same depth each survey due to constant baseflow (either bed sand flow or deeper groundwater sources), though in the case of G01 the constant water depth was also aided by its location upstream of a concrete culvert.

A number of the waterholes received very limited or no flow during the Assessment and therefore the depth slowly reduced. At the same time electrical conductivity in these waterholes gradually increased through evapoconcentration. For the waterholes that received flow, electrical conductivity was diluted, only to again slowly increase as waterhole depth decreased (Figure 3.6).

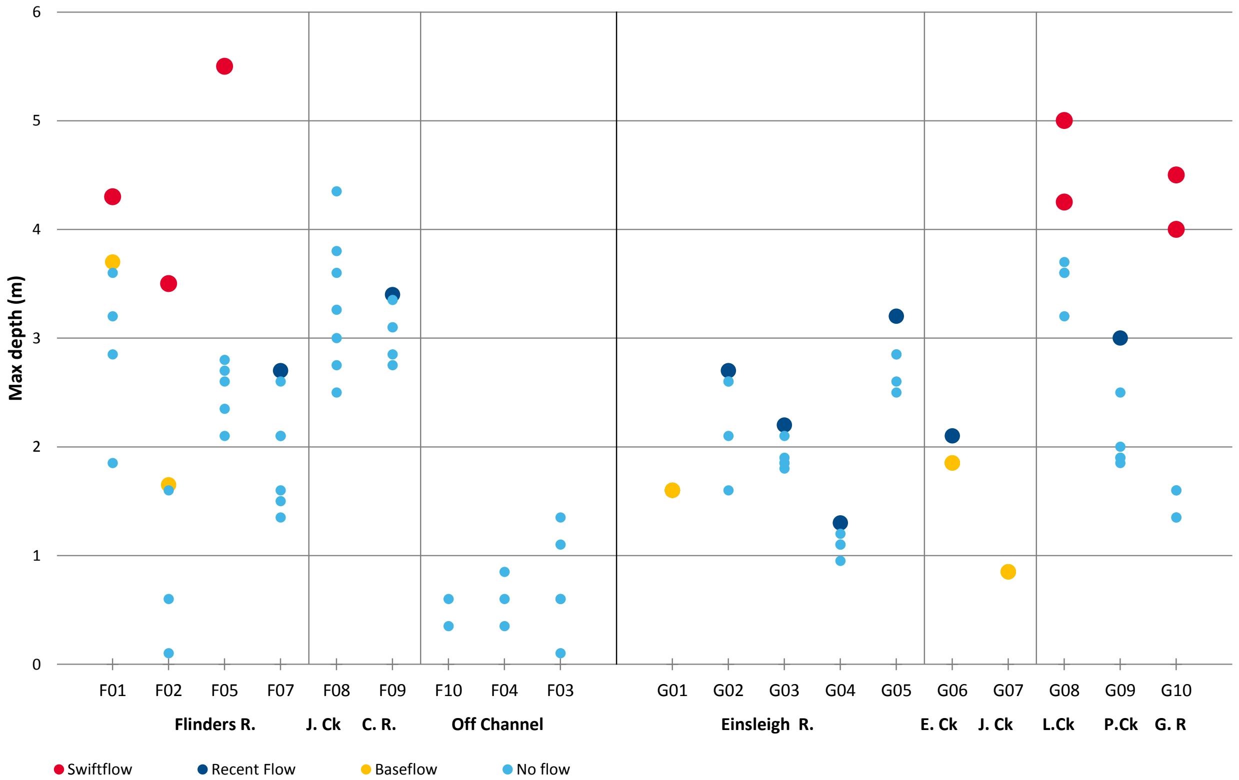
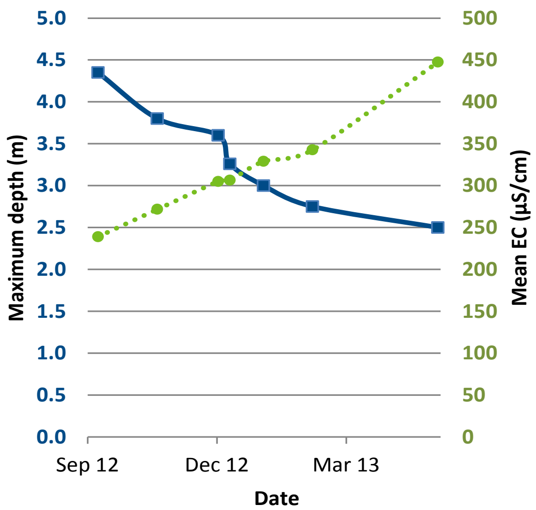


Figure 3.5 Maximum water depth (m) measured in each waterhole during each survey, grouped according to flow class

a)



b)

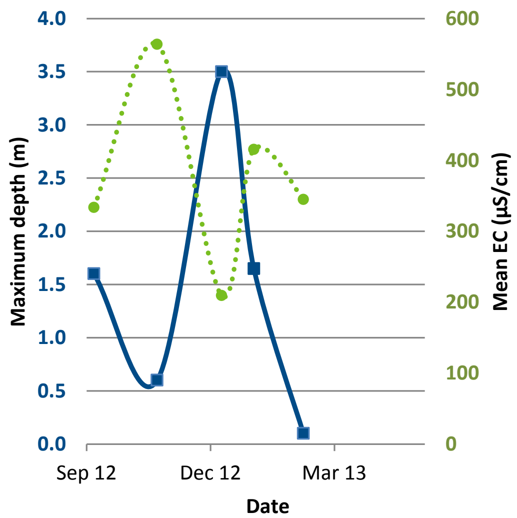


Figure 3.6 Pattern of the changing relationship between waterhole depth and electrical conductivity in a waterhole receiving. (a) no flow, F08; and (b) flow, F02. Green line, electrical conductivity. Blue line, maximum depth

3.4.2 WATER CLARITY

Turbidity (NTU) obtained from depth profiles taken through the water column down to within 0.1 to 0.2 m of the bottom revealed that the waterholes examined in the Flinders catchment were considerably more turbid compared than the waterholes examined in the Gilbert catchment (Table 3.5). Even the highest turbidity recordings in the Gilbert catchment, which occurred during flow, were still only within the range of values recorded under base flow in the Flinders catchment (Figure 3.7). The highest turbidities were recorded at F08 possibly owing to the large surface area and increased wind fetch resuspending benthic sediments into the water column. On some occasions during profiling, turbidity levels near the bottom suddenly increased dramatically (to values ranging from 100 to 6000 NTU), because the sensor probe had disturbed and resuspended bottom deposits of very poorly consolidated find sediment (see Figure 3.2). This phenomenon was observed on more than one occasion at all waterholes other than G07, but occurred more commonly in the Flinders catchment than the Gilbert catchment (in 50 of the 132 turbidity profiles in the Flinders catchment compared to 18 of the 166 profiles in the Gilbert catchment). Since these elevated recordings are not indicative of normal conditions within the water column, the elevated bottom turbidity measurements have been excluded from this water quality dataset. Nevertheless, the fact that some parts of the substrata were covered with a thick layer of fine sediment is ecologically significant and a noteworthy finding.

Table 3.5 Summary turbidity (NTU) data for Flinders and Gilbert catchments

CATCHMENT	N	MAXIMUM	80TH PERCENTILE	MEDIAN	20TH PERCENTILE	MINIMUM
Flinders	33	281.6	136.6	49.1	29.3	15.4
Gilbert	32	113.5	24.9	14.2	5.8	2.6

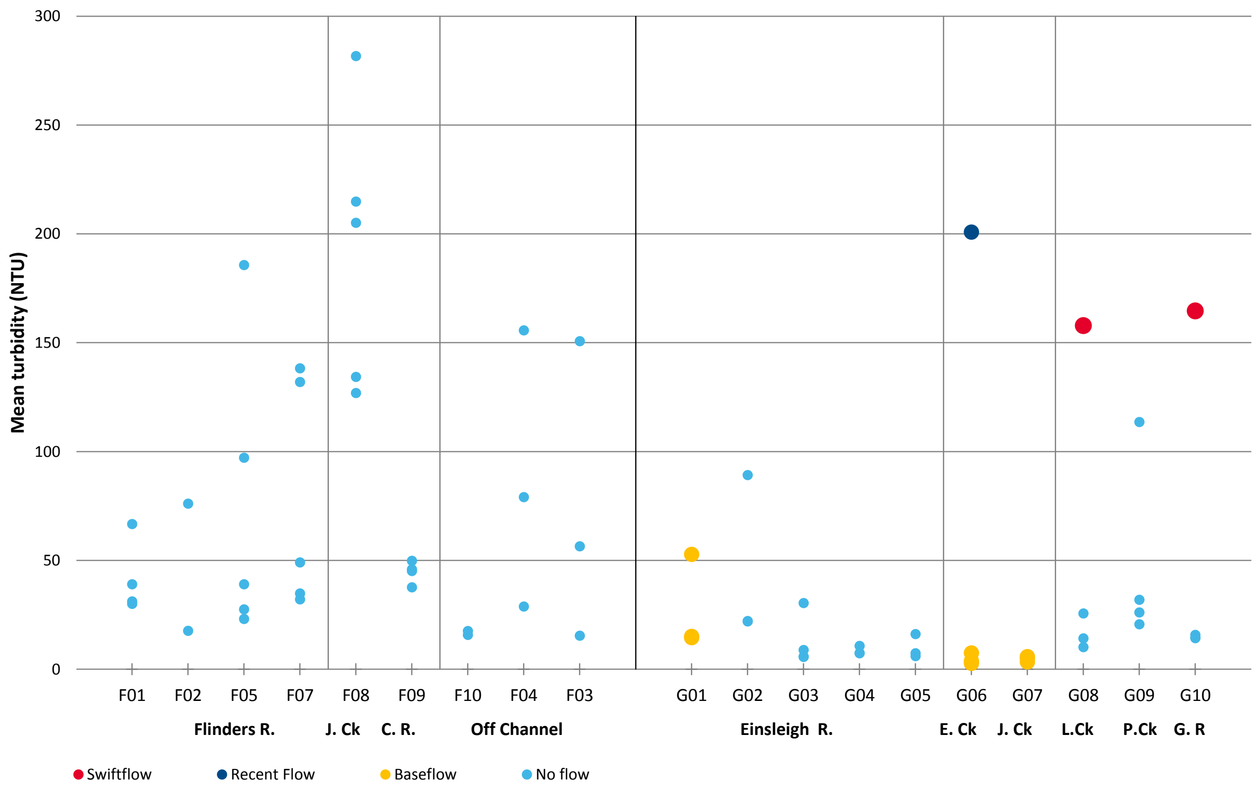


Figure 3.7 Mean turbidity (NTU) recorded in each waterhole during each survey, grouped according to flow class

Inflow of water consistently reduced the calculated euphotic depth to total depth (Z_{eu}:Z) index values (i.e. the depth to which effective light penetrates into the water column compared to the depth of the water column) due to the combined effects of increased turbidity and increased waterhole depth (Figure 3.8). The benthos at F01, F05, F08 and F09 never become completely photic at any time during the Assessment and at F02 and F07 it only became completely photic (i.e. received a sufficient amount of light to see the secchi disk at the waterhole bottom) when the water became so shallow that the waterholes had almost dried out. The off-channel waterholes in the Flinders catchment were always very shallow and therefore completely photic across the whole benthos. In the Gilbert catchment, however, G08 was the only waterhole where the entire benthos did not become photic on at least one occasion.

In the Flinders catchment, most waterholes were already turbid prior to inflow event and thus a high proportion of the benthos was already aphotic and this limited the relative magnitude of the changes that could occur following the flow event experienced during the Assessment (Figure 3.9a). Conversely, prior to inflow events, most of the deeper waterholes in the Gilbert catchment had higher index values indicating that they were clear enough to support autotrophic production at the bottom. Reduced clarity during inflow could therefore adversely affect benthic communities, making the sudden (and continued) reduction in clarity more ecologically significant (Figure 3.9b).

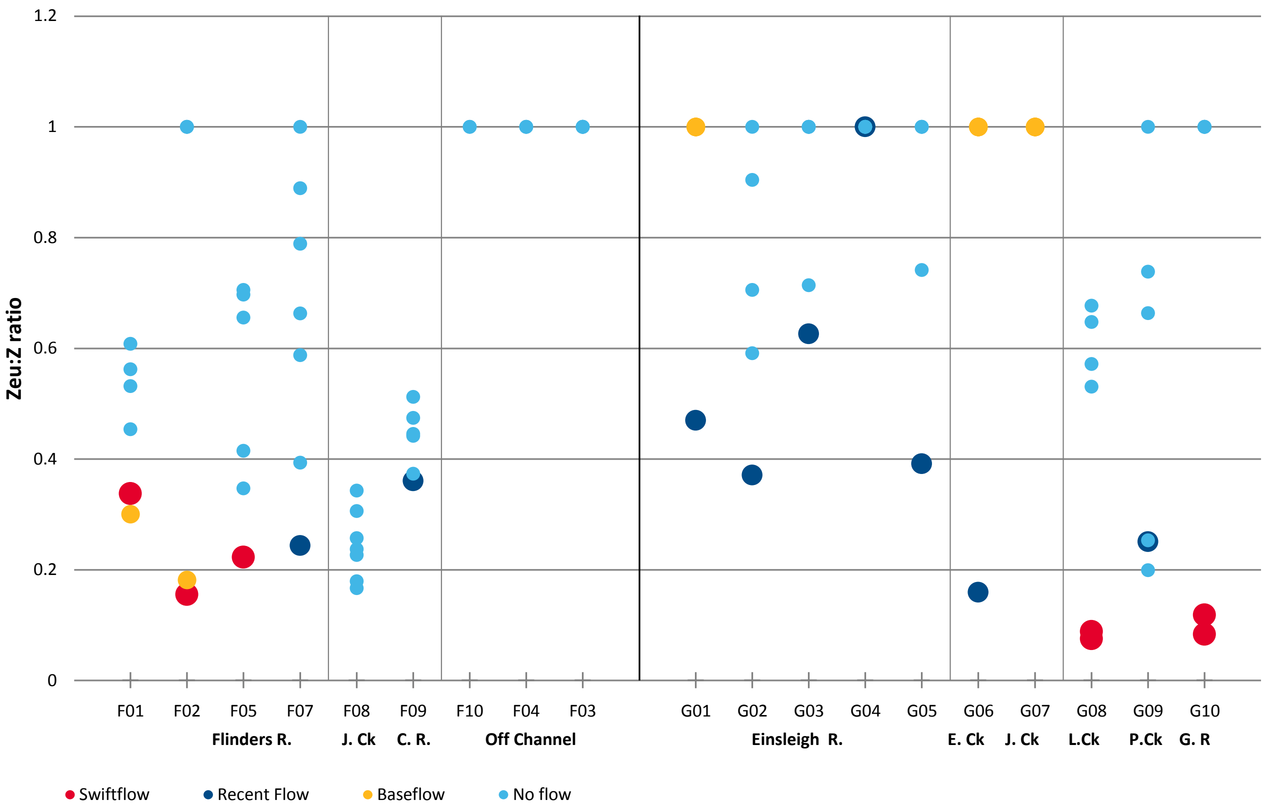


Figure 3.8 Calculated euphotic depth to water depth (Zeu:Z) ratio for each waterhole during each survey. Values ≥ 1 indicate that light reached the benthos across the entire waterhole. A value of 0.2 for example would indicate that light penetrated to a depth equivalent to 20 % of the deepest point in the waterhole

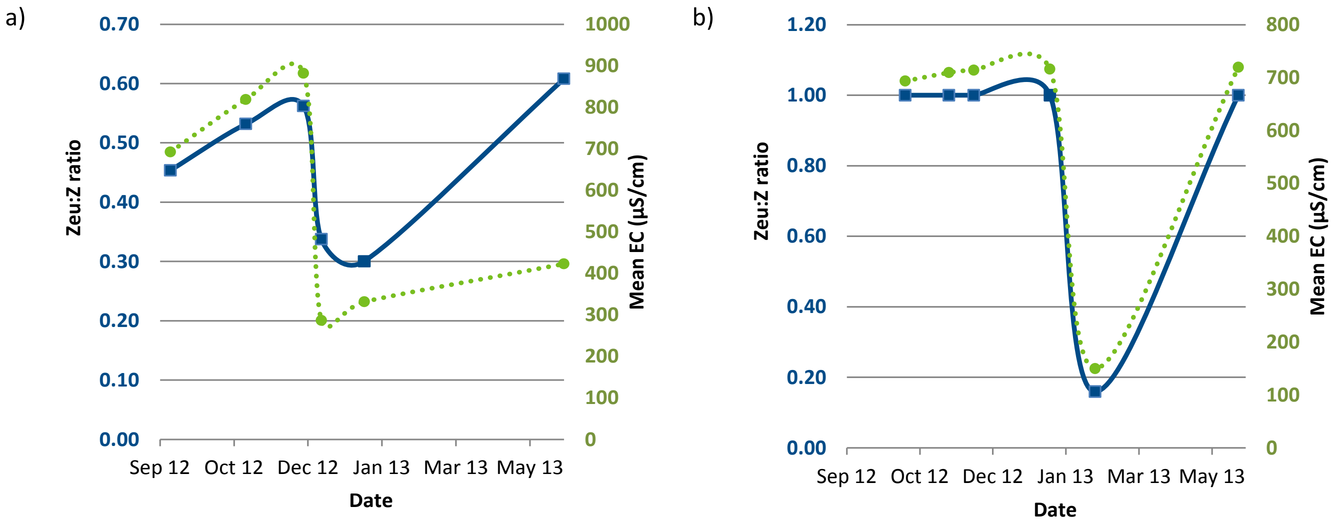


Figure 3.9 Relationship between calculated euphotic depth to water depth (Zeu:Z) ratio and water column mean electrical conductivity (as a surrogate for flow) at: a) F01, an example from the Flinders catchment; and b) G06, an example from the Gilbert catchment, showing the greater magnitude of change in euphotic depth to water depth ratios in response to an inflow event. Figure shows electrical conductivity (green dashed line) and Zue:Z ratio (blue line)

Secchi depth (m) to waterhole depth ratio (Z_{sec}:Z) values are shown in Figure 3.10. This ratio provides an indication of how much of the water column was photic (i.e. received a sufficient amount of light to see the secchi disk). Values $\geq$ 1 indicate that the secchi disc could be seen on the bottom at the deepest part of the waterhole. Lower values indicate limited depth to light penetration into the water column. These ratio values were very low at the Flinders catchment waterholes (Figure 3.10). Exceptions to this situation occurred in the off-channel waterholes and at F02 where on occasions the water depth was sufficiently low for light to reach the bottom, even though turbidity was still high. The ratio was reduced to 0.1 at waterholes in the Flinders catchment where swift or recent inflow occurred, and to below 0.2 in the Gilbert catchment under similar conditions. Waterhole G04 appears to be an exception because following a recent flow event (likely associated with the environmental release of water from Kidston Dam in January 2013; Pers. Comm. Department of Natural Resources and Mines) the ratio was one, even though the flow increased total suspended solids from 13 mg/L in the previous survey to 150 mg/L, but the water was still shallow enough for the available light to reach all the benthos.

There is a strong relationship between turbidity and secchi depth when pooling all the data across the two catchments (Figure 3.11). Because of the comparatively clearer waters of the Gilbert catchment waterholes, even minor variations in turbidity cause large changes in the depth of light penetration, and in most cases will alter the light climate of the water column and benthos. Conversely, in the Flinders catchment, especially those waterholes where turbidity exceeds about 40 NTU, further increases in turbidity have little effect on depth of light penetration and would have much less effect on the light climate of the water column and benthos. That is, the light climate and thus productivity and ecology of clear waterholes (such as those in the Gilbert catchment) are more readily impacted by even slight changes in turbidity than are the less clear waterholes of the Flinders catchment.

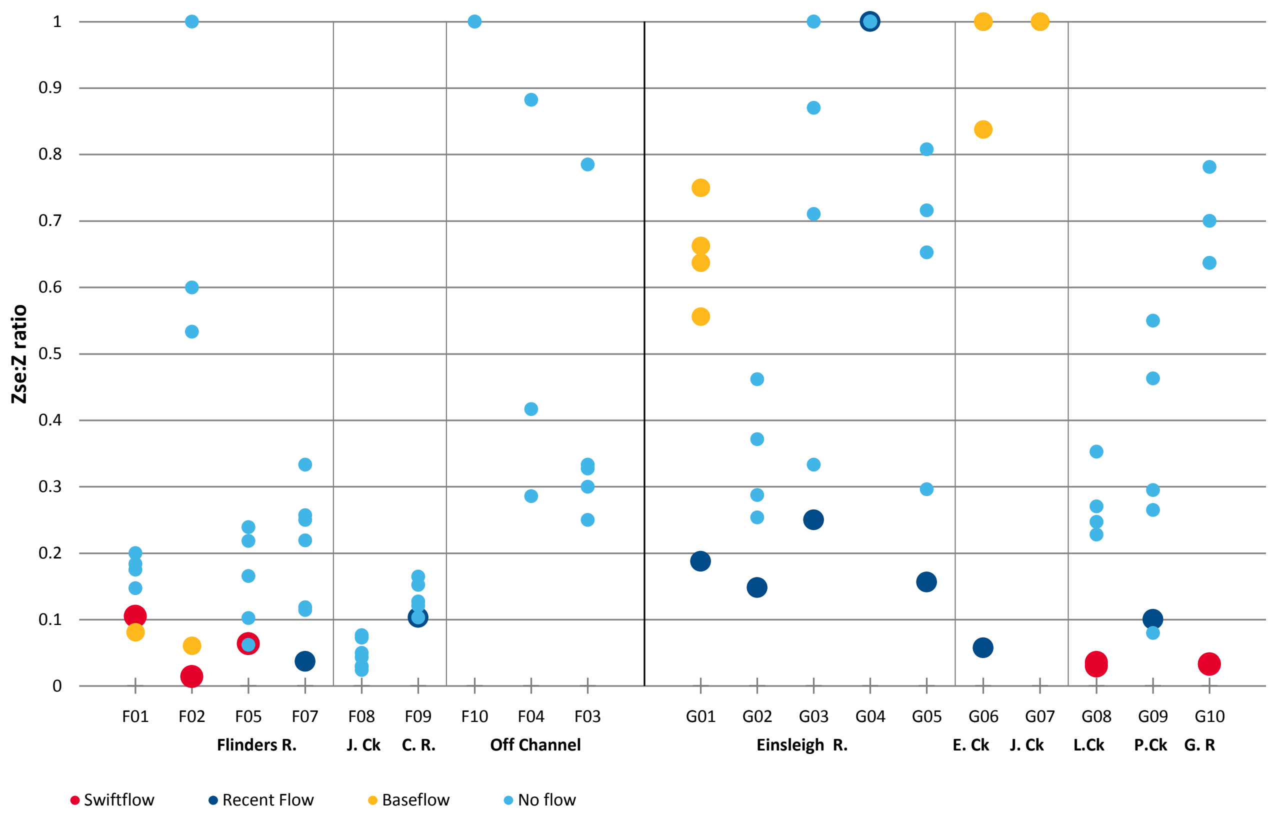


Figure 3.10 Calculated secchi depth to water depth (Zsec:Z) ratio for each waterhole during each survey

The correlation between total suspended sediments and turbidity (i.e. the correlation between the mass concentration of suspensoids that cause light to scatter and the amount of light being scattered) was quite weak in the Flinders catchment (Figure 3.12). This is typically the case when dealing with ambient water quality data sets which contain few flow event samples. In datasets which include event samples with very high turbidity there is generally a strong correlation between TSS and turbidity because the suspensoids responsible for turbidity during events mainly comprise inorganic soil particles with fairly consistent density and light scattering properties. However, under the field conditions here the suspensoids comprise a variable mix of phytoplankton, zooplankton, organic detritus and suspended sediment; each of which has distinctive light scattering properties and substantially different densities. Hence the correlation between TSS and turbidity often breaks down in productive waters that have been resident in a waterhole long enough to accumulate biomass. The waterholes in the Flinders catchment contained higher and more variable phytoplankton concentrations than the Gilbert catchment waterholes (see Figure 3.29), and consequently there was no correlation between TSS and turbidity (Figure 3.12). The R^2 value for the Gilbert catchment is somewhat inflated due to the inclusion of a few event samples which were proportionately much higher than the ambient levels. Nevertheless, there was still some correlation between TSS and turbidity, presumably because the phytoplankton concentrations in the Gilbert catchment were significantly lower and less variable.

The lack of any large scale flow events during the Assessment is evident in the relatively low maximum TSS concentrations recorded. Much higher concentrations can be expected in both catchments with higher event flows and this would probably produce a stronger relationship between TSS and turbidity.

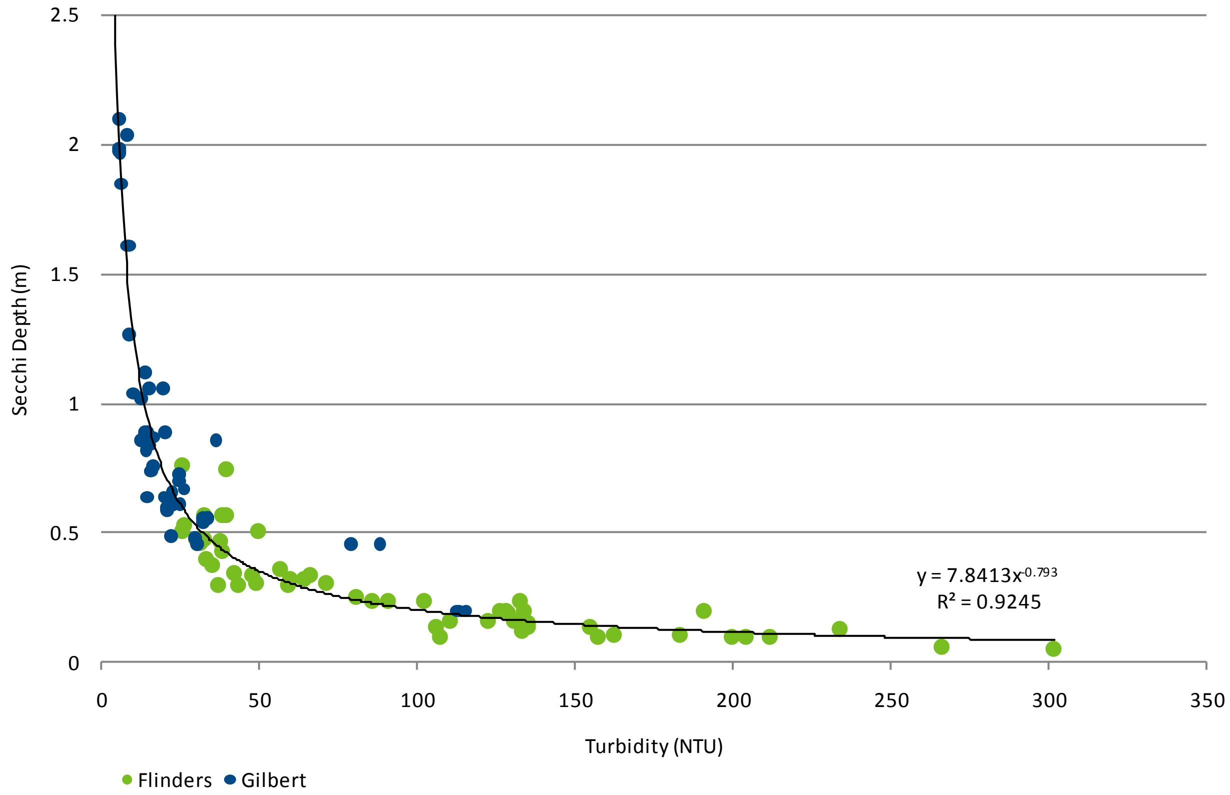


Figure 3.11 Relationship between turbidity (NTU) and secchi depth (m) by pooling all data across both catchments is strong with a distinct separation of the two catchments along the relationship curve

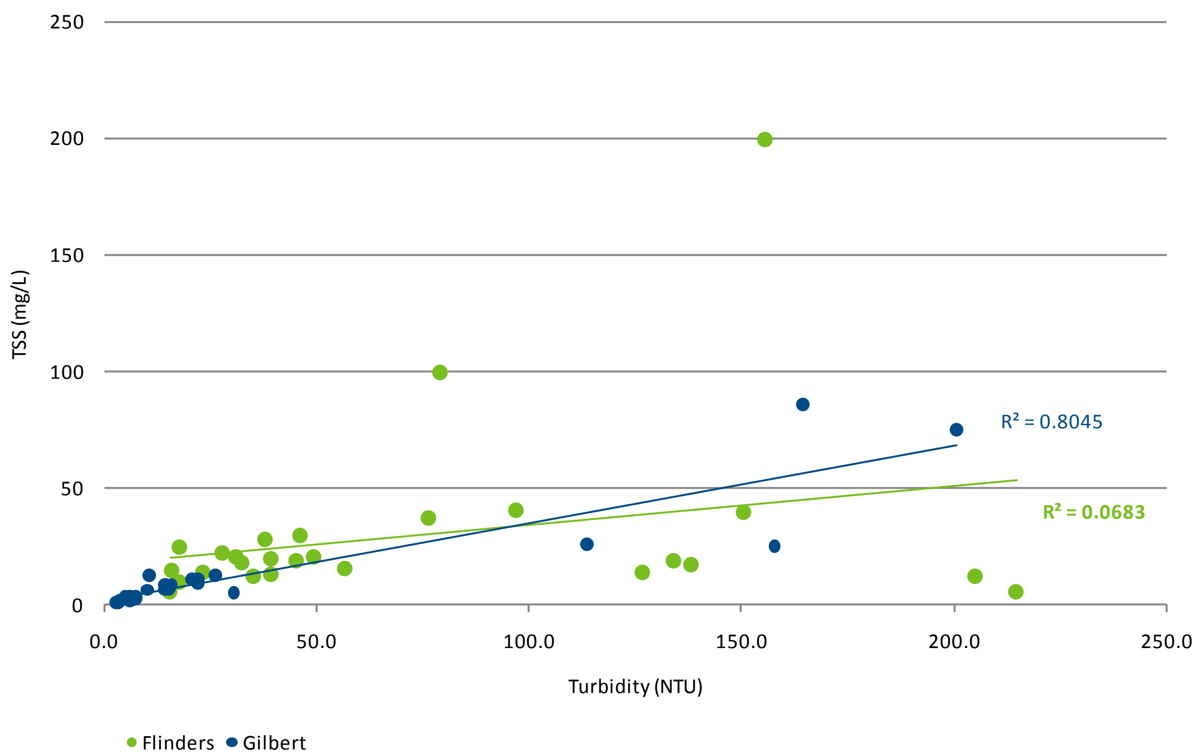


Figure 3.12 Relationship between turbidity (NTU) and total suspended sediments (mg/L) for each catchment is strongest for Gilbert catchment with a very weak relationship in Flinders catchment

There is a correlation between electrical conductivity and secchi depth in the Gilbert catchment, but not so in the Flinders catchment (Figure 3.13). The strong positive relationship in the Gilbert catchment is probably related to groundwater flow (both bed sand and deep groundwater) as a major driver of clarification processes, either by providing sufficient baseflow to displace turbid surface runoff or by inducing flocculation. Since groundwater generally has higher electrical conductivity than surface runoff it would be reasonable to expect some correlation between water clarity indicators (in this case secchi depth) and electrical conductivity. Conversely, no such correlation occurs in the Flinders catchment because most waterholes have higher turbidity (low secchi depth measurements), and experience little or no groundwater inflow (Jolly et al., 2013). Some of the ephemeral waterholes experience sufficient evapoconcentration to eventually develop high electrical conductivity values even in the absence of groundwater inflow, and due to the unusually dry conditions electrical conductivity values at most of the Flinders catchment waterholes were almost certainly somewhat higher than they would be in a more normal rainfall year. In addition, the potential role of wind, and waterhole depth and aspect were not considered here but might also a significant influence. Under this scenario, wind over a long waterhole fetch might resuspend sediments regardless of electrical conductivity of a waterhole. Additional data would be necessary to examine the extent of this influence.

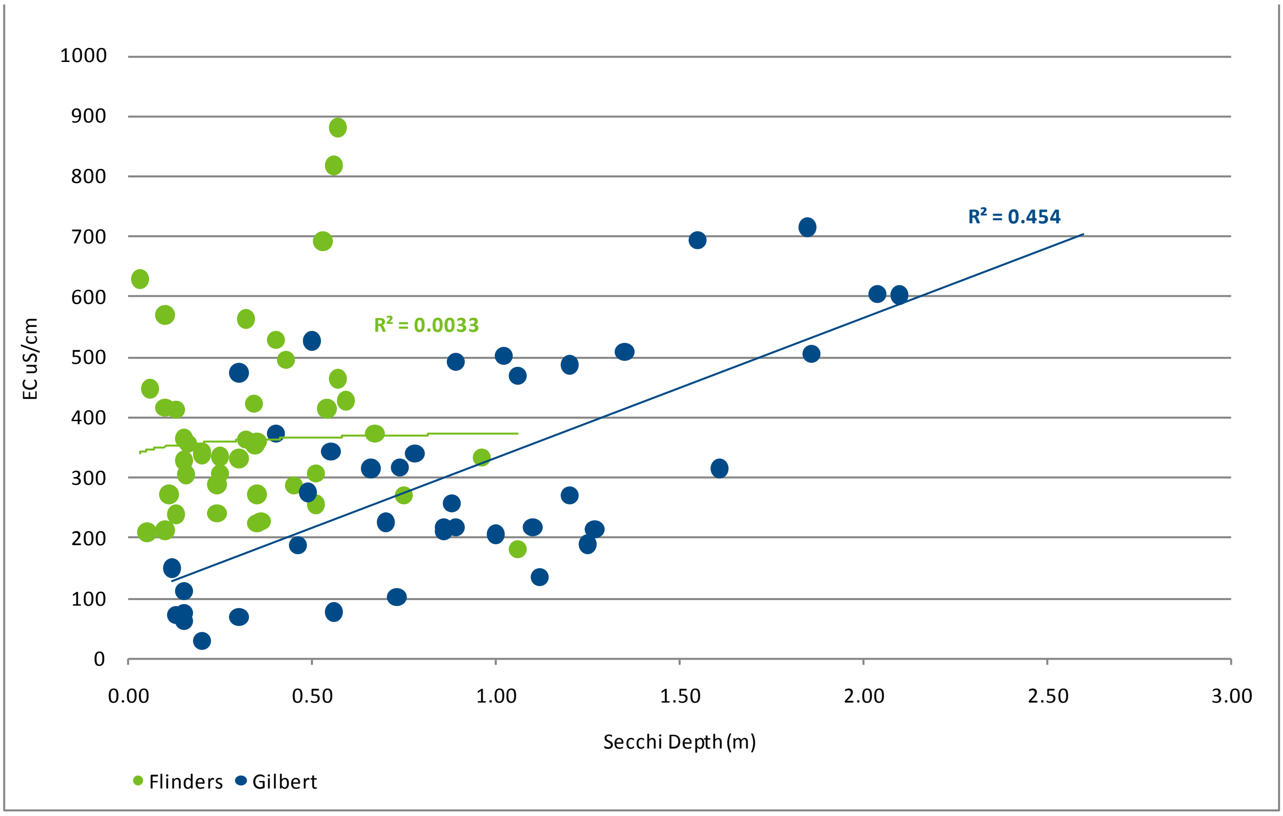


Figure 3.13 Relationship between secchi depth (m) and electrical conductivity (µS/cm) for each catchment is strongest for Gilbert catchment with no relationship in Flinders catchment

Dissolved oxygen cycling

Field profiling

Dissolved oxygen (DO) concentration profiling was conducted once per trip at a variable time of day, making it difficult to generalise results. The available data indicate that most sites were diurnally stratified, showing that overnight they mix and separate during the course of a day lessening the development of hypoxic conditions. The profiling data for each trip represent only one stage of the diel cycle. Nevertheless, the data in the following plots provide a useful portrayal of the immense spatio-temporal variability caused by these cyclical processes.

Since DO generally declines with depth, bottom measurements are indicative of minimum DO concentrations at the time when the profiles were conducted. Notably bottom measurements of less than 10% were recorded on six occasions, and concentrations below 30% on 19 occasions (Figure 3.14). These results are influenced strongly by the time of day the profiling occurred. The occurrence frequency of very low measurements would almost certainly higher if profiles were conducted in the mornings – at the time of day when DO concentrations are generally lowest. The maximum DO concentrations, which generally occur at the surface, reveal no values below 40% (Figure 3.15). These maximum values are above limits defined by Butler and Burrows (2007) as generating acute stress for tropical Australian freshwater fish.

The response of dissolved oxygen to inflow is shown in Figure 3.16. In this example from the Flinders catchment, F09 had low concentrations during early stages of the Assessment (40 to 60%), and reduced promptly following the inflow event in late December 2012 to concentrations that are likely to cause acute stress on fish and aquatic invertebrates (Figure 3.16). Whether the critical concentrations extended a few days or many months before returning to the pre-event concentrations, is not known with the data available, though DO was still low in May 2013. The maximum concentrations which were seemingly less influenced by inflow (Figure 3.16b). It is the mean profile concentrations that are most concerning. These show a substantial reduction (to 40%) in oxygen associated with flow though the lag effect of the reduced oxygen is not known, except that conditions improved to almost pre-event conditions by the May 2013 survey.

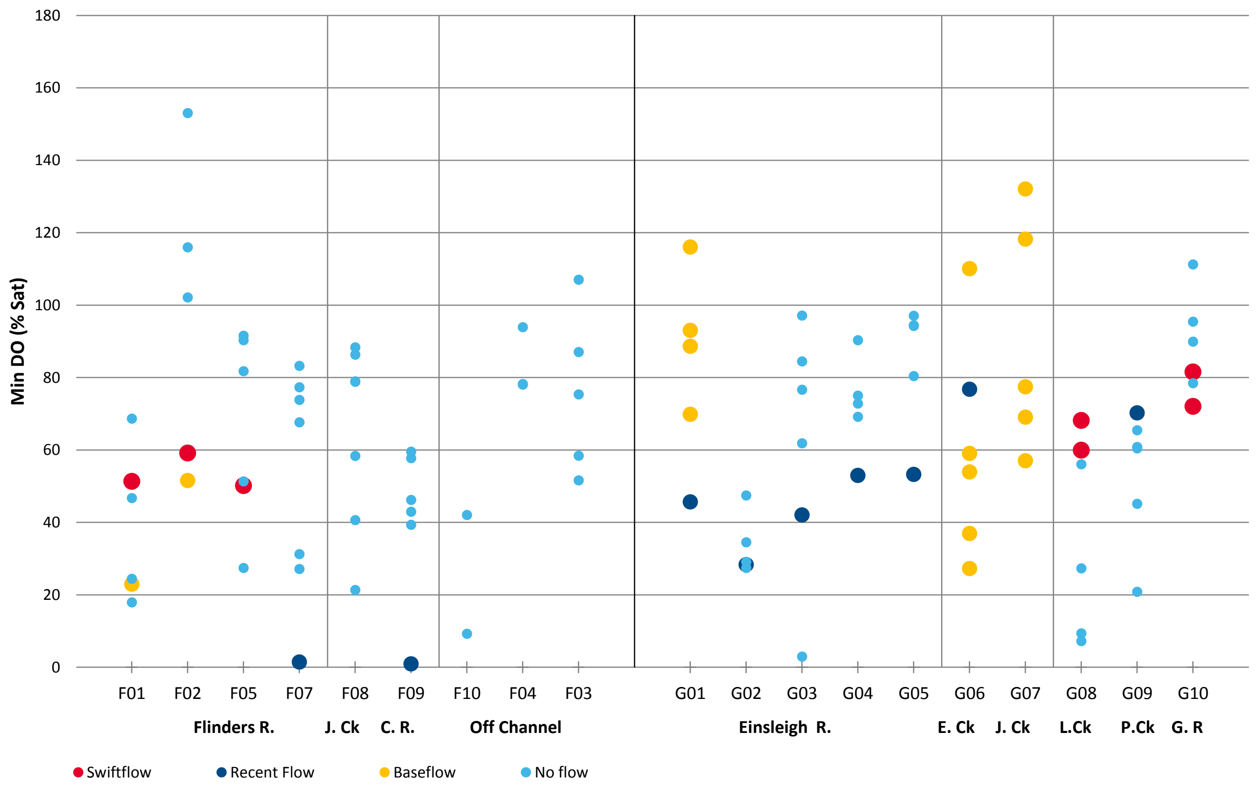


Figure 3.14 Minimum dissolved oxygen (% saturation) recorded in depth profiles

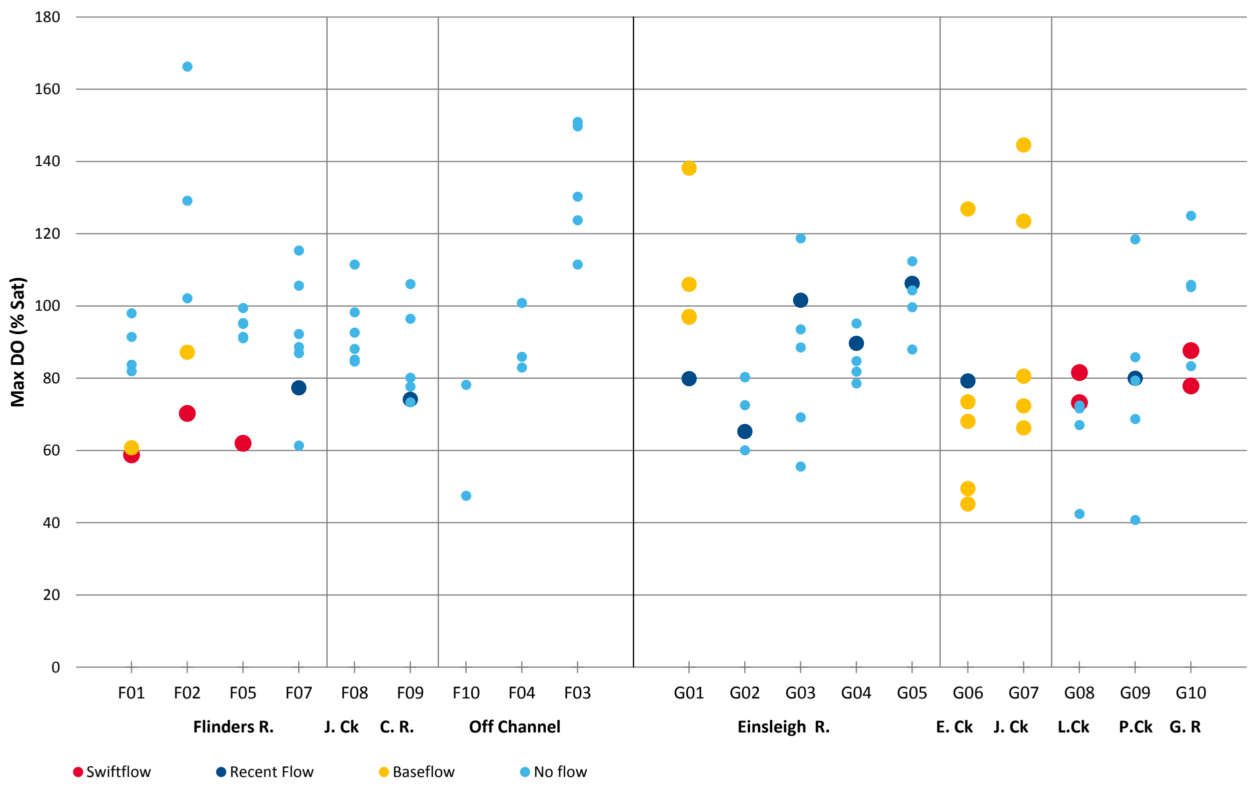
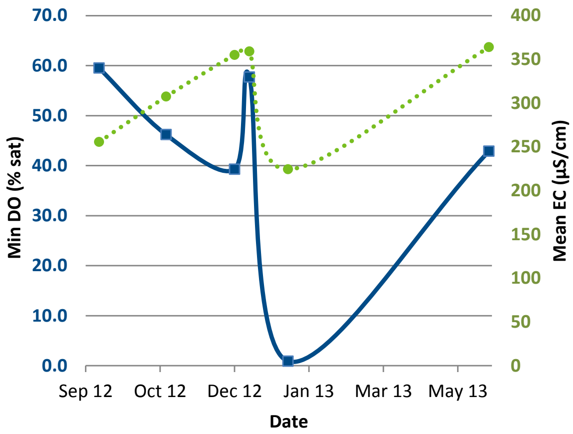
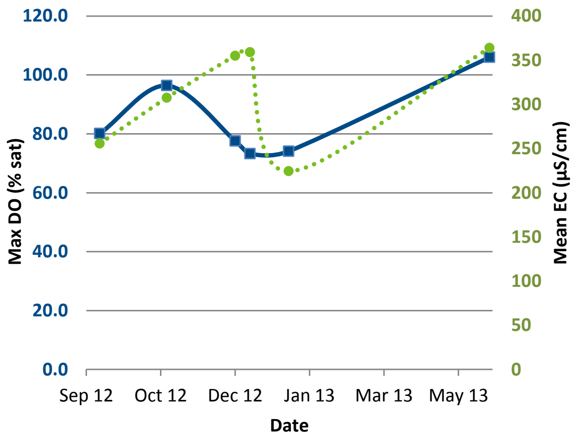


Figure 3.15 Maximum dissolved oxygen (% saturation) recorded in depth profiles

a)



b)



c)

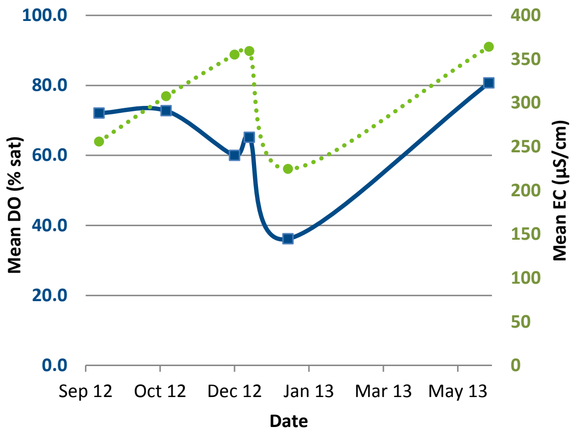


Figure 3.16 Dissolved oxygen (% saturation) recorded in depth profiles at F09 in response to mean water column electrical conductivity during the Assessment. a) minimum; b) maximum; and c) mean values recorded. Green line, electrical conductivity. Blue line, mean DO % saturation

Diel dissolved oxygen cycling

Data on diel cycling were obtained from deployment of Hydrolab data loggers. Diel dissolved oxygen cycling was present at all waterholes where loggers were deployed (though quite attenuated at G02). Several waterholes experienced very low daily minimum dissolved oxygen concentrations (Figure 3.17), the lowest concentrations at G08 and G09 being below 30% saturation, which is low enough to be acutely harmful to sensitive local fish species (Butler and Burrows, 2007). The maximum daily dissolved oxygen concentrations at G02 and G08 were still always near to or below saturation (Figure 3.18). Some waterholes that had higher mean dissolved oxygen concentrations exhibited very pronounced diel cycling and at times this led to very low daily minima. This was most evident at G04 in January 2013 following a minor stormwater inflow event (diel range 14.6 to 192.5%), at F03 in December 2012 (diel range 9.3 to 191.6%), and F09 in December 2012 (diel range 31.4 to 169.5%) (see Appendix E and F).

Dissolved oxygen concentrations below 30% have the potential to asphyxiate sensitive fish species and concentrations below 10% would be acutely stressful to even the more hypoxia tolerant species, including some invertebrates. The Hydrolabs were deployed near the surface and dissolved oxygen concentrations may have been more depleted at depth. G04 and F03 were diurnally stratified at the time they recorded their low dissolved oxygen concentrations but those minima occurred early in the morning (before diurnal stratification had established). Thus, it is likely the low concentrations extended through the entire water column, providing no refuge for hypoxia sensitive species and thus creating conditions that could potentially cause a fish kill. Waterhole F09 was stratified for most of the time, suggesting that concentrations at depth would have been much lower than the surface value of 31% recorded at this waterhole.

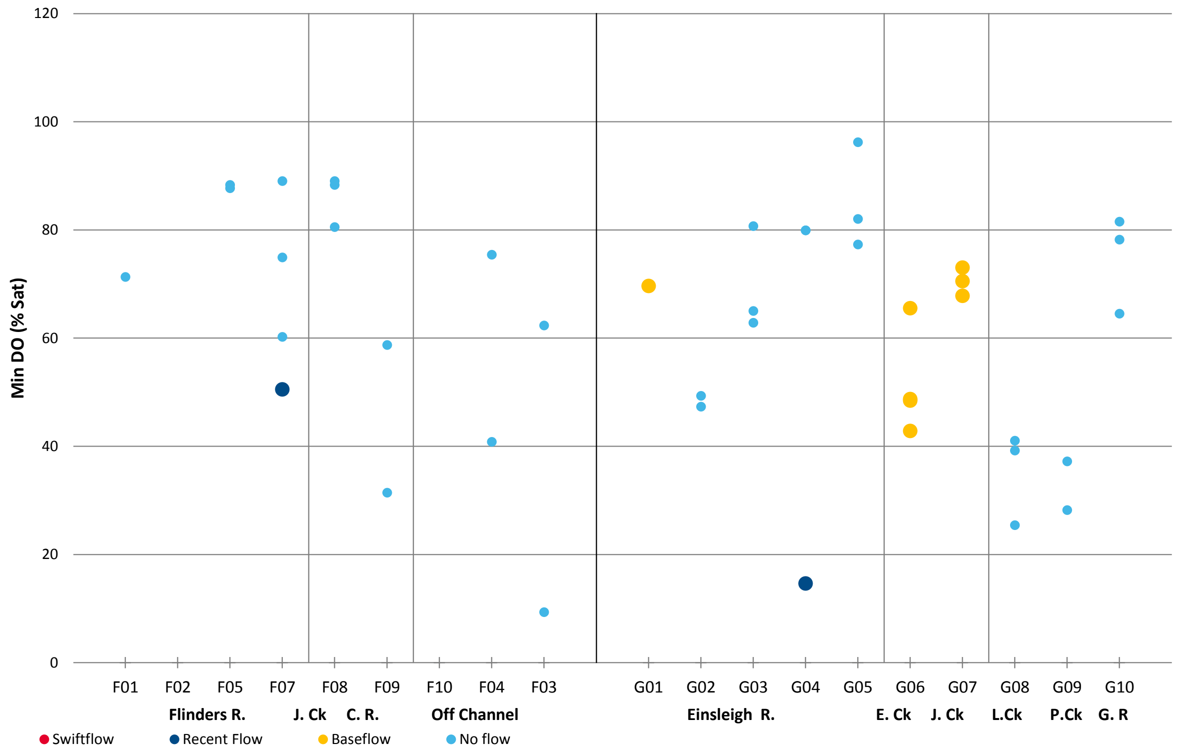


Figure 3.17 Minimum dissolved oxygen (% saturation) logged using the Hydrolab

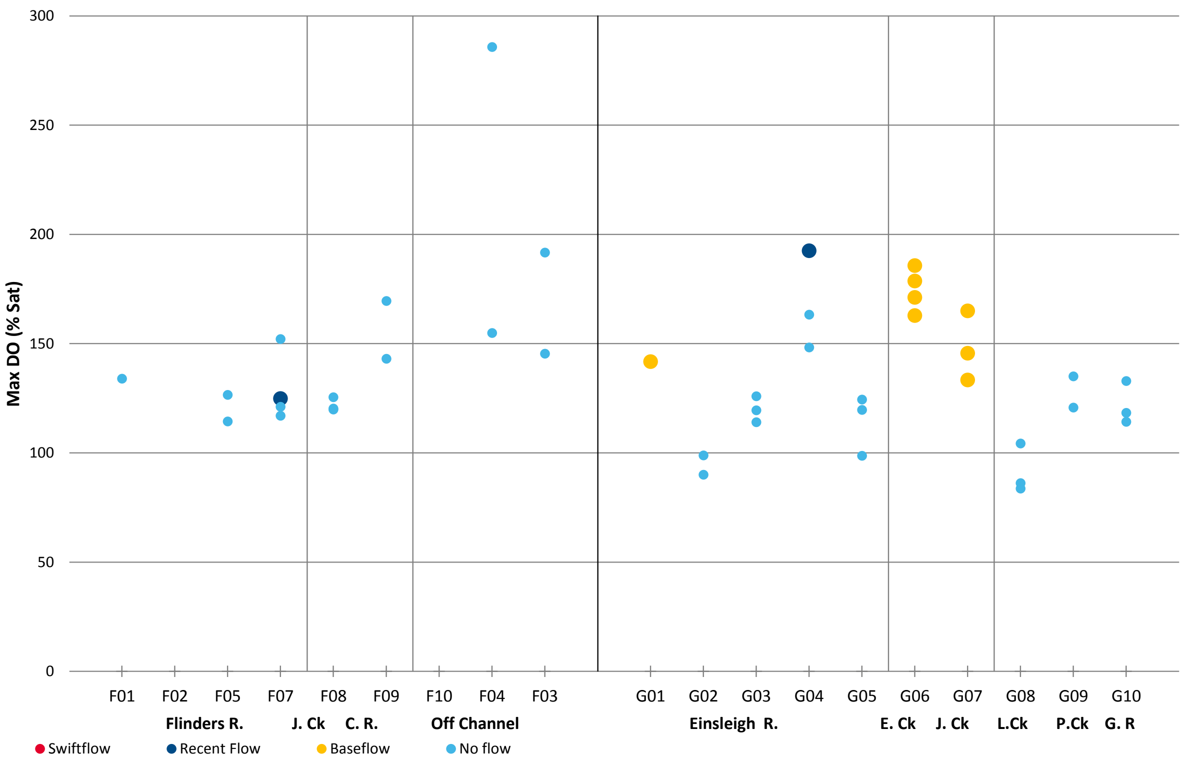


Figure 3.18 Maximum dissolved oxygen (% saturation) logged using the Hydrolab

pH

pH varies considerably over the course of a day and therefore interpretation of the data should consider the time of day at which the profile was conducted. As for dissolved oxygen, pH data from the profiling exercises are displayed as minimum (Figure 3.19) and maximum (Figure 3.20) data plots to illustrate the spatio-temporal variability of the data.

In stratified waters, pH generally declined at least moderately with depth. Hence the maximum values plotted are indicative of the surface pH level at the time of profiling. As would be expected, the lowest maximum values at each waterhole tended to coincide with inflow events, however, all of the values were measurably higher then fresh stormwater (which is generally saturated with carbonic acid from the air and therefore has a pH < 6.5). This suggests that the water had been in the system for some time and/or that it was a mixture of old and new water. This is not surprising given that the flow events were not large, and in most cases had been generated by rainfall in subcatchments some distance upstream of the monitored waterholes. Overall, pH were quite high given that profiling was not always carried out at the time of the day when pH would be at its diel maximum, and that the data set includes a number of inflow events which would have temporarily decreased pH. Discounting flow events, G02, G08 and G09, the waterholes with the lowest mean dissolved oxygen concentration also reported the lowest pH. This was to be expected because carbon dioxide production (which lowers pH) is usually accompanied by oxygen consumption (i.e. more oxygen was being consumed through respiration than was being produced by photosynthesis and conversely more carbon dioxide was being produced by respiration than was being consumed by photosynthesis). Those were also the only waterholes in the Assessment area that did not report pH greater than 8.4, and G02, G06, G08 and G09 were the only other waterhole that never exceeded 8.6. In fact overall 20% of the results for each catchment were greater than or equal to 8.8. Above a pH of 8.7, there is little or no free carbon dioxide available for photosynthesis and carbon must be obtained from dissolved bicarbonate. Cyanobacteria and submerged macrophytes are able to access bicarbonate whereas green algae do so poorly. Thus, any primary production occurring at pH levels in excess of 8.7 is likely due

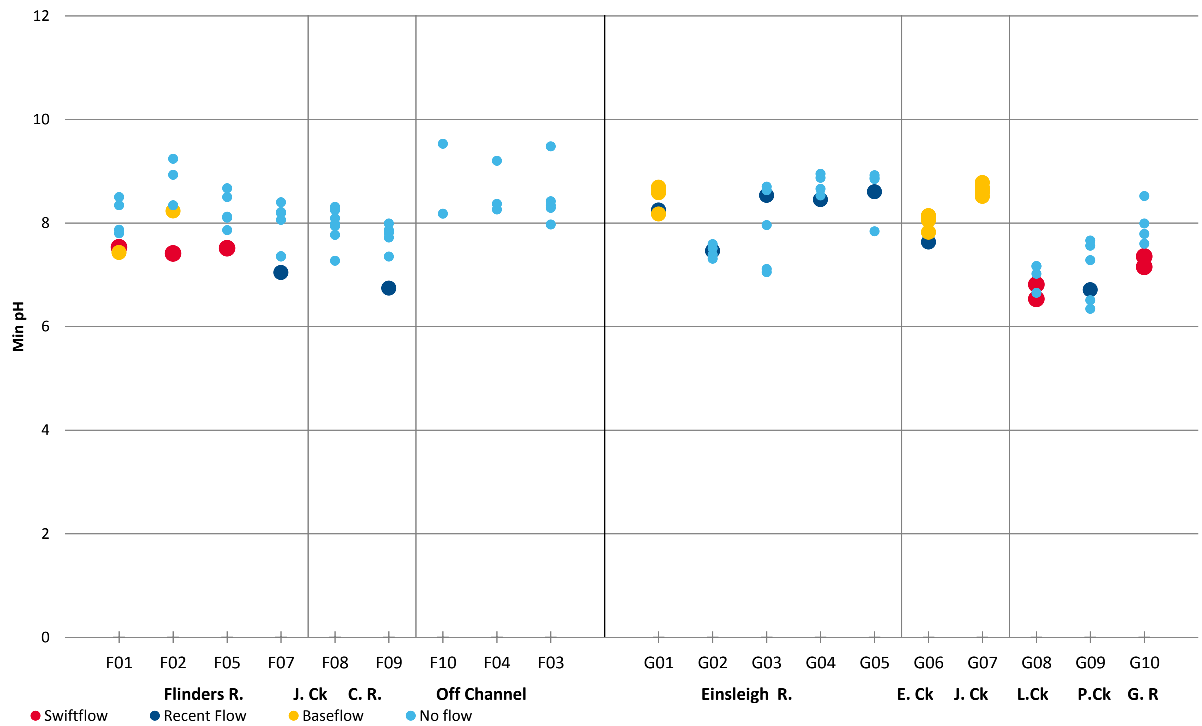


Figure 3.19 Minimum pH recorded during depth profiling

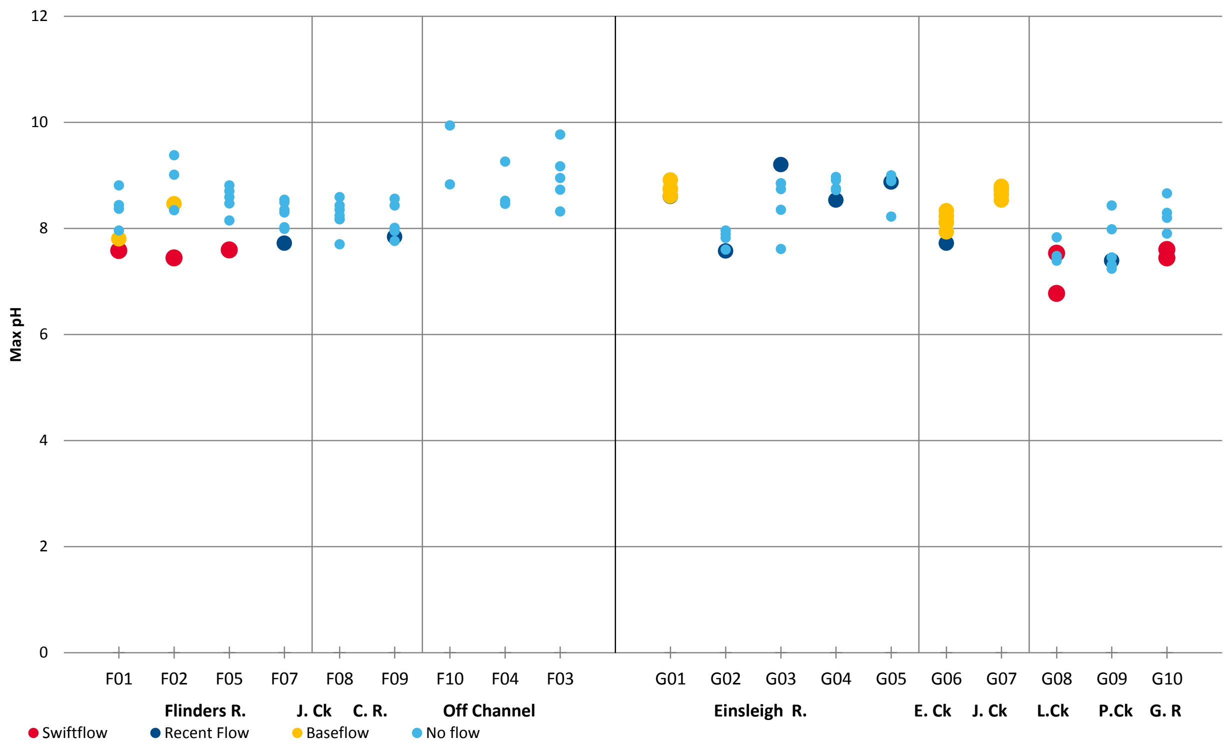


Figure 3.20 Maximum pH recorded during depth profiling

Ammonia toxicity increases substantially with increasing pH, for example, the ANZECC (2000) trigger value for ammonia is 2180 µg/L at pH 7.0, 900 µg/L at pH 8.0, 240 µg/L at pH 8.8, and only 180 µg/L at pH 9. The pH data collected in this investigation indicate that most of the study waterholes other than perhaps G02, G08 and G09 were sufficiently alkaline to be at risk of toxicological effects should inputs or instream accumulations of ammonia occur.

Water temperature cycling

The low cost and reliability of temperature loggers allows deployment of numerous devices for long periods, providing a very large dataset. Key elements of the continuous temperature logging data related to water quality are analysed here but the larger dataset in relation to temperature as an important parameter in its own right is evaluated in more detail in Chapter 4.

In general, waterholes in the Flinders catchment tended to have higher maximum surface water temperatures and lower minimum surface water temperatures than waterholes in the Gilbert catchment (Table 3.6 and Table 3.7). The higher maximum values in the Flinders catchment can be attributed to higher turbidity, as more solar radiation would be absorbed within the turbid surface layer. The lower minimum values recorded at the Flinders sites may be due to their generally smaller volume (i.e. they had less thermal mass and therefore heated and cooled more quickly). Daily maximum temperature values in the surface water actually exceeded the proposed safe temperature limit of 33 °C (Burrows and Butler, 2012) for 50% of the sampled period in the Flinders catchment and almost 40% of the sampled period in the Gilbert catchment, suggesting that surface conditions would not have been comfortable for thermo-sensitive species (Figure 3.21). In fact 20% of the values reported in the Gilbert catchment were between 36 and 38.6 °C, which could be acutely stressful to many freshwater fish species (Burrows and Butler, 2007).

Table 3.6 Summary maximum surface water temperature (°C) recorded by continuous temperature loggers over the days preceding each survey

CATCHMENT	N	MAXIMUM	80TH PERCENTILE	MEDIAN	20TH PERCENTILE	MINIMUM
Flinders	33	38.6	36.1	33.1	28.5	24.8
Gilbert	38	35.4	34.4	32.0	29.9	23.6

Table 3.7 Summary minimum surface water temperature (°C) recorded by continuous temperature loggers over the days preceding each survey

CATCHMENT	N	MAXIMUM	80TH PERCENTILE	MEDIAN	20TH PERCENTILE	MINIMUM
Flinders	33	35.3	31.2	28.4	23.4	18.0
Gilbert	38	33.8	31.3	29.7	27.5	22.3

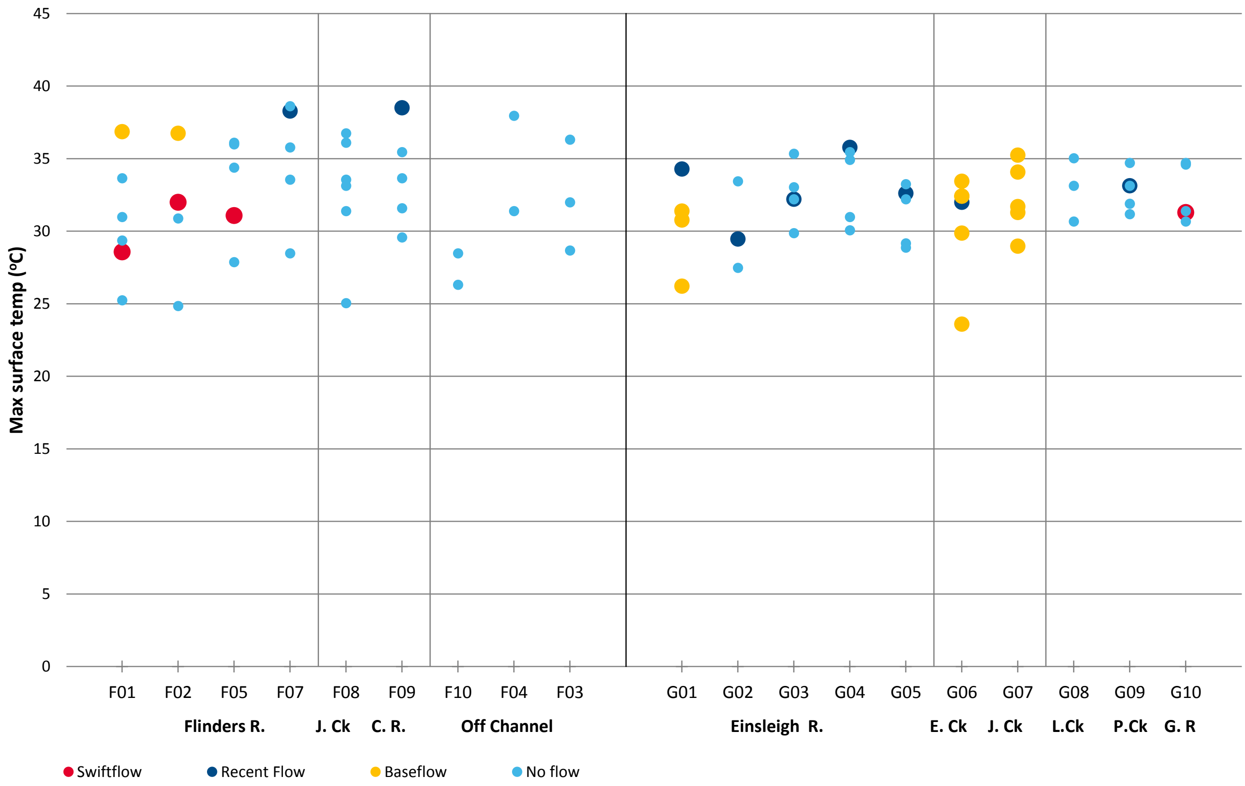


Figure 3.21 Maximum recorded surface water temperature using continuous loggers over the days preceding each survey

Daily maximum temperatures near the bottom were typically cooler than surface temperatures, especially in the Flinders catchment where the median value was lower than the Gilbert catchment (see Appendix E and F). This supports the notion that more of the thermal energy was being absorbed at the surface at the turbid Flinders catchment waterholes. Effectively, the turbid surface layer was shading the bottom water. Notably the proposed safe temperature limit of 33 °C was only exceeded near the bottom of the water column on a few occasions in each catchment and on most occasions by less than 1 °C (Figure 3.22). Accordingly, it would generally have been possible for fish to avoid exposure to the surface extremes by simply moving into the bottom layer, provided that there was enough dissolved oxygen available at that depth.

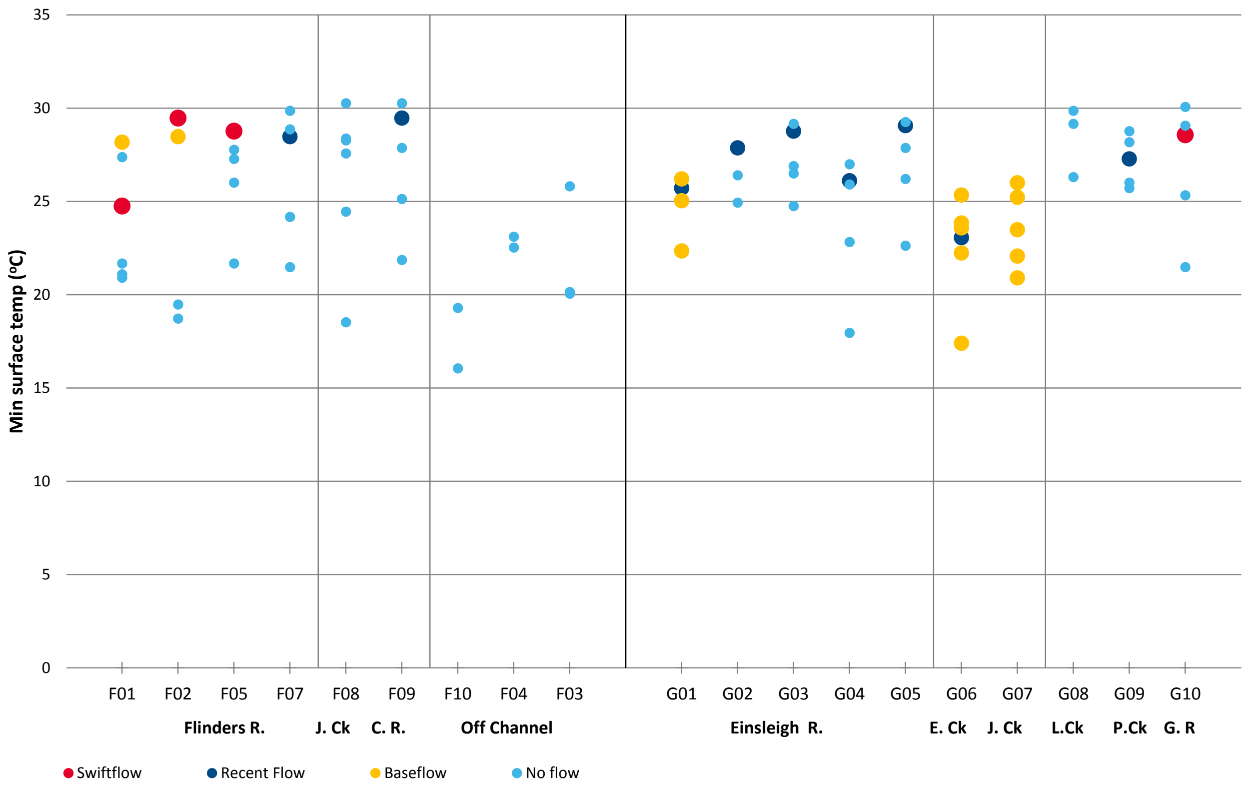


Figure 3.22 Minimum recorded surface water temperature using continuous loggers over the days preceding each survey

The relative stability of waterhole stratification was examined by calculating the percentage of time that the surface water temperature exceeded the bottom temperature by a specified margin. Percentage values based on a margin of 0.4 °C, which is the point at which we can be more than 95% confident that the temperature difference is greater than zero (based on the measured accuracy of the temperature loggers), indicate that mixing generally occurred when swiftflow was present but was otherwise quite rare during the periods leading up to each sampling trip. It is nevertheless noteworthy that the data logging records for the periods between monitoring trips indicate that mixing does occasionally occur in the absence of flow due to periodic changes in the weather (windy, cloudy days for example, see raw data in Appendix E and Appendix F). The typical pattern is for these waterholes to be stratified for about 30 to 80% of each day, although waterholes F01 and F07 were stratified to at least some extent most of the time (except when swift flows were present) and periodically went for weeks at a time without mixing.

At the margin of 1.5 °C, differences between the turbid Flinders catchment waterholes and clear Gilbert catchment waterholes becomes evident (Figure 3.23). The turbid Flinders catchment waterholes generally maintain strong stratification for far longer periods of the day, and in several cases for the majority of the day. Apart from a brief period of stable stratification at G01, no Gilbert catchment waterhole maintained strong stratification for more than about 40% of the time. However, it is noteworthy that the temperature differential at most waterholes still reached 1.5 °C for at least a brief period every day.

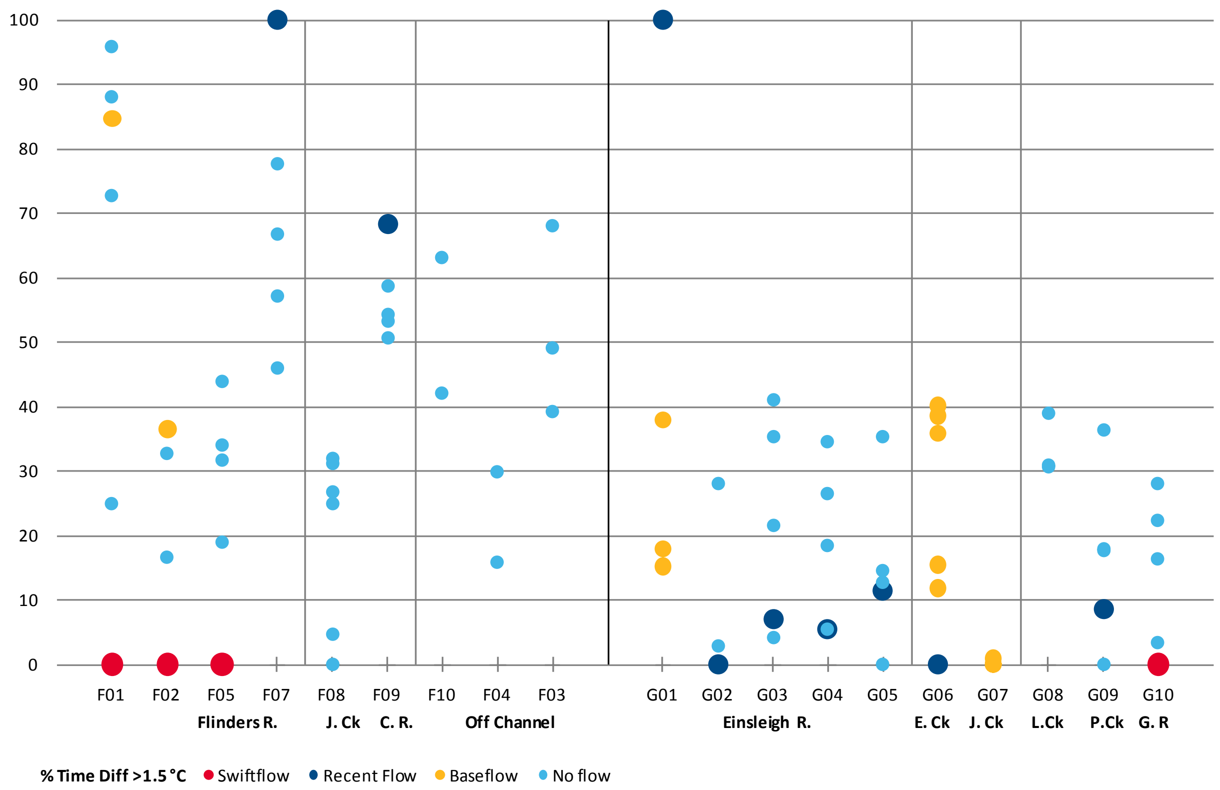


Figure 3.23 Percentage of time that the surface water was more than 1.5°C warmer than the bottom waters using continuous loggers over the days preceding each survey

Reduction in water depth as waterholes dry through evaporation leads to increases in water column temperatures (Figure 3.24). In these examples here both waterholes experienced a reduction in water depth and did not receive any inflow during the Assessment. Waterhole F03, an off-channel waterhole, dried completely by the January 2013 survey, whereas in F08 reduced more rapidly between September 2012 and January 2013 (approximately 1.5 m) and a further 0.5 m between January and May 2013. In both waterholes, the maximum bottom water temperature increased initially reaching critically high temperatures by early summer. In the case of F08 (Figure 3.24a) water temperature peaked by January 2013 (approximately 36°C) and then slowly reduced to approximately 30°C by the February 2013 survey before the logger failed. In F03 (Figure 3.24b) the maximum profile water temperature was reaching 40°C shortly before the waterhole dried out, which is well above the thermal tolerance of many northern freshwater fish species (Burrows and Butler, 2012). The very high water temperature is probably a function of reduced water depth.

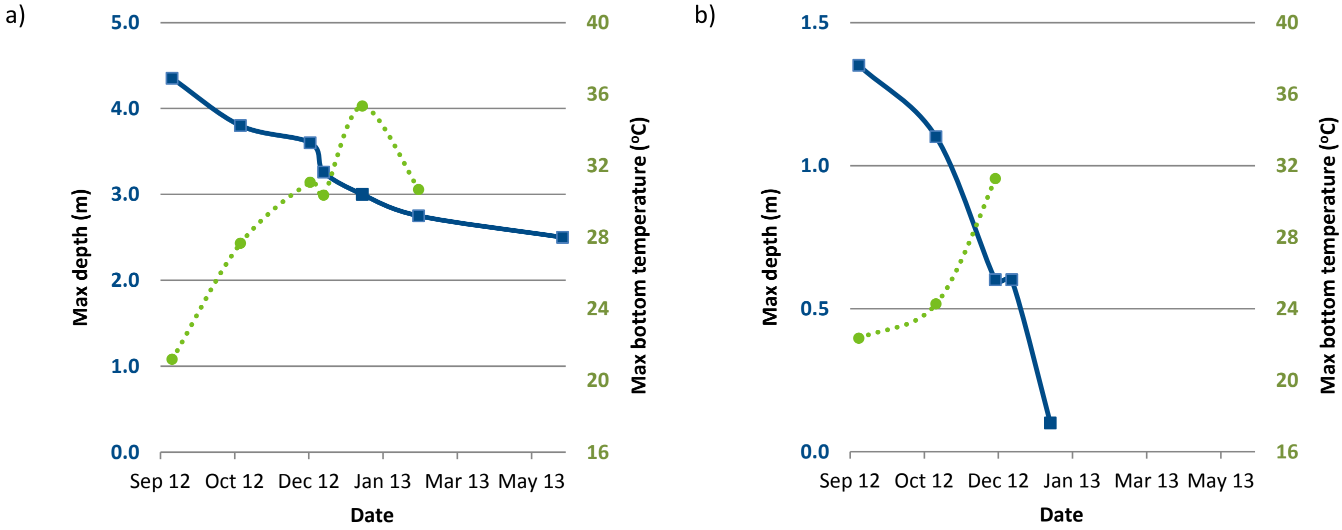


Figure 3.24 Maximum water depth (m) and maximum bottom water temperatures (°C) recorded using continuous temperature loggers at: a) F08 and, b) F03. This figure shows that as water depth decreases (blue line), the bottom water temperatures increase (green line), reaching critical limits for fish particularly during mid-summer. In F08 the logger failed after the February 2013 download, while in F03 the logger failed after the December 2012 download and before the waterhole was completely dry by late January 2013

Nutrients and chlorophyll

Nitrogen

Higher total nitrogen concentrations were recorded at the Flinders catchment waterholes compared to the Gilbert catchment waterholes (Table 3.8). As for total suspended sediments shown earlier most of the event concentrations for total nitrogen were not as high as might normally be expected in these types of catchments, reflecting the smaller size of these events, though the baseflow at F02 and recent flow at G04 were exceptions (Figure 3.25). Total nitrogen concentrations measured at the off-channel waterholes were elevated, possibly a consequence of animal impacts on relatively small stagnant waterholes. Conversely, the perennial waterholes in the Gilbert catchment maintained lower and more consistent concentrations, which is typical of groundwater supported systems.

A significant proportion of the total nitrogen was in dissolved organic form, which is typical of grazed catchments, especially at times when flows are insufficient to mobilise soil particulates. The elevated urea concentrations at the off-channel waterholes (see Appendix E and F) implicate animal urine as a major nitrogen source, supporting the contention of direct inputs from livestock. Ammonia levels were generally moderate although the two highest concentrations could have been toxic if pH values had been higher at the time. For example the 353 µg N/L result at F02 would have exceeded the ANZECC guideline if the pH had been 8.60 or higher, but it coincided with a surface pH value of 8.26. The other high value of 146 µg N/L at G04 would have exceeded the ANZECC guideline if the pH had been 9.1, but the maximum pH recorded on that trip was 8.40. Ambient dissolved inorganic nitrogen concentrations were generally moderate and within the normally expected ranges for these kinds of waters. In relative terms, inflows caused greater nitrogen concentration increases than was evident for other forms of nutrients. This is symptomatic of events that do not generate sufficient runoff to dilute solutes, as also evidenced by the somewhat higher than normal conductivity levels that were recorded for inflow events.

Table 3.8 Summary total nitrogen concentrations (µg N/L) recorded during the Assessment

CATCHMENT	N	MAXIMUM	80TH PERCENTILE	MEDIAN	20TH PERCENTILE	MINIMUM
Flinders	37	6446.0	1744.4	800.0	505.2	297.0
Gilbert	34	1443.0	578.8	477.0	301.2	160.0

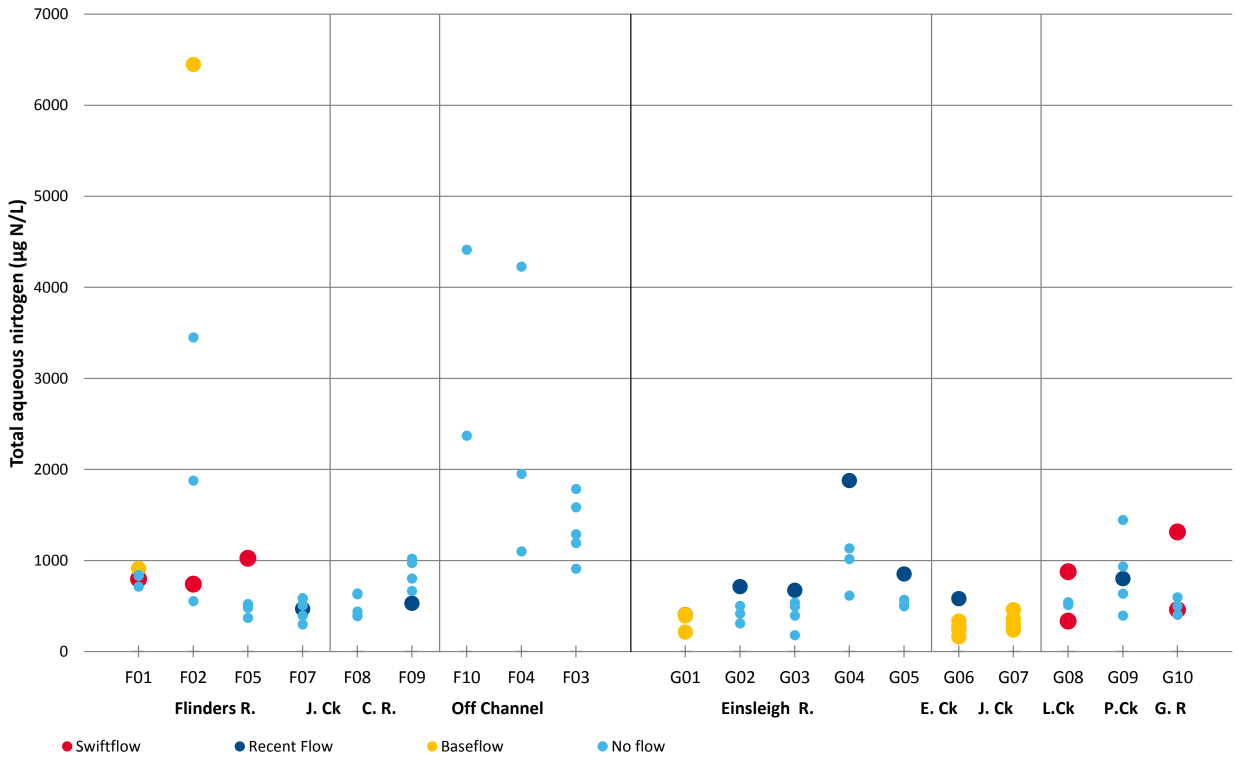


Figure 3.25 Total aqueous nitrogen (µg N/L) recorded in each waterhole during each survey

Phosphorus

Similar to nitrogen, higher total phosphorus concentrations were recorded at the Flinders catchment waterholes compared to the Gilbert catchment waterholes (Table 3.9). The total phosphorus concentration results obtained during flow events were not as high as might normally be expected, probably reflecting the smaller size of these events (Figure 3.26). Concentrations measured at the off-channel waterholes were elevated, possibly a consequence of animal impacts on relatively small stagnant waterholes. Conversely, the perennial waterholes in the Gilbert catchment maintained lower and more consistent concentrations, which is typical of groundwater supported systems. A significant proportion of the total phosphorus was in dissolved organic form, which is typical of grazed catchments especially at times when flows are insufficient to mobilise soil particulates.

Table 3.9 Summary total phosphorus concentrations (µg P/L) recorded during the Assessment

CATCHMENT	N	MAXIMUM	80TH PERCENTILE	MEDIAN	20TH PERCENTILE	MINIMUM
Flinders	37	662.0	146.8	82.0	41.0	19.0
Gilbert	34	92.0	51.6	31.5	21.0	14.0

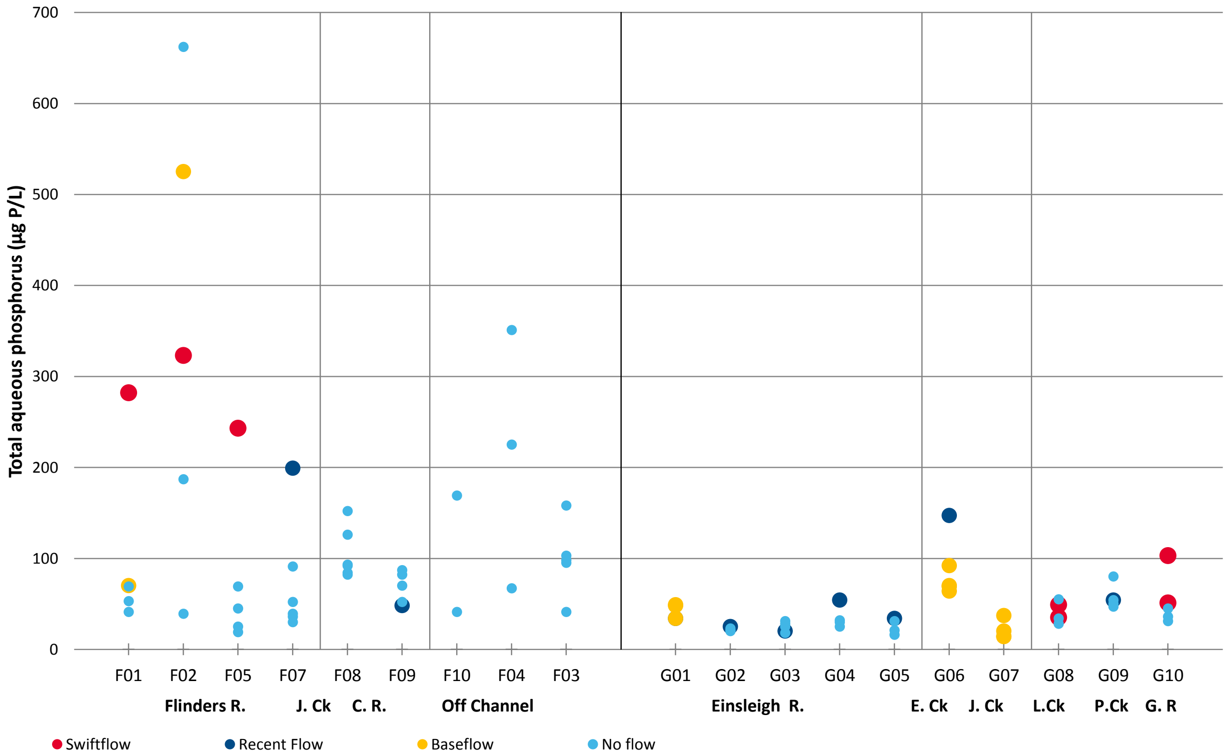


Figure 3.26 Total aqueous phosphorus (µg P/L) recorded in each waterhole during each survey

Total chlorophyll-*a*

Examination of surface and depth integrated chlorophyll-*a* concentrations revealed little differences even during no flow conditions, though base flow conditions demonstrate some differences in results from the different methods of chlorophyll sampling. As other water quality parameters were only sampled from near the surface, we only refer to surface chlorophyll data hereafter. In seasonal tropical systems such as these, we have also found that total chlorophyll (sum of the active chlorophyll-*a* and inactive phaeophytin-*a*) is a more reliable indicator of phytoplankton biomass than chlorophyll-*a* alone, hence its use here. Overall waterholes in the Flinders catchment had higher surface total chlorophyll-*a* concentrations than waterholes in the Gilbert catchment (Table 3.10). Total surface chlorophyll-*a* generally declined during swiftflows, indicating that the runoff was reasonably fresh and some flushing had occurred (Figure 3.27). However, concentrations still ranged from 1.2 to 8 µg/L for a swift flow event. In proper flushing events concentrations would be virtually undetectable (i.e. these results indicate that these were basically pre-flush events, although waterhole F01 appears to have been virtually flushed out). It also seems that following some inflow where concentrations decline, total chlorophyll-*a* concentrations quickly become elevated above pre-flush conditions, when access to nutrients are available. In the case of F02, concentrations during the February 2013 survey were the highest for this waterhole, but it is not clear whether concentrations were higher between surveys and that the February 2013 result reflects falling concentrations again (Figure 3.28).

The perennial Gilbert catchment waterholes (G06 and G07) had the lowest chlorophyll-*a* concentrations which is not unexpected given that flow would constantly wash away phytoplankton, thus limiting biomass accumulation. G01 had slightly higher concentrations again for a perennial waterhole under baseflow conditions, but that waterhole was a deep pool and has a small concrete causeway regulating flow downstream which almost certainly contributes to a higher water residence time. The other Einasleigh River waterholes maintained similar concentrations to G01, making them somewhat lower than most of the other lentic waterholes sampled. The chlorophyll-*a* concentrations recorded at G08 and G09, the waterholes with low dissolved oxygen and pH values suggestive of a low photosynthesis to respiration ratio, actually had similar phytoplankton biomass to most waterholes in the Flinders catchment. This suggests that the excess respiration was probably attributable to high benthic respiration rates rather than low photosynthesis rates.

Table 3.10 Summary total chlorophyll-*a* concentrations (µg/L) recorded during the Assessment

CATCHMENT	N	MAXIMUM	80TH PERCENTILE	MEDIAN	20TH PERCENTILE	MINIMUM
Flinders	36	247.3	36.1	11.8	8.5	4.4
Gilbert	34	35.5	12.6	4.0	1.6	0.9

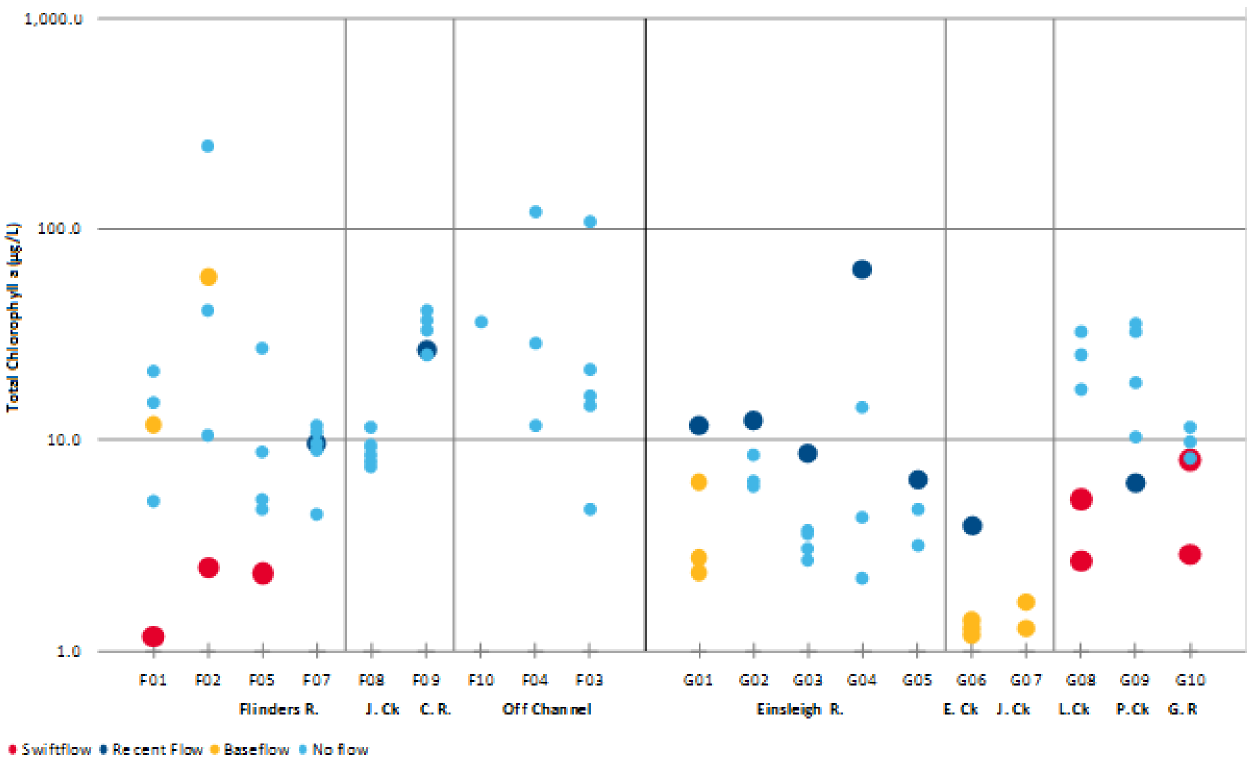


Figure 3.27 Total chlorophyll-*a* (µg/L) recorded in each waterhole during each survey

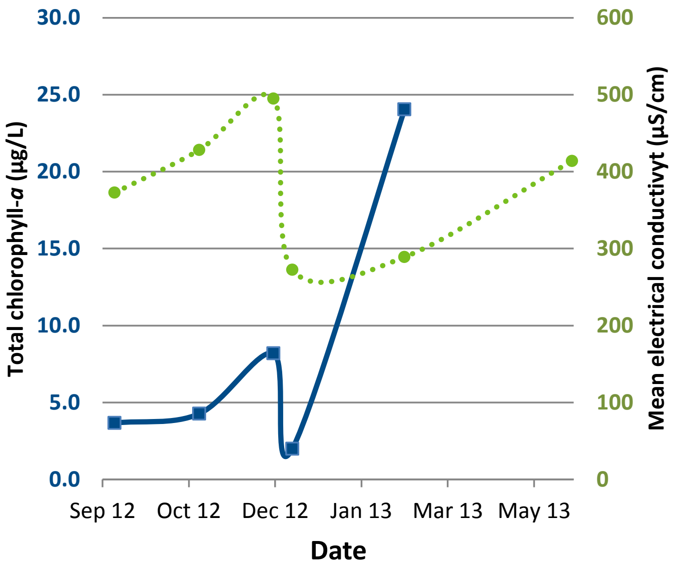


Figure 3.28 Total chlorophyll-*a* (µg/L) recorded at F02 during the Assessment

The relationship between nutrients and total chlorophyll-*a* shows that most of the particulate nutrient (both nitrogen and phosphorus) measured is bound up in phytoplankton with the highest particulate nutrient concentrations coinciding with highest phytoplankton concentrations (Figure 3.29, Figure 3.30). Once again there is an obvious separation between catchment with the highest concentrations in the Flinders catchment sites compared. In both catchments, there was a strong positive relationship between the diel dissolved oxygen amplitude and total chlorophyll-*a* concentrations, indicating that much of the cycling is driven exclusively by phytoplankton under no flow conditions (Figure 3.31).

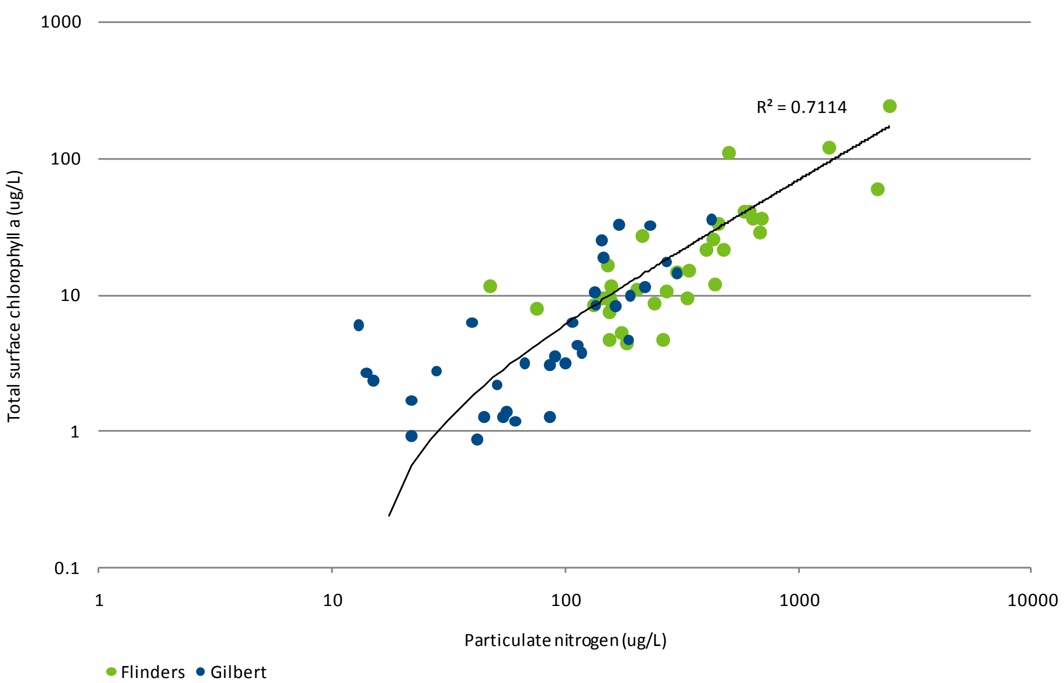


Figure 3.29 Correlation between total surface chlorophyll-*a* and particulate nitrogen concentrations. Plot includes data for baseflow and no flow conditions only

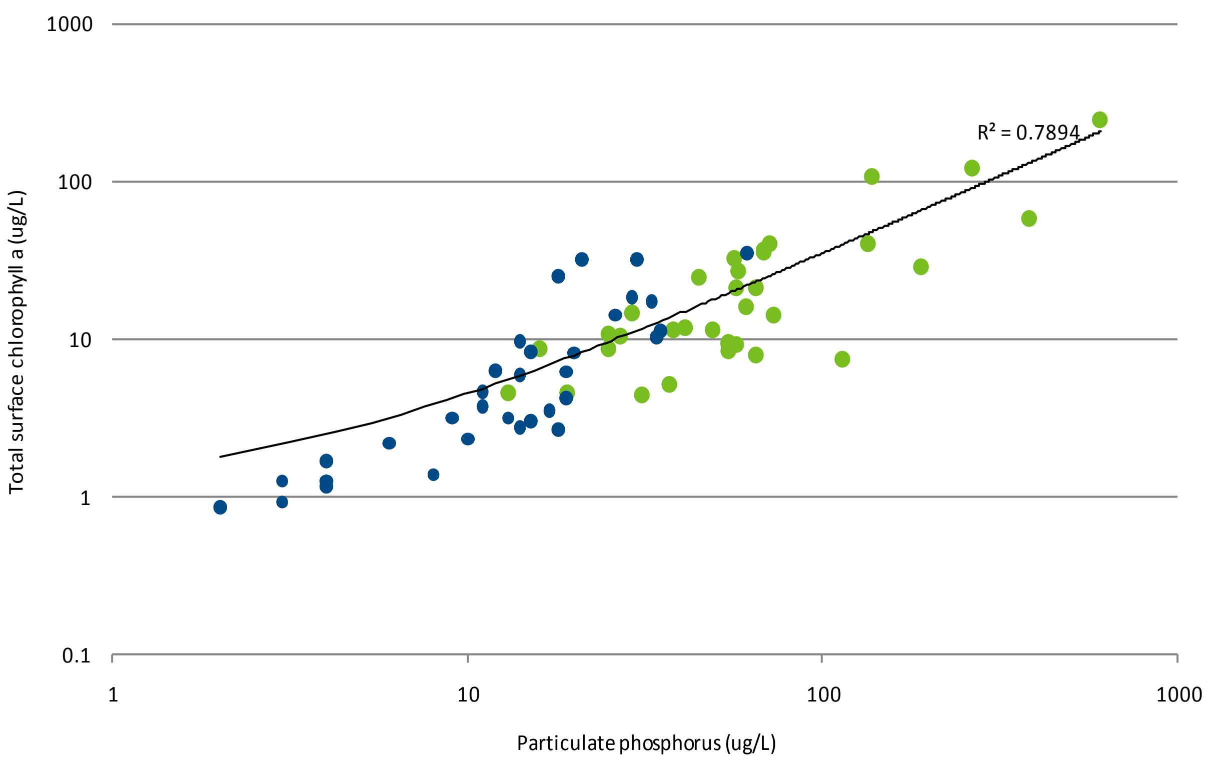


Figure 3.30 Correlation between total surface chlorophyll-*a* and particulate phosphorus concentrations. Plot includes data for baseflow and no flow conditions only

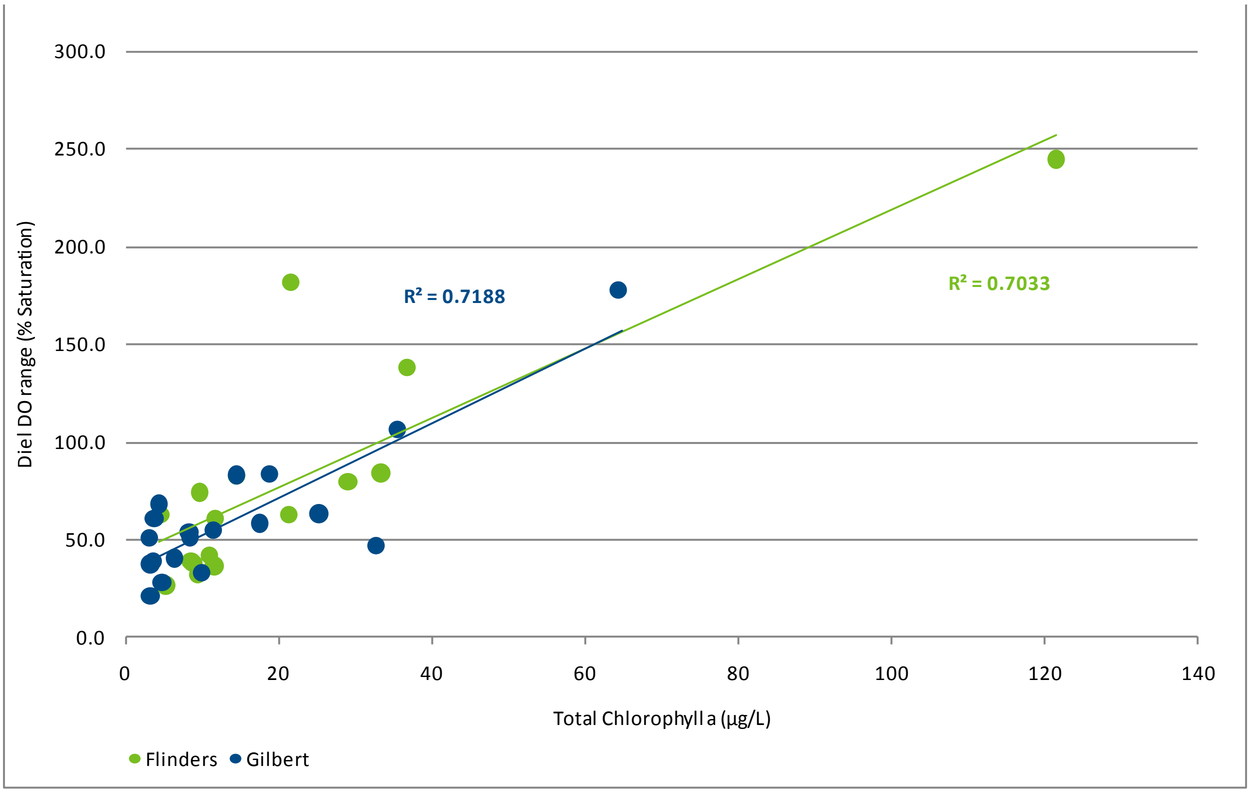


Figure 3.31 Correlation between the dissolved oxygen diel amplitude and total chlorophyll-*a* concentrations under no flow conditions only

Ionic composition

In contrast to the Gilbert catchment waterholes the measured hardness of waters sampled in the Flinders catchment was low to moderate and generally unaffected with flow (Figure 3.32). Both of the two perennial waterholes near Mount Surprise (G06 and G07) had particularly hard water, while G08, G09 and G10 had particularly soft waters. Almost 70% of the water hardness in the Flinders catchment is from calcium, which is more than the Gilbert catchment where between 30 to 50% of the hardness is related to available calcium (Figure 3.33). Greater than 55% of the anion composition is bicarbonate dominated, especially in the baseflow driven waterholes of the Gilbert catchment.

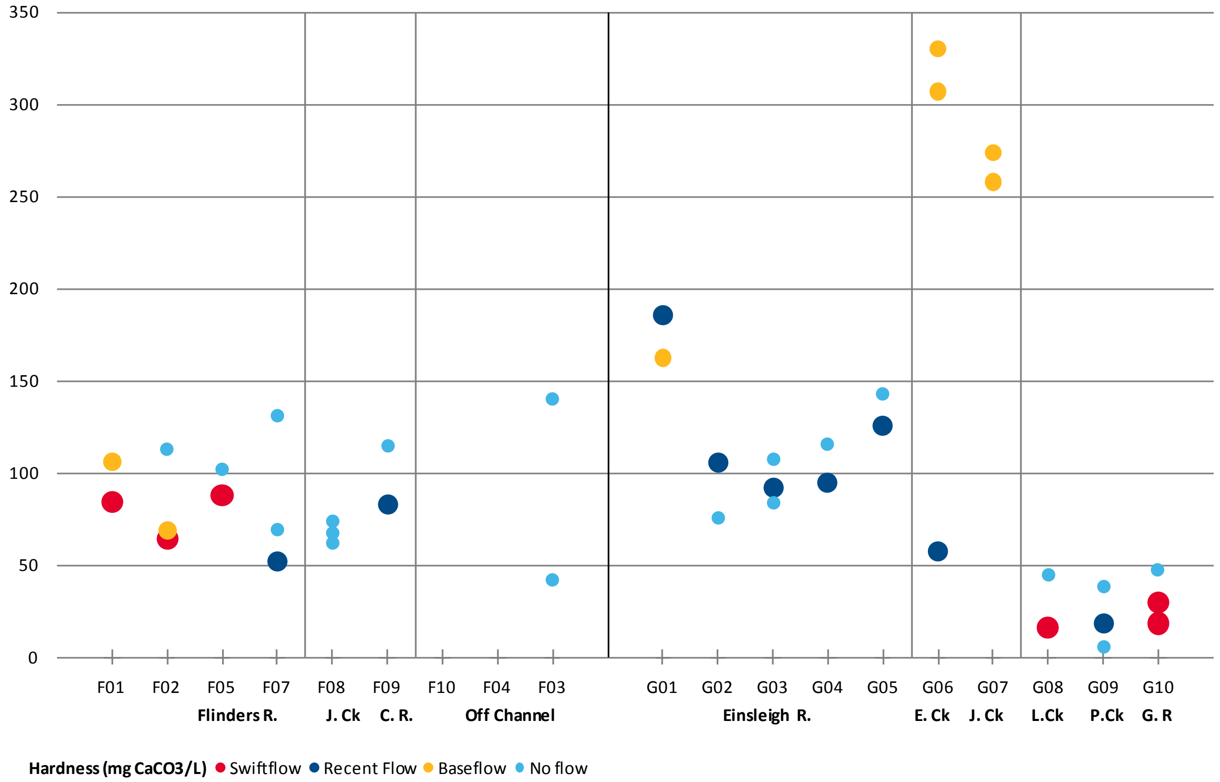


Figure 3.32 Water hardness in each waterhole during each survey

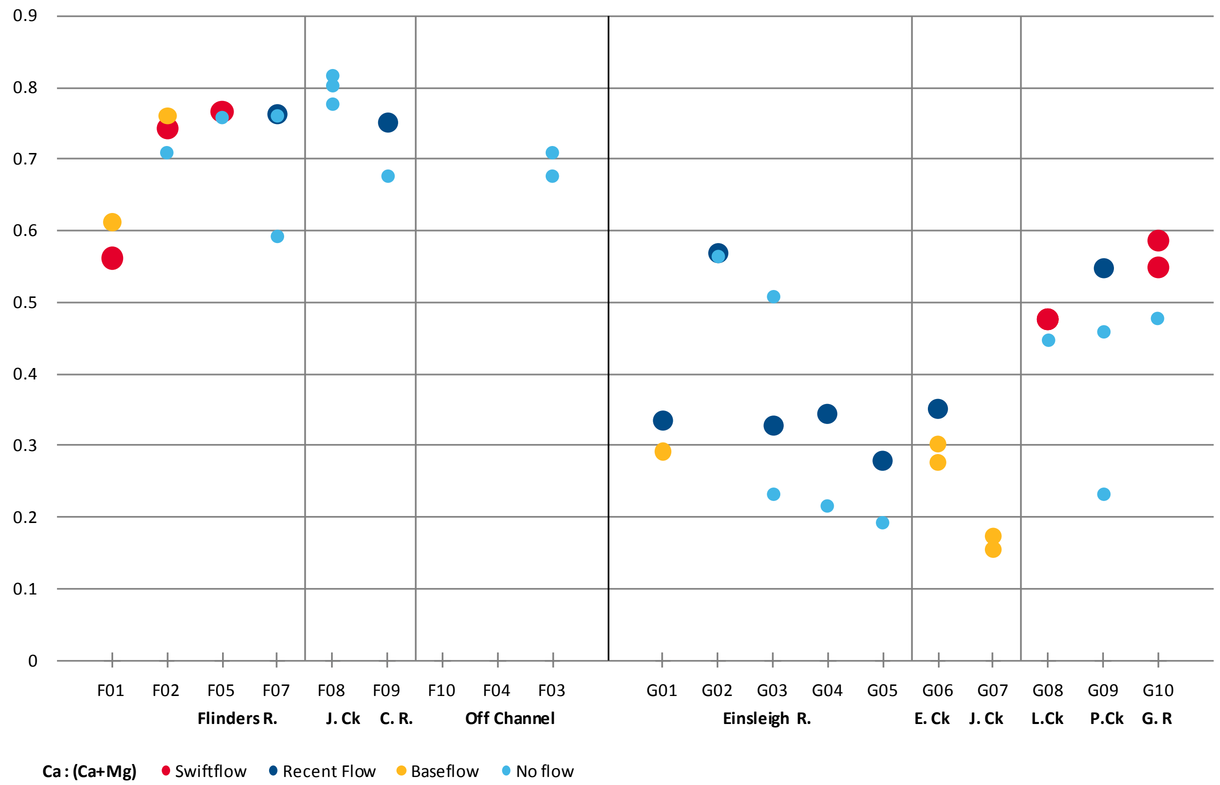


Figure 3.33 Ratio of calcium to calcium and manganese calculated for each waterhole during each survey

3.5 Discussion

The water quality conditions observed during this study provide a preliminary understanding of the ecological processes operating within waterholes of the Flinders and Gilbert catchments, under the climatic conditions experienced during the Assessment. Overall the Flinders catchment waterholes were considerably more turbid than the Gilbert catchment waterholes. Because of the comparatively clear waters of the Gilbert, even minor variations in turbidity cause large changes in the depth of light penetration as occurred during minor flow events at some waterholes. Waterhole clarity is a key driver of ecosystem processes and the phototrophic community is particularly vulnerable to changes in turbidity and light availability. Conversely, in the turbid waterholes of the Flinders catchment, variations in turbidity will have comparatively little effect upon the depth of light penetration through the water column.

Stratification is an important characteristic of waterholes in the Assessment. The development of thermal stratification prevents circulation within the water body such that the bottom and surface layers may have very different water quality characteristics. Under these conditions, bottom waters, isolated from gas exchange contact with the atmosphere and often receiving less sunlight, are prone to becoming severely hypoxic. Stratification was most pronounced in waterholes of the Flinders catchment, where the turbidity retained heat within the surface layers, strengthening stratification. In the clear waters of the Gilbert catchment, where sunlight and heat could penetrate deeper, most commonly stratification usually formed late in the afternoon but disappeared overnight. Whilst this diel formation and breakdown of stratification creates considerable limnological variability, the overnight mixing of surface and bottom waters lessened the development of hypoxic conditions early in the morning (a time when dissolved oxygen is normally at a minimum). Strong stratification is a characteristic of waterholes during the benthic autotrophy phase (e) described in the conceptual model (Figure 3.1).

Higher nutrient concentrations and chlorophyll-*a* concentrations were recorded in the Flinders catchment waterholes than the Gilbert catchment waterholes. Strong correlations between nutrients and chlorophyll *a* suggest that much of the particulate nutrients measured were bound up in phytoplankton biomass. As predicted in the conceptual model, phytoplankton biomass declined during swifter periods of flow although chlorophyll concentrations remained detectable. There was a significant concentration of chlorophyll in flowing waters and supporting the notion that most waterholes were not properly flushed during the Assessment. Furthermore, chlorophyll concentrations quickly recovered after the flow events to concentrations measured prior to the event.

Capturing water during the peak of an event hydrograph (either by water harvesting or construction of dams) can potentially reduce the efficiency and frequency of flushes and waterhole reset events. The longer term effects of reduced flushing have not yet been examined in the Assessment area due to the short term duration of the Assessment. Due to the unusually dry conditions that prevailed some waterholes actually experienced no flow events at all and those which did were not properly flushed out. Notably the few flow events that occurred were small and isolated enough to suggest that even moderate water harvesting could easily have reduced flows to the point where there was insufficient water to top up downstream waterholes, let alone flush them out. Despite the failed wet season, most investigated waterholes were maintaining reasonable instream conditions early in the dry season, suggesting that the ecosystems were coping in the short term. Unfortunately the field monitoring activities associated with this project ceased at that time, so there was no opportunity to ascertain whether or not those waterholes were capable of maintaining healthy conditions through to the end of the dry season, noting that there is no guarantee that the next wet season will bring drought-breaking rains.

However, it is noteworthy that some waterholes were already exhibiting signs of drought stress towards the end of the investigation. For example several Flinders catchment waterholes which had held water for the duration of the previous dry season were actually drying out by the end of this investigation, even though they had received enough wet season inflow to temporarily refill them on at least one occasion. This suggests that seepage losses were much greater this year than they had been the previous year, and implies that the water table had fallen to the point where groundwater levels were now below the level of the streambed (mostly notably at F02). Accordingly, it appears that these waterholes will only be properly recharged if there is enough stream flow to firstly recharge the alluvial groundwater reserves associated with that section of the stream. There is not sufficient existing data to be able to infer how much flow would be required to accomplish that objective, but it is obviously much larger than the standing water volume in the waterholes. There is currently no means to determine whether any other waterholes will suddenly begin to dry out as water tables continue to decline further as the drought progresses.

Moreover, most of the larger waterholes (e.g. G05, F08) that were still present at the end of the investigation were supporting quite high phytoplankton biomass, and as a consequence diel cycling of DO was already apparent even though it was only the beginning of what could potentially be a long drought. There were also a layer of unconsolidated fine sediments on the bottom at most waterholes. This material, which would not normally be present at that time of the year (because it would normally have been flushed out by wet season flows), has the potential to inhibit benthic productivity by preventing light from reaching the bottom, even if the overlying water column is quite transparent (particularly so in Gilbert catchment waterholes). Sedimentary materials of this kind also have the potential to alienate macroscopic invertebrate fauna, but can at the same time enhance the productivity of heterotrophic microbiota by providing organic carbon and physical substrate. Waterholes G08 and G09 were in fact beginning to become heterotrophic during this Assessment. This had resulted in the development of hypoxic conditions suggesting that these waterholes were already experiencing some adverse effects from excessive biomass accumulation. It seems likely that similar problems would have become evident at other waterholes over the course of the dry, especially during the hot summer months leading up to the next wet. The occurrence probability and severity of such effects will likely be greatly exacerbated if the next wet season (2013/2014) proves to be as dry as that experienced during the Assessment.

For some river reaches, particularly on the Gilbert, groundwater is responsible for persistent baseflows throughout the year (Jolly et al. 2013). Base flows are both important in sustaining perennial waterbodies but also play a vital role in maintaining water clarity. One of the principle risks identified in this investigation is concerned with changes in groundwater inputs as a result of increased groundwater abstraction. Shifts in flow duration, water permanency and ambient water clarity as a result of reduced groundwater intrusion will impact upon river ecology changing the trophic basis and fundamentally altering food web structure. Furthermore, reduced inflows and decrease dilution rates are likely to increase susceptibility of waterholes to other anthropogenic stresses.

3.5.1 TYPOLOGY OF WATERHOLES

Based on the assembled water quality and biological data, waterholes can be classified into three contrasting types which share a number of important inherent ambient water quality traits that underpin their functional ecology and vulnerability to various anthropogenic impacts (Table 3.11). All the waterholes studied in the Flinders catchment were Type 1, but most of the Gilbert catchment waterholes were a mixture of Types 2 and 3 (with one or two potentially qualifying as Type 1). However, transitions between waterhole types are possible and even likely. During wetter years and especially La Niña periods some of the Type 2 waterholes would receive sufficient baseflow to be classed as Type 3, and Type 1 waterholes could become Type 2. Whilst with the given data set it is impossible to assert whether transitions between waterhole types occur more broadly, there is sufficient information to infer that transitions among types are more likely to occur in the Gilbert catchment. This is due to the higher and more frequent rainfall (see Figure 2.9 and Figure 2.10), and the existence of a number of perennial streams (i.e. there is greater potential for more prolonged and widespread baseflow to occur in the Gilbert catchment).

Table 3.11 Typology of waterholes in the Flinders and Gilbert catchments

TYPE	DESCRIPTION	WATERHOLES
1	Ephemeral with little or no groundwater baseflow. Persistently turbid enough to prevent light reaching the bottom unless the water is < 1 m deep (i.e. Z_{eu}:Z < 1, unless Z < 1)	All Flinders catchment waterholes G08, G09, G10

2	Ephemeral and episodically turbid but become clear enough during the dry season for light to penetrate to the bottom (i.e. Z_{eu}:Z > = 1) due to displacement by baseflow or settling of solids	G02, G03, G04, G05
3	Perennial and clear (Z_{eu}:Z > = 1, except for brief periods during swift flow events). These waterholes are representative of an entire reach, rather than an independent waterhole	G01, G06, G07

Type 1

Type 1 waterholes are usually turbid enough to prevent sunlight from reaching the bottom and accordingly, in deep pools benthic algal growth is often restricted to the shallow edges of the water body (Bunn et al., 2006; Arthington and Balcombe, 2011). There is usually sufficient light penetration to support phytoplankton growth in the surface water layer and because there are no flows to carry the phytoplankton away, biomass can accumulate to quite high levels compared to lotic (flowing) waters. Accordingly, the near-surface water layer of deep pools often supports high levels of autotrophy, which results in a net production of oxygen and consumption of carbon dioxide during the day, and the reverse at night, while most of the benthos is primarily heterotrophic tending to consume oxygen and produce carbon dioxide all the time. The situation is different in very shallow waterholes because light can usually reach the bottom even when turbidity is quite high, and stratification is less likely to occur.

Water level in Type 1 waterholes gradually decline over the course of the dry season due to the combined effects of evaporation and infiltration, often eventually breaking up into a disconnected series of shrinking waterholes. The size and permanency of these waterholes and the rate at which they shrink varies widely and depend on the morphology and extent of riparian shading (width), but also effective fetch for wind action, and the height and the degree of channel incision below the levees (Hamilton et al., 2005). Most of the aquatic fauna species which occupy these habitats are incapable of surviving desiccation, hence, their continued survival is contingent on the existence of permanent waterholes, and in some of the drier catchment areas permanent water is rare enough to suggest that even quite small waterholes may play a vital role as drought refugia.

In the turbid waters of Type 1 waterholes stratification has a particularly significant effect on the ways in which productivity is partitioned. At the benthos autotrophy tends to be light limited but in the surface layer it is not. The factors which limit the productivity within the surface water partition have not been studied in detail. However, it is apparent from the data collected here that nitrogen to phosphorus ratio varies sufficiently over time to expect that either could be limiting at certain times. The results also indicate that pH are high enough for inorganic carbon availability to be a limiting factor for any phytoplankton species that cannot obtain carbon from bicarbonate ions (there is no free carbon dioxide present in high pH waters). Biomass accumulation is also limited by the capacity for the phytoplankton to remain suspended within the photic surface layer (many common phytoplankton species such as diatoms may gradually sink into the aphotic zone).

In all waterhole types, the surface water layer is subject to substantial diel temperature fluctuations and daily maximum values are quite high in the Flinders and Gilbert catchment ranging up to 39°C, which is potentially stressful for most local fish species (Burrows and Butler, 2012). The warmer surface waters in Type 1 waterholes is also assisted by higher turbidity which has a higher thermal mass and therefore most of the solar radiation is stored in the surface turbid waters. Temperatures in the bottom layer are cooler and do not fluctuate as severely as seen in Type 2 and 3 waterholes. Maximum daily bottom temperatures in fact barely exceed 33 °C which is the physiological limit of the most sensitive local species tested to date, fly-specked hardyhead (*Craterocephalus stercusmuscarum*) (Burrows and Butler, 2012), a species which is present in the Gilbert catchment, but notably, has never been recorded in the Flinders catchment (see Chapter 5).

Type 2

Type 2 waterholes display many of the same characteristics of Type 1. They are turbid early after the last of the river flow and remain so for some time after surface runoff and tail water flow draining tributaries ceases. Surface waters gradually become warmer, assisted by the thermal storage of heat caused by their turbid nature, while bottom layer waters are generally cooler much the same as Type 1. However, the major difference from Type 1 is that these waterholes have a sufficient baseflow to assist with displacing turbid wet season waters, an important requirement in the clarification process. The supply of groundwater is typically sufficient to maintain waterhole levels or slow the process of evaporation such that these waterholes are generally able to withstand the dry season. As the clarity of the water column continues to improve, so too does the euphotic depth reaching the bottom waters and promoting the growth of aquatic vegetation in these waterholes. There was evidence of this in several waterholes in the Gilbert catchment (e.g. G03, G04) where aquatic vegetation commenced growing and was particularly obvious by the January 2013 survey.

Clear, non-flowing waterholes in the Gilbert catchment also tend to be less thermally stratified and instead are well mixed throughout the water column as evidenced by the high percentage of time that the difference remained below 0.4°C. At this stage, benthic autotrophs begin to establish in the margins and the waterhole bottom areas leading to retention of biomass, nutrients and overall productivity which is moderate compared to Type 1 waterholes. At this point, when waters are clearer, water quality is usually quite good. However, at this stage Type 2 waterholes are now also quite susceptible to any rapid change in water quality. For example, even small changes in turbidity can cause large changes in the light climate. In situations where clear waterholes have developed extensive communities of submerged aquatic plants, large and rapid changes in light quickly depletes dissolved oxygen concentrations as the vegetative matter breaks down. At this point, exotic aquatic plants can take hold including paragrass *(Urochloa mutica)*, hymenachne (*Hymenachne amplexicaulis*) and water hyacinth (*Eichhornia crassipes*) (from knowledge attained following the Burdekin irrigation scheme). This is a key issue as irrigation development can also lead to increased nutrient runoff from irrigated farms (Chapter 6). This process can contribute to severe water quality induced stress for aquatic biota and sometimes fish kills. Such changes in waterhole conditions have been documented in the lower Burdekin irrigation district in response to the downstream delivery of turbid waters to previously clear reaches (Burrows and Butler, 2007; Butler et al., 2007).

Type 3

Type 3 waterholes provide more stable aquatic habitats than ephemeral/intermittent reaches (Type 1 and 2), and they are inherently less vulnerable to many of the main water quality related stresses and pressures (both natural and anthropogenic) that commonly impact on streams in this region. Compared to other waterhole types they have superior dilution and dispersion capacity (thus limiting the severity and duration of exposure to elevated contaminant concentrations associated with pulse input events), and they are less prone to develop hypoxia, temperature extremes or to suffer from excessive accumulation of planktonic biomass (it is washed to downstream waters). The water is also much harder compared to the surface stormwater inflow waterholes where the water is much softer. They are, however, vulnerable to impacts from chronic/persistent inputs of contaminants (i.e. sediments contributing to increased turbidity) or of water that is of different quality to that of the natural baseflows. Impacts of that kind could occur if water from an impoundment were to be used to supplement natural baseflows. This has, for example, occurred in the Burdekin floodplain irrigation area, where chronically turbid water from the Burdekin Falls Dam has been used to supplement flows in the lower reaches of the river and its associated floodplain distributaries (Faithful and Griffiths, 2000). As a consequence, the ecology of hundreds of kilometres of Type 3 and 2 streams has been dramatically altered in that catchment, creating entirely new artificial stream types (Burrows and Davis, 2009). Some of these still support functional, albeit unnatural ecosystems, but many suffer from problems such as severe aquatic weed invasions, chronic and/or episodic hypoxia problems, frequent occurrences of episodic fish kills and localised extirpation of native fish species. Those floodplain creeks and wetlands that receive tailwater runoff from irrigated farms have experienced even more severe problems due to episodic inputs of very poor quality water containing, for example, BOD and ammonia concentrations high enough to be acutely toxic to fish. Accordingly, although Type 3 reaches are less susceptible to impacts than ephemeral reach types, they are by no means invulnerable to human perturbations.

The consistent baseflows promote mixing of the water column and this imposes limits on the extent to which instream biological and limnological processes influence conditions in the water column. Hence, stable stratification of the water column is relatively rare, although diurnal stratification still occurs for most of the year (i.e. waters mix during the night but become stratified during daylight hours due to the formation of thermal density gradients that are too steep to allow warm surface waters to mix with the cooler underlying waters). This prevents free transfer of gases through the water column and can result in the development of vertical gradients in dissolved oxygen and carbon dioxide with the latter resulting in pH stratification. However, because biological consumption of oxygen and carbon dioxide is generally occurring in both water layers, and since the layers mix at least once per day, these variations are generally quite subtle.

A significant proportion of introduced contaminants are carried downstream and the effects of localised riparian inputs can accumulate in the process. Stream waters are also constantly evaporating as they flow downstream which increases contaminant concentrations. This effect is generally most evident for major ions (i.e. salts), chlorophyll (i.e. phytoplankton) and particulate nutrients (much of which, under baseflow conditions, is contained in phytoplankton).

3.5.2 VULNERABILITY OF WATERHOLES TO AGRICULTURAL WATER USE

Many Queensland rivers are naturally leveed so the surface runoff from riparian farm properties often drains away from the main river into small creeks and tributary streams which eventually enter the river some distance downstream (in some cases the distance can be considerable). This sort of drainage characteristic has been reported for the Herbert floodplain (Pearson et al. 2003), Burdekin (DNRMW, 2006) and the Elliot River, Molongle Creek, Rocky Ponds irrigation areas (Butler et al., 2009). However, almost all of the monitoring to detect the impacts of farming has been done in the main rivers adjacent to the farm properties, so as much as 80-90% of the farm runoff is probably being missed. The consequence of this (apart from the need to be judicious when selecting monitoring site locations) is that the initial receiving waters for farm runoff are often much smaller waterways than the adjacent river. Typically, because of their small catchment area and the low frequency of rainfall, they are very poorly flushed and highly ephemeral. However, some creeks can maintain valuable (potentially locally or regionally significant) permanent and semi-permanent waterholes, especially in areas where groundwater springs occur and/or where the stream intersects the local water table.

These waterholes are particularly vulnerable to impacts from agricultural runoff. Their catchment areas are often so small that farm properties can occupy a significant proportion of the watershed and consequently there may be little or no available dilution of agricultural runoff. These streams may be either Type 2 or Type 3, but in either case the waterholes they contain are generally small, poorly mixed and highly prone to becoming eutrophic and/or hypoxic especially in free range grazing areas where they are frequently subject to excessive inputs of organic matter and nutrients in the form of manure and excreta, and/or disturbances to bottom sediments caused by wading or wallowing animals. The waterholes are most vulnerable at the end of the dry season when temperatures, instream biomass, biological turnover rates, respiratory oxygen consumption and evapoconcentration are all at or near their annual maximum. They are particularly susceptible to adverse effects from pre-flush runoff events (i.e. rain events that wash catchment runoff into the stream without generating enough stream flow to wash it away). Provided that the stormwater is not of such poor quality that it is acutely toxic (a proviso which may not always be met in agricultural catchments), larger events may provide some relief by generating sufficient flow to flush out accumulated biomass and aerate and mix the water. However, smaller streams such as these are rarely flushed out properly, so the effects of chronic inputs of sediment, nutrients and/or organic matter often tend to accumulate to some extent from year to year, until there is a very large scale (low recurrence frequency) flood event. Moreover, it is important to remember that flushing involves washing contaminants downstream into other parts of the receiving environment, and can therefore simply translocate existing problems.

These vulnerabilities have important ramifications for water management and assessment. Notably, runoff from farms may in some cases constitute the majority of water that is available to replenish the waterholes, so the tactic of capturing/detaining pre-flush runoff from farm properties (something which is fairly easily accomplished in these drier catchments) may not be a feasible option to pursue, because it would starve the stream of water (i.e. pre-flush flows may cause some water quality problems, but poor quality water will still often be better than no water at all). Accordingly, ambient water quality management will largely hinge on the development and adoption of on-farm practices that ensure that runoff is of good quality, noting that existing data provide reasons to suspect that current best practices, although improving with recent research programs, may not be adequate to protect these kinds of receiving waters.

Susceptibility to different kinds of contaminants and impacts varies between stream types, so management measures that have proven effective in one situation may not necessarily work as well in another. Some of the main differences are:

- Type 1 waterholes persistently maintain turbidity levels that are high enough to ensure that further increases in turbidity would have little effect on the depth to which light penetrates the water column, hence their light climate is only subtly affected by inputs of light-absorbing materials such as fine inorganic suspended sediment (i.e. clays and inorganic colloids) or colour-forming humic matter. Conversely, Type 2 waters are clear for much of the time and can therefore develop significant biomass of benthic plants and algae. As long as the water remains transparent enough to support photosynthesis these plants help to oxygenate the water, but if the water column becomes turbid for light to reach them, the plants consume oxygen, and in cases where the plant biomass is large this can cause oxygen deficiencies severe enough to cause fish kills. The amount of suspended sediment or colour-forming organic matter required for that to happen is quite small (i.e. in clear waters small changes in turbidity cause large changes in the transparency), hence Type 2 waters are potentially very susceptible to adverse effects from quite small pulse inputs of turbid/coloured water. The Type 2 waterholes examined were not supporting a particularly large biomass of benthic algae or macrophytes, and would not therefore have been susceptible to such acute impacts, although it is yet to be determined if that status will be maintained during the course of the current drought. Significantly, however, the productivity of these waterholes is mainly limited by nutrient availability, and has the potential to increase substantially should nutrient loading be enhanced, for example, by inputs of fertiliser from croplands or excrement from livestock;
- Evidence of increased productivity due to enhanced nutrient inputs (i.e. cultural eutrophication) has been observed in most north Queensland catchments where intensive agriculture has been pursued. However, this enhanced productivity can be manifested in numerous different ways depending on circumstances. Type 1 waterholes provide conditions that favour the establishment of autotrophic species that are capable of obtaining sunlight at or near the water surface. This comprises emergent and floating macrophytes and motile forms of phytoplankton, in particular, cyanobacteria (which can rise to the surface by adjusting their buoyancy). Which of these species becomes dominant depends on a variety of stochastic factors such as the suitability of the hydraulic conditions, substratum type and the random deposition of plant propagules (for example by waterbirds). As a general rule, Type 1 waterholes do not provide habitat conditions suitable for macrophytes and therefore tend to develop cyanobacteria blooms if they become eutrophic. However, some emergent plant species are highly invasive weeds and have the capacity to alter habitat conditions in their own favour, if they get a foothold. For example emergents such as para grass, hymenachne and typha can gradually alter the composition of the substratum by trapping and binding fine sediments, and they can also retard stream flow thus reducing flushing efficiency and creating conditions conducive to the colonisation for other plants. Seasonal drying of the streambed is an important mechanism for preventing the establishment of such species, and any alterations that reduce the duration and frequency of dry periods have the potential to promote infestations. Even relatively minor releases of irrigation tail water during dry periods and/or the construction of quite small weirs or bund walls, which detain water for longer periods than normal, have the potential to cause such problems. Also the likelihood of infestations will be substantially enhanced if invasive grass species are being intentionally propagated by graziers, and

especially if there are ponded pastures in the upper catchment areas of the receiving streams. Emergent weeds release their photosynthetic oxygen into the air rather than into the underlying water and at the same time they contribute organic carbon to the water column where it is decomposed by oxygen-consuming microbes, hence dense assemblages of emergents generally cause the water to become hypoxic, sometimes severely so. If Type 2 waters become eutrophic dense submergent macrophytes (and associated epiphytic periphyton) can establish which compete quite successfully for nutrients reducing the probability of phytoplankton blooms occurring and perhaps reducing the invasive success of emergent plant species. Submerged plants generally oxygenate the water but only as long as they receive enough light each day to continue photosynthesising. In eutrophic situations diel DO cycling can be quite low and conditions below the plant canopy can also become hypoxic. However, even quite dense assemblages can contain enough oxic microhabitats to sustain fauna communities, as long as light availability is not restricted – noting that in cases where biomass is very high, a few days of overcast weather may be sufficient to cause an oxygen sag.

- Type 1 waterholes are more prone to thermal stratification and if they become eutrophic they are prone to developing hypoxic bottom waters (because there is no biological oxygen production in the bottom layer but there is a lot of respiratory oxygen consumption). Consequently, productive Type 1 waterholes are prone to developing chronic hypoxia and related problems such as instream accumulation of ammonia or hydrogen sulphide generated by anaerobic decomposition and respiration processes. Productive Type 2 waterholes can also thermally stratify and they can also develop measurable oxyclines, but because oxygen can be produced at the benthos, bottom waters are less prone to becoming chronically hypoxic or accumulating undesirable anaerobic respiration by-products. Overly productive Type 2 waterholes can still develop hypoxia-related problems though these tend to be episodic rather than chronic (e.g. brief oxygen sags each morning and more prolonged ones at times when conditions prevent adequate light from reaching the bottom) which makes them more difficult to detect.

4 Waterhole water temperature regime

4.1 Summary points

- Daily mean waterhole profile water temperatures are quite similar in the Flinders and Gilbert catchments, increasing from ~ 22^{o}C to 32^{o}C as the dry season evolves;
- Daily mean waterhole water temperature is not greatly influenced by waterhole depth, but shallower waterholes have a much larger diurnal temperature fluctuations and this will affect the suitability of these waterholes as aquatic habitats;
- High time resolution waterhole water temperature measurements reveal important aspects of their thermal regime that help assess their suitability as aquatic habitats;
- Diurnal temperature fluctuations can help define when waterholes are stratified and also respond to waterhole water clarity and potentially any groundwater influence;
- Frequency curves can be used to estimate how long the thermal regime in a waterhole is above optimal and also the lethal thresholds for fish;
- Turbid waterholes can sustain bottom water temperatures throughout the entire summer period that are more thermally suited for fish;
- Waterhole water temperatures can be modelled with reasonable accuracy and the model can be used to simulate how waterhole temperature increases with climate change;
- Although waterhole water temperature only increases by just over 1 degree under a warmer climate (Scenario C), this has a marked effect on the amount of time water temperatures exceed optimal and also lethal thresholds for fish; and
- Preliminary investigation of the estimation of waterhole water surface temperature using satellites indicates that current data are of too low a resolution to make accurate measurements using this technique.

4.2 Introduction

Waterhole water temperature is arguably the most important water quality parameter since it both directly affects habitat suitability for aquatic biota and the rates of many important physical, chemical and biological processes (Burrows and Butler, 2012). For many aquatic organisms, such as fish, temperature directly controls their metabolic rate and therefore influences growth, resource allocation for reproduction and ultimately population size (Jobling, 1995). Growth rates and development in fish tend to increase with temperature up to an optimum provided there is sufficient food available (McCauley and Casselman, 1981; Regier et al., 1990). As temperatures increase beyond this optimum, growth rates decline and fish become more susceptible to environmental stresses such as low concentrations of dissolved oxygen (Pearson and Pendridge, 1992) and, ultimately, fish can experience lethal effects (Cherry and Cairns, 1982). Irrigation developments where the level of water extraction results in smaller waterhole volume and/or reduced flows can be expected to lead to increased water temperature. Additionally, changed land management practices associated with irrigation development (e.g. the Burdekin River irrigation area; (Burrows and Butler, 2007; Tait and Perna, 2000)) may result in reduced shading from bankside riparian vegetation, a major contributing factor to significant increases in water temperature. As it is a dry tropical region, biota living in waterholes in the Assessment area may already be experiencing stressful and even potentially lethal water temperatures and any further increase may be a significant additional stress. Hence, the importance of considering water temperature as part of the Assessment.

This section describes the high time resolution (20 min) continuous water temperature measurements made in an instream sub-set of the 20 waterholes studied in Flinders and Gilbert catchments (see Figure 2.12) between September 2012 and May 2013. These data are examined in order to quantify how waterhole water temperature changes as the dry season evolves and how water temperature varies between the surface and bottom of the waterholes. The effect of waterhole size (depth) on temperature is also examined and comparisons are made between instream waterholes in the Flinders and Gilbert catchments. An energy balance model is used to estimate waterhole water temperature and its predictions are compared to measured waterhole water temperature.

To explore how often waterhole water temperature approaches and exceeds thresholds that may be detrimental to fish, the 20 min waterhole water temperature data are used to derive frequency curves that show how often water temperature exceeds any given temperature threshold. The exceedance times for two preliminary thresholds for: 1) optimum growth; and 2) lethal effects are illustrated under both current and future climates (see Petheram and Yang, 2013). The impacts of climate change on waterhole water temperature and the rate of decrease in waterhole depth during the dry season are also presented.

Finally, given the current lack of water temperature data in northern Australian waterbodies and the large spatial scale over which such information could be useful, this chapter explores the possibility of obtaining estimates of waterhole water temperature from satellite data. To examine this possibility, additional water temperature and water surface temperature data (using an infra-red thermometer) were recorded in three waterholes (G05, F05 and F08), and also Lake Fred Tritton, on six occasions between October and December 2012, when a LandSat TM 7 satellite with thermal sensor was passing overhead.

4.3 Methods

4.3.1 MODELLING WATERHOLE WATER TEMPERATURE

Waterhole water temperature was estimated using the equilibrium energy balance model described by McJannet et al. (2008). The model was originally developed for estimating daily evaporation from open water bodies of various sizes (ranging from waterholes ~ 60 m wide to lakes ~ 600 km^2 in area), but it also calculates the mean water body temperature in order to specify the changes in heat storage. The main input of energy to the model is solar radiation and the main losses are via heat conduction to the atmosphere and evaporation. For in-stream river channel waterholes it is also possible for energy to enter/leave the waterhole if there is flow in the river, however, this effect can be ignored as here only waterhole water temperatures (see Section 3.3.2) in the latter part of the dry season when flow has ceased are modelled. The input of cooler groundwater to waterholes is also problematic in this water temperature modelling. The model does not account for energy exchanges with groundwater and this effect is discussed later in the comparison of modelled and measured water temperatures.

The waterhole water temperature model requires daily weather data which were obtained for each of the waterhole locations from the SILO database (http://www.nrw.qld.gov.au/silo/). The SILO database consists of interpolated meteorological variables on a 0.05° (5 km) grid for the whole of Australia (Jeffrey et al., 2001). The particular variables available from SILO used by the waterhole water temperature equilibrium model are air temperature, vapour pressure, solar radiation and rainfall. The model also requires daily mean wind speed (to calculate the evaporation rate) and as this is not available in the SILO database, a fixed wind speed of 2 m/sec for all waterhole locations was used. Waterhole evaporation rate is also dependent on the waterhole size, both its area and its depth. Waterhole area affects the 'wind function' (McJannet et al., 2012) used in calculating evaporation and here a fixed characteristic area of 10,000 m^2 was adopted; equivalent to a waterhole 100 m x 100 m. Waterhole depth primarily affects heat storage and the model is run from the beginning of the year so that its depth predictions match waterhole depth measurements made in each waterhole during October or November 2012. The effect of these various assumptions on the predicted waterhole temperatures is discussed further in the results section (Section 4.3.1).

4.3.2 TEMPERATURE MEASUREMENTS DURING SATELLITE OVERPASS DAYS

The days during the Assessment when IR instruments were deployed during a LandSat TM 7 overpass across each of the Assessment area are shown in Table 4.1. The only waterhole not included in the survey was F09 because although this section of the Cloncurry River met the bank size requirements, the actual waterhole surface area dried quickly and remained small over the course of the field work. Lake Fred Tritton was also included as it is the largest waterbody within the Assessment area, and provides a calibration point.

On the dates provided in Table 4.1, a floating pontoon was deployed the day before the overpass and left until the day after the overpass. Figure 4.1 shows a photograph of the pontoon, which supported an infra-red thermometer (Apogee, MI-200 series) to measure the water surface or 'skin' temperature. The pontoon also supported an array of within water temperature sensors (Hobo, Onset Corporation – same loggers used in the continuous temperature monitoring) from 0.05 m below the surface to the bottom of the waterhole at 0.25 m intervals. Data from all of the temperature sensors were recorded using Hobo loggers at 30 min intervals (this is the minimum logging interval for the infra-red thermometer).

Table 4.1 LandSat TM 7 overpass dates when ground based infra-red skin temperature measurements were made at five waterholes in the Flinders and Gilbert catchments during the Assessment

Gilbert; G05	Flinders; F05 and Lake Fred Tritton	Flinders; F08 and F09
11 October 2012	03 November 2012	25 October 2012
12 November 2012		12 December 2012
28 November 2012		

Figure 4.1 Pontoon on the Einasleigh River near Mount Surprise (waterhole G05) showing the infra-red thermometer (on the left) and the string supporting the water temperature profile sensors (on the right)

LandSat TM 7 imagery for each of the dates shown in Table 4.1 was downloaded via the Unites States Geological Survey GLOVIS website (http://glovis.usgs.gov/). The LandSat TM 7 data in the thermal band from GLOVIS are collected at 60 m resolution. However, these data are then 'resampled' using a cubic convolution method to give 'smoothed' 30 m pixel data. Cubic convolution looks at the 16 nearest cell centres to the output cell and fits a smooth curve through the points to find a smoothed value.

In advance of a full analysis of LandSat TM 7 thermal data that would include individual atmospheric corrections on each overpass day, a preliminary feasibility study was carried out. Firstly, scenes were inspected for cloudiness and those where there was significant cloud around the target waterholes were not analysed. Secondly, for those scenes not adversely affected by clouds, raw imagery from the LandSat TM 7 thermal band were visually inspected to ascertain the degree to which mixed pixels were likely to be affecting how waterhole water temperature are able to be interpreted from the Landsat image brightness values. Mixed pixels would result from both the inherent mixed response of the raw thermal signal near a water/land interface and the resampling that has occurred in the imagery.

4.4 Results

4.4.1 CONTINUOUS WATER TEMPERATURE DATA

Typical examples of the continuously recorded 20 min waterhole water temperature data are shown in Figure 4.2. Data for Flinders catchment waterhole F05 (Type 1 waterhole; Table 3.11) and Gilbert catchment waterhole G05 (Type 2 waterhole; see Table 3.11) are shown in Figure 4.2, which shows that diurnal fluctuations in air temperature are much higher than those in the waterhole water. This is because evaporation from the waterhole keeps the water cooler than the air, especially around midday. Water temperatures at the bottom of each waterhole are lower than at the surface for most of the day, but they usually become similar overnight. The diurnal oscillation in bottom temperature gives a good indication of whether there is thermal stratification in the waterhole. For example, in the Flinders waterhole F05 (Figure 4.2a) the bottom temperature diurnal amplitude is very small for most of the period shown. This means that this waterhole is thermally stratified and that very little solar energy reaches the bottom of this waterhole. In contrast, bottom temperature oscillations in the Gilbert catchment waterhole G05 are large (Figure 4.2b) and this is characteristic of a well-mixed waterhole with no stratification. Waterhole temperature measurements made during the sampling trips (see Chapter 3) confirm that waterholes in the Flinders catchment were more highly stratified than in the Gilbert catchment. Mixing conditions can change in a waterhole, as shown by the period of increased mixing in waterhole F05 during January and February 2013. The degree of mixing in a waterhole can affect its suitability as an ecological habitat and also the accuracy with which waterhole water temperature can be modelled.

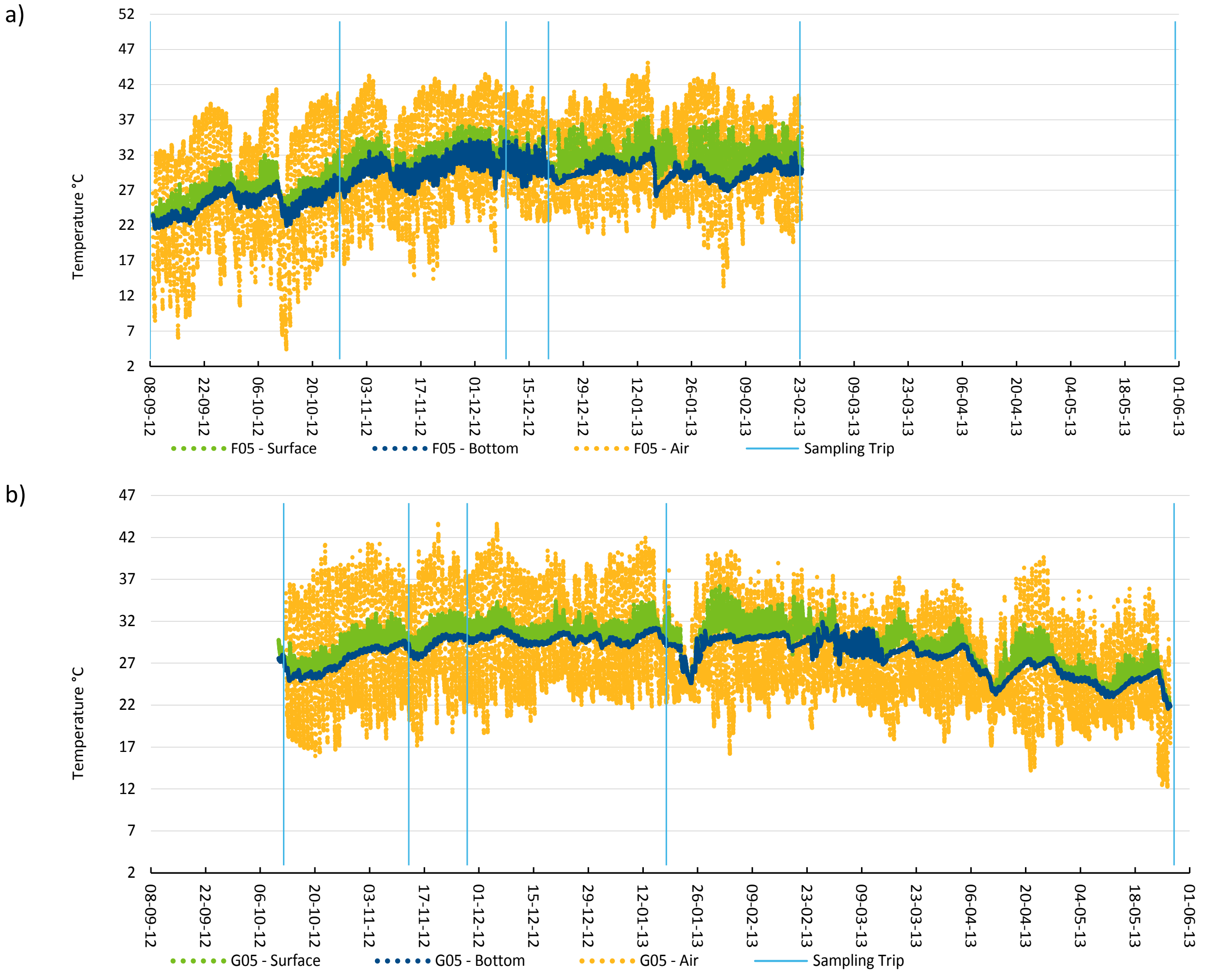
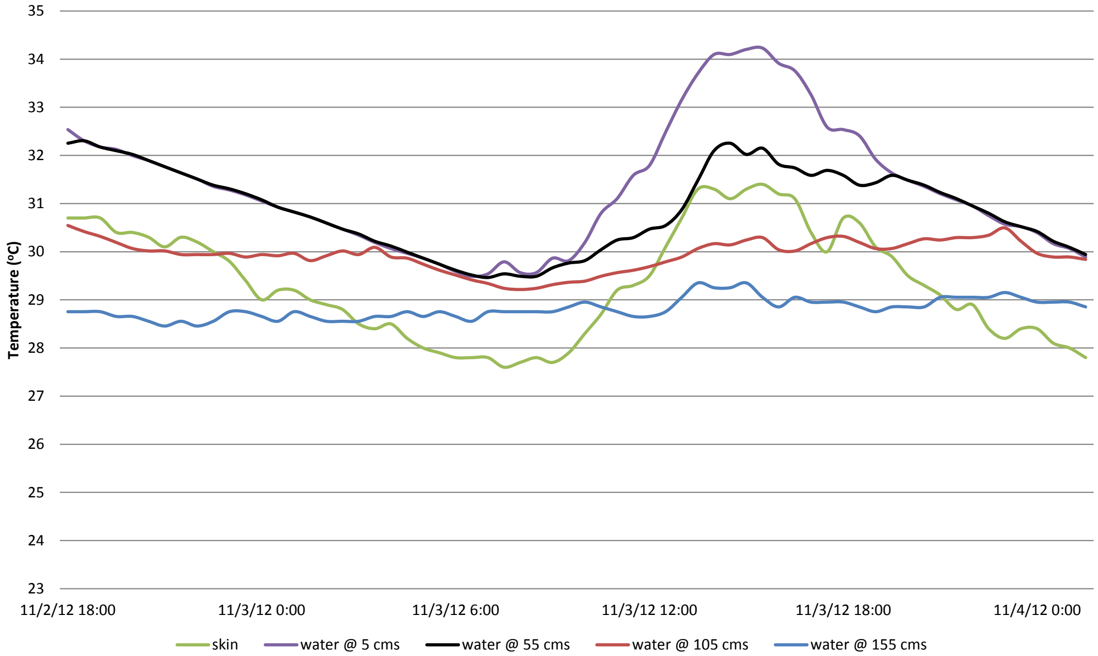


Figure 4.2 Temporal fluctuations in water temperature in: a) Flinders catchment waterhole F05 (note logger failure after February 2013 survey); and b) Gilbert catchment waterhole G05. Surface water temperature is shown in green, bottom water temperature in blue and air temperature in yellow

More detail of the diurnal behaviour of waterhole water temperature in the Flinders and Gilbert catchments is shown in Figure 4.3 (a) and (b) respectively, using data recorded at multiple water depths during a satellite overpass day. The diurnal amplitude of water temperature is much larger in the Flinders catchment waterhole compared with the Gilbert catchment waterhole. For example, in the top 5 cm water temperature changes by ~5 °C in the Flinders catchment waterhole compared with only 1.5 °C in the Gilbert catchment waterhole. Weather conditions at the two locations on the two different days were quite similar; both were clear, rain free days with high radiation inputs (Flinders 26 and Gilbert 24 MJ m^{-2}) and high temperatures (Flinders maximum 41 °C and Gilbert maximum 35 °C), so it is unlikely that the observed differences in water temperature are entirely due to the prevailing weather. Surface ‘skin’ temperatures recorded by the infra-red thermometer are also shown in Figure 4.3 and these are several degrees cooler than the water at the top (0.05 m) of the waterholes, during the day and at night. This is due to the cooling effect of evaporation from the waterholes.

(a)



(b)

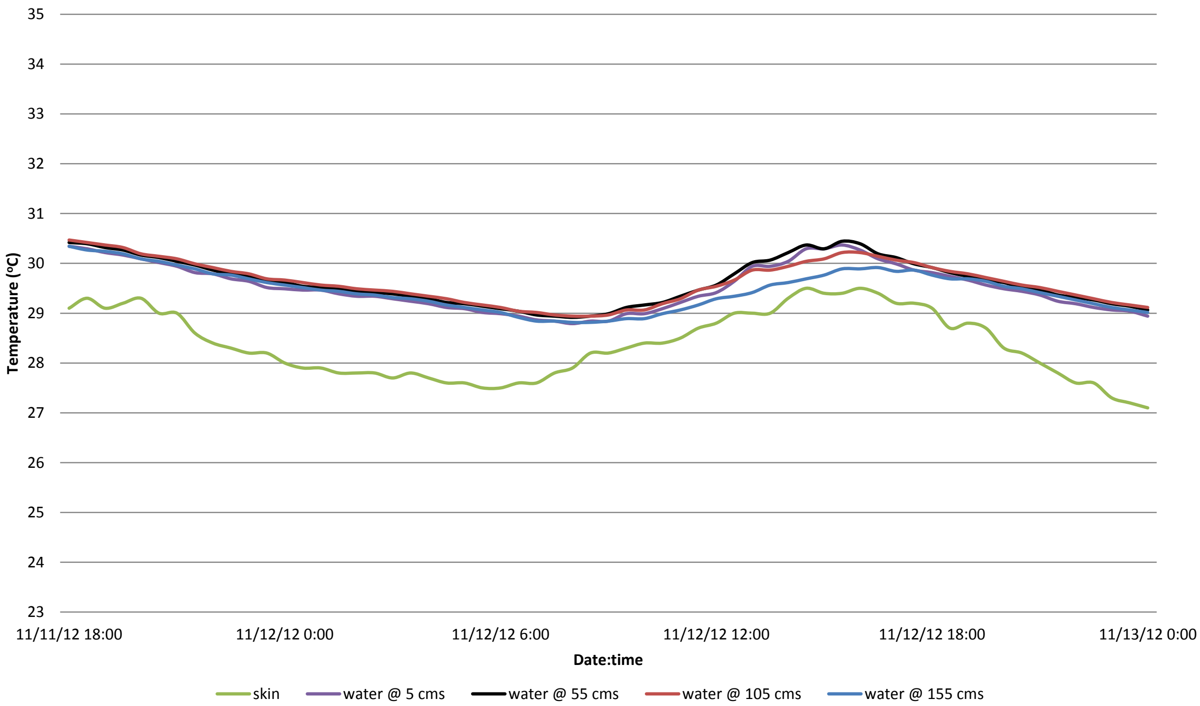


Figure 4.3 Diurnal changes in river waterhole water temperature in: a) the Flinders River (waterhole F05 on 3 November 2012); and b) the Einasleigh River (waterhole G05 on 11 November 2012) at 4 depths below the surface. Also shown is the surface 'skin' temperature recorded by the infra-red thermometer

Another striking difference between the thermal regimes in these two waterholes is the change in temperature with depth (Figure 4.4). During the day the changes in temperature with depth in the Einasleigh River waterhole (G05) are much less than those in the Flinders River waterhole. This can be clearly seen in Figure 4.4, which shows a plot of water temperature with depth in both waterholes at

15:00 hrs; the time when thermal gradients are near their maximum. At this time water at the surface (0 to 0.3 m) is nearly 5 °C warmer than water at 1.5 m in the Flinders River waterhole. In contrast, the equivalent temperature difference in the Gilbert catchment (Einasleigh River) waterhole is only 0.5 °C. This difference in water temperature gradients is likely to be caused by differences in turbidity, as the waterholes in the Flinders catchment are less clear than those in the Gilbert catchment (see Chapter 3). In more turbid waterholes incident light is preferentially absorbed in the surface layers, thereby causing a relatively large increase in the temperature near the surface. Conversely, in the clearer water of Gilbert catchment waterholes, deeper light penetration leads to less difference between the surface and deeper water temperatures. Water body clarity has been measured in the current investigation (see Chapter 3) and also estimated in several catchments of the Gulf of Carpentaria by Lymburner and Burrows (2009) using LandSat remote sensing. Both studies have found that most waterholes in the Flinders catchment were always turbid, whereas waterholes in the Gilbert catchment contained much clearer water.

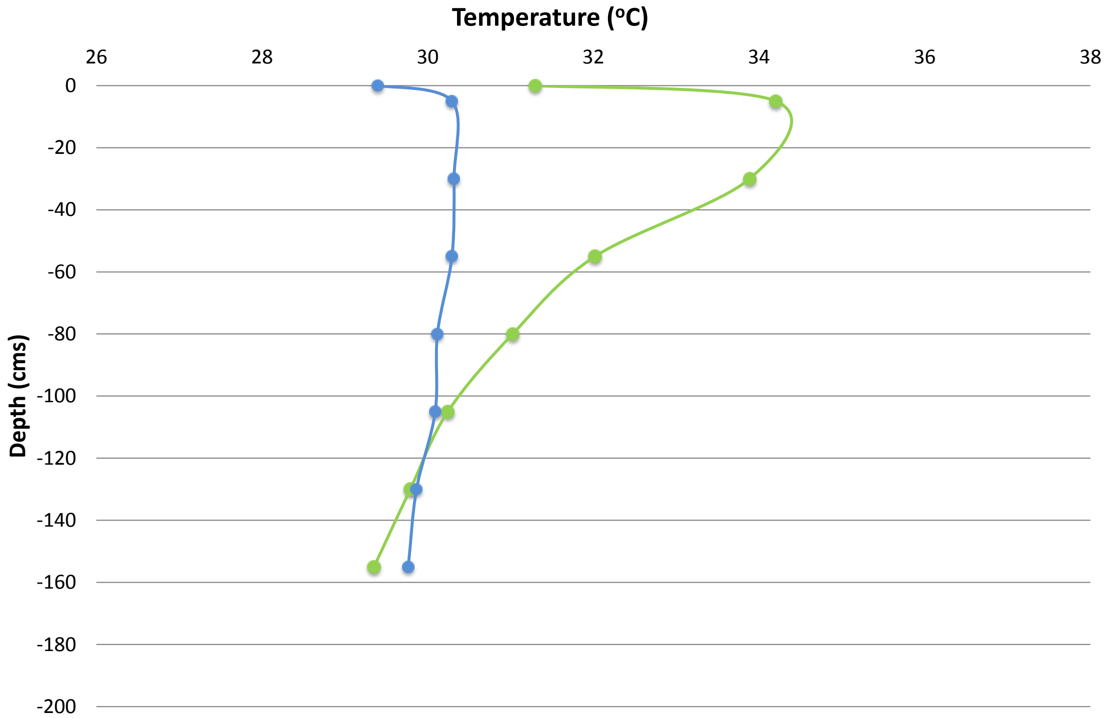


Figure 4.4 Gradients in river waterhole water temperature with depth at 15:00 in: a) the Flinders River waterhole F05 on 3 November 2012 (green line); and b) the Einasleigh River waterhole G05 on 11 November 2012 (blue line)

4.4.2 MODELLING WATERHOLE WATER TEMPERATURE

The seasonal trend in waterhole water temperature for waterhole F05 in the Flinders River is shown in Figure 4.5. The daily mean waterhole water temperature for the entire water column (i.e. mean of the surface and bottom readings) is around 23 °C in mid-September 2012 and this rises steadily to nearly 33 °C towards the end of November 2012. Water temperature generally follows air temperature, but is less erratic due to the thermal mass of the water damping out the higher frequency changes in air temperature. Modelled water temperature follows the measured water temperature very closely, especially up to mid-December 2012. After this date there are occasional flows of water and as the waterhole temperature model does not account for these, there tends to be greater differences between the modelled and measured temperatures. This effect shows up in the regression between modelled and measured temperatures (Figure 4.6). The line fitted to the points up to the 14 December 2012 has a regression coefficient (R^2) of 0.96; and in this zero flow period the model predicts water temperature to within 1 degree (on average). Flows entered this river reach on 15 December 2012 and again on several occasions during the next few months. The green crosses in Figure 4.6 show that the modelled water temperature was less well correlated with the measured water temperature in this period. Modifications to the model to account for flows would need to be made to improve the model predictions for flowing streams.

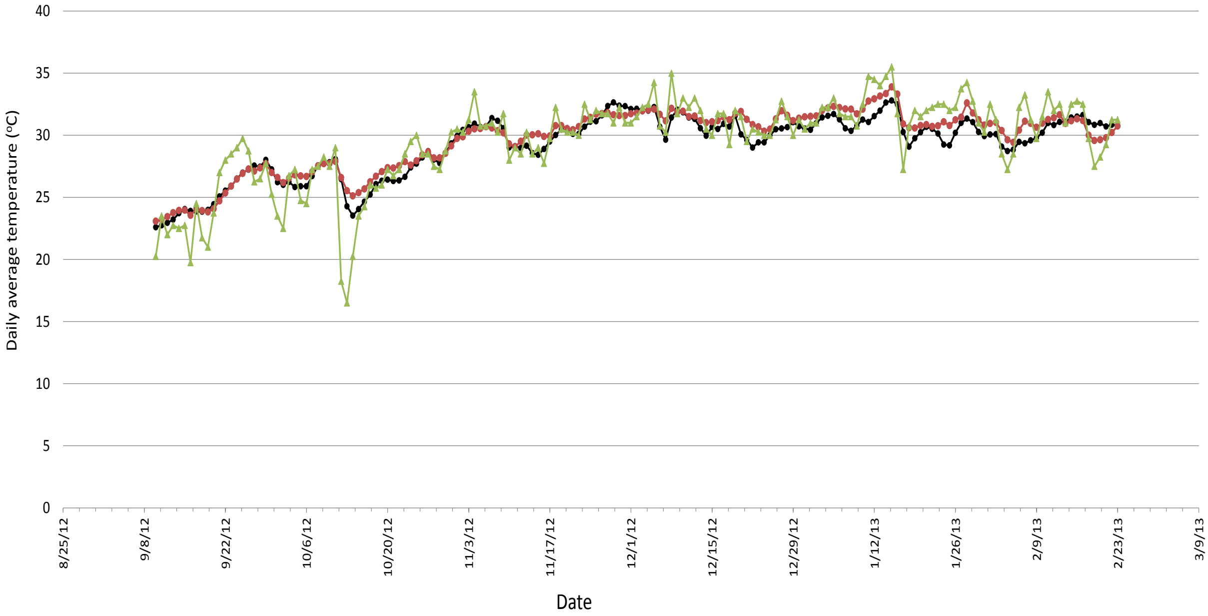


Figure 4.5 Temporal fluctuations in water temperature in waterhole F05 in the Flinders River near Richmond. Measured daily mean profile water temperature (black dots) is compared with modelled water temperature (red dots). Mean daily SILO air temperature (green triangles) for the location is also shown

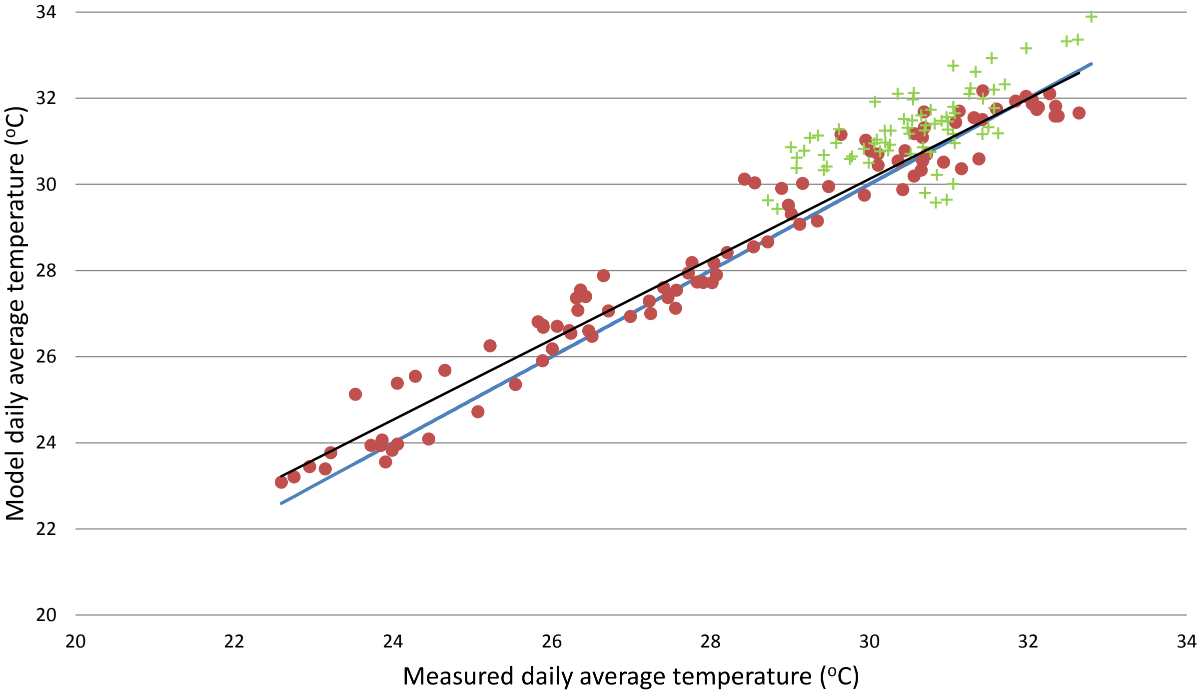


Figure 4.6 Comparison of modelled and measured water temperature in Flinders River waterhole F05. The regression fitted to the measured mean water temperature; solid red points (blue line) recorded during the period of zero flow (9/09/2012 to 14/12/2012) has the form y = 0.93x + 2.2 (R^2 = 0.96). Data points recorded after 14/12/2012 are shown using green crosses. The 1:1 line is shown in back

A time trend in water temperature was recorded in a deeper waterhole in the Flinders River, F07 (Figure 4.7), which was ~ 2.2 m deep in Nov/Dec 2012. The depth of waterhole F05 around the same time was ~ 1.4 m (Table 4.2). Despite its greater depth, this waterhole (F07) had a similar mean temperature to waterhole F05 (Table 4.2) and although the model again follows the time trend very well it tends to overestimate the profile mean (mean of the surface and bottom readings) water temperature by about 1 ^{o}C; Figure 4.7 and Table 4.2. The model overestimation of waterhole F07 water temperature is unlikely to be due to systematic differences between the SILO air temperature (which is a key input to the model) and actual air temperature recorded at the waterhole as these agree to within a few tenths of a degree (see Table 4.2).

This figure also shows the measured surface and bottom water temperatures for F07 (Figure 4.7). This shows that the model temperature follows the surface temperature, rather than the mean or bottom profile temperature. This is confirmed in Figure 4.8 where the regression of model temperature and mean profile temperature is offset by ~ 1 ^{o}C, whereas the regression of the model and the surface water temperature falls almost exactly on the 1:1 line. This means that the water temperature model gives a good estimate of the surface water temperature in deeper waterholes, rather than profile mean or bottom water temperatures.

In waterholes where there is a highly non-linear change in temperature with depth (as in some deep waterholes and waterholes which are thermally stratified, see Chapter 3) the arithmetic mean of two measurements made near the surface and near the bottom may not be a good representation of the true water profile mean temperature. If the water profile has a relatively thick layer of warmer temperatures overlying a thinner layer of cooler temperatures then the mean of the surface and bottom readings will tend to be an underestimate of the true profile mean water temperature. Temperature readings at more than two depths may therefore be required if the profile mean water temperature is required.

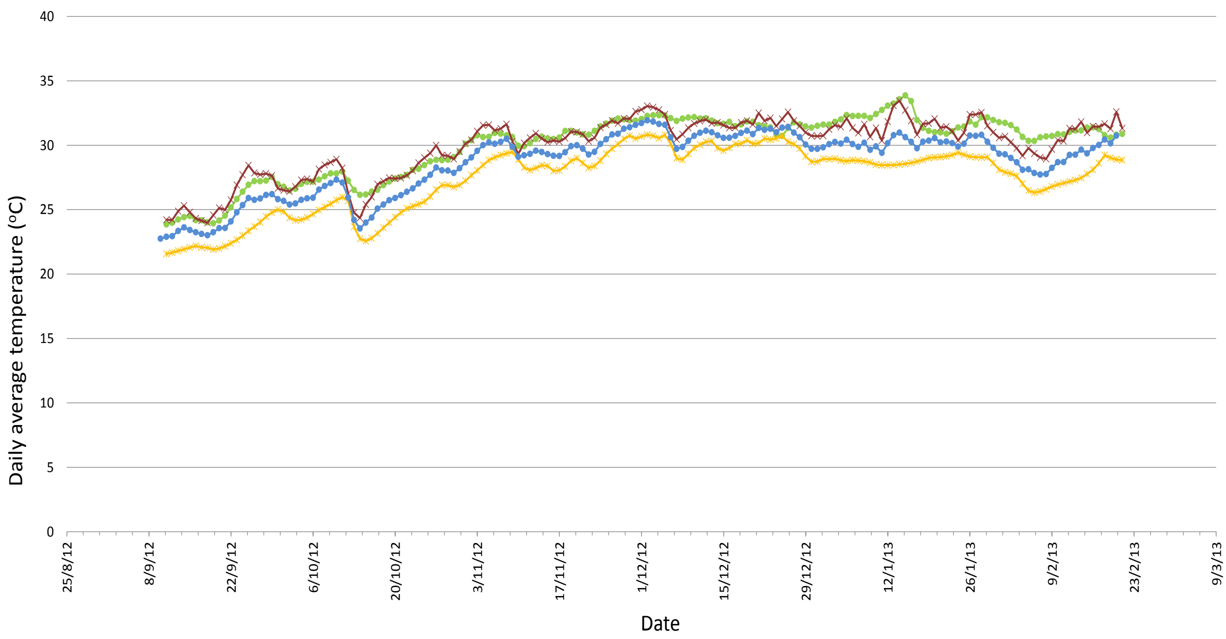


Figure 4.7 Temporal fluctuations in water temperature in waterhole F07 in the lower reaches of the Flinders River. Measured daily mean profile water temperature (blue dots) is compared with modelled water temperature (green dots). Also shown is the time trend of surface (red crosses) and bottom (yellow crosses) water temperature

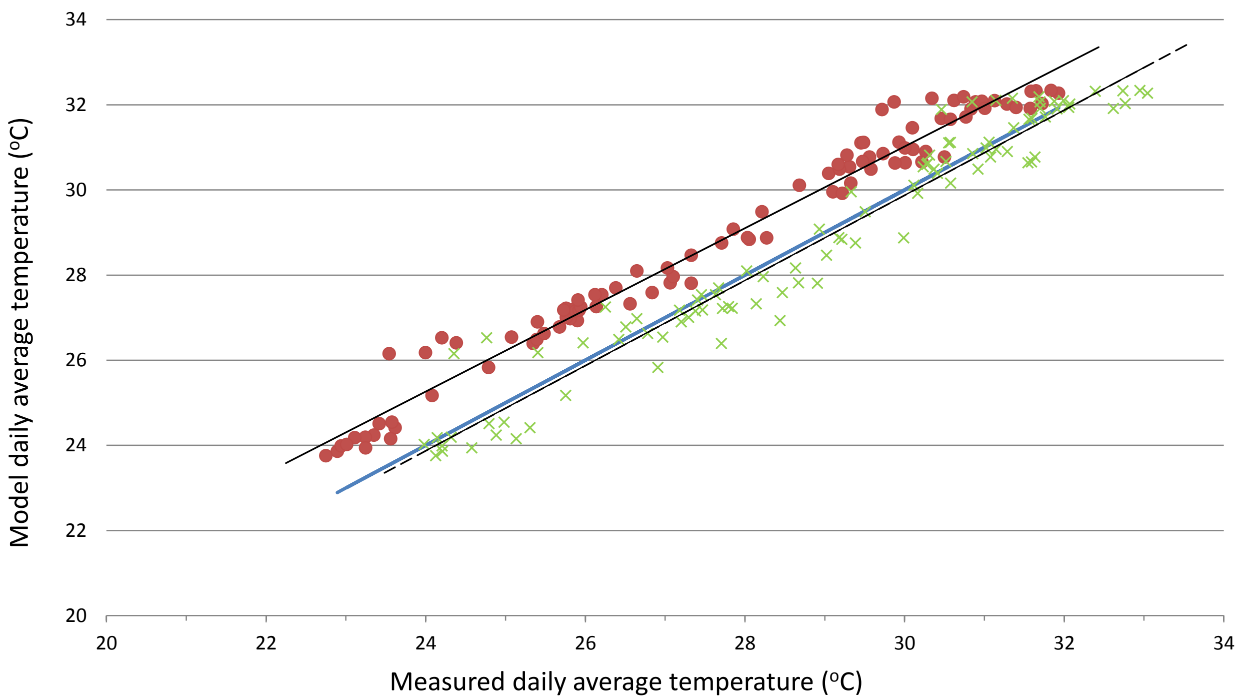


Figure 4.8 Comparison of modelled and measured water temperature in Flinders River waterhole F07. The regression fitted to the measured mean water temperature; solid red points (black line) recorded during the period of zero flow (9/09/2012 to 14/12/2012) has the form y = 0.96x + 2.2 (R^2 = 0.97). Also shown is the regression fitted to the measured surface water temperature; green crosses (dashed black line). The 1:1 line is shown in blue

In some waterholes the difference between the model and measured mean daily profile temperature is around 2 °C (Table 4.2). In these waterholes, modelled water temperature also exceeds the water temperature measured near the surface of the waterhole. An example of this is shown for Gilbert catchment waterhole G06 in Figure 4.9. The time trend in water temperature in this waterhole is similar to those observed in the Flinders catchment, rising from ~ 25 °C in mid-October to ~ 30 °C in December 2012 and falling in January 2013 when there were periods of rainfall, river flow and lower air temperatures. Modelled water temperature follows a similar pattern, but is higher than both the surface and mean profile water temperatures. This offset is about 1.5 °C and can clearly be seen in Figure 4.10. There are two main possibilities that could cause the model temperature to be high. Firstly, if the waterhole was shaded it would not receive the full insolation that is used as an input to the model. The model offset could be reduced to zero if shade reduced the insolation by ~ 20%. However, the waterhole temperature recordings were made near the midpoint between the river banks and it is clear that there is no shade across this part of the river waterhole. A second possibility is that the wind speed is higher than the fixed 2.0 m/sec used in the model. The effect of increasing wind speed is shown in Figure 4.10 and at a value of 2.9 m/sec (optimised) there is no offset between modelled and measured mean profile water temperatures. This demonstrates that at waterholes where the wind speed is significantly different from 2.0 m/sec it may be necessary to obtain local values of wind speed in order to get more accurate predictions of model water temperature. Unfortunately, wind speed data are not available for any of the waterholes studied in the national SILO database.

Table 4.2 Summary of the mean modelled and measured waterhole water temperature data in the Flinders and Gilbert catchments for the 30 day period 15 November to 14 December 2012

Waterhole	Daily mean water temp (°C)	Model water temp (°C)	Model – measured water temp (°C)	Daily mean air temp (°C)	SILO air temp (°C)	SILO-measured Air Temp (°C)	Daily amplitude average temp (°C)	Daily MAX temp gradient (°C)	Mean depth (m)	Water clarity[1]	Groundwater influence[2]	Riparian score[3]
G04	30.1	30.2	0.0	30.0	29.1	-0.9	5.5	3.7	0.7	Clear	Low	7
G05	30.4	30.2	-0.2	30.0	29.3	-0.7	1.4	2.4	2.4	Clear	Low	11
G06	27.9	29.6	1.7	29.0	28.2	-0.9	3.9	5.0	1.5	Clear	Low	11
G09	31.0	31.7	0.7	31.4	31.5	0.1	4.6	2.4	1.8	Intermediate	Low	8
G10	31.5	31.9	0.5	31.4	31.6	0.1	3.1	2.9	1.1	Clear	Low	7
F01	28.8	31.0	2.2	31.1	31.8	0.6	2.2	5.1	3.0	Intermediate	High	9
F05	31.1	31.4	0.3	31.1	31.5	0.3	4.4	2.4	1.4	Intermediate	Nil	10
F07	30.6	31.7	1.1	32.1	31.8	-0.2	2.2	4.6	2.2	Intermediate	Nil	9
F08	29.2	31.7	2.4	32.4	32.0	-0.4	3.0	4.0	2.9	Turbid	Medium	7

[1] Chapter 3

[2] Jolly et al. (2013)

[3] from Table 5.2, Table 5.3

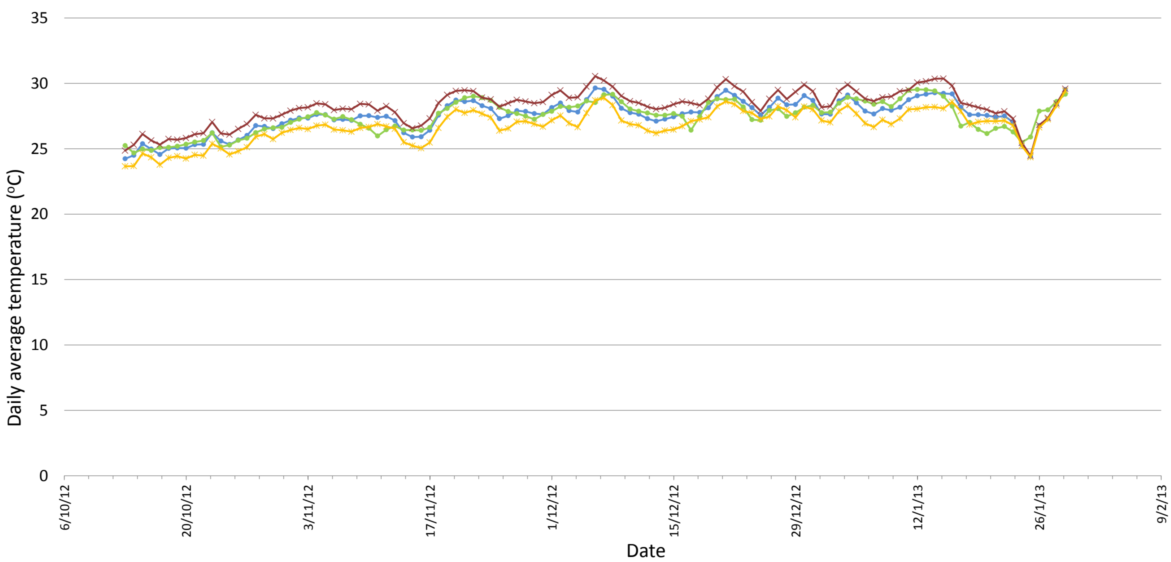


Figure 4.9 Temporal fluctuations in water temperature in waterhole G06 in the upper reaches of the Gilbert catchment. Measured daily mean profile water temperature (blue dots) is compared with modelled water temperature (green dots). Also shown is the time trend of surface (red crosses) and bottom (yellow crosses) water temperature

Dry season trends in the other Flinders and Gilbert catchment waterholes are similar to those already shown for G06, F05 and F07. The performance of the water temperature model at other waterholes is summarised in Table 4.2 which shows that it agrees with measured mean profile water temperatures to within ~ 1 ^{o}C at waterholes G04, G05, G09, G10, F05 and F07. Model discrepancies of around 2 degrees occurred at G06 (as illustrated above) and F01 and F08. Again these model overestimates may arise because these latter 3 sites were windier than 2.0 m/sec. Table 4.2 also shows that SILO air temperatures were within 1 degree of air temperatures measured on the bank near each waterhole, so it is unlikely that errors in the SILO air temperature (used as an input to the model) can account for the model/measured discrepancies seen at G06, F01 and F08.

The waterhole summary data in Table 4.2 show that there is little variation in daily mean waterhole profile temperature within or between the two catchments at any given time. This confirms a similar result obtained during the manual sampling trips to waterholes (see Chapter 3). The range of daily mean temperatures close to the time when waterhole temperatures are maximum (i.e. averaged over the 30 day period 15 November and 14 December 2012) was from 28 to 32 ^{o}C and is very similar to the range found in Chapter 3 and by Burrows and Butler (2012) in many northern Australian rivers. The lack of temperature variation between waterholes is confirmed in Figure 4.11, which shows that profile mean waterhole temperatures do not vary with waterhole depth (the fitted line has an R^2 of 0.14). There is a slightly better correlation between waterhole depth and daily maximum surface temperature (R^2 = 0.50; Figure 4.11). Shallower waterholes therefore reach higher daily maximum temperatures, but are only slightly warmer over the entire water depth. Further evidence for higher temperature maxima in shallow waterholes is shown in Figure 4.2 where waterholes less than 1 m deep experience diurnal temperature amplitudes around 5 ^{o}C; much higher than the ~ 2 ^{o}C observed in waterholes over 2 m deep.

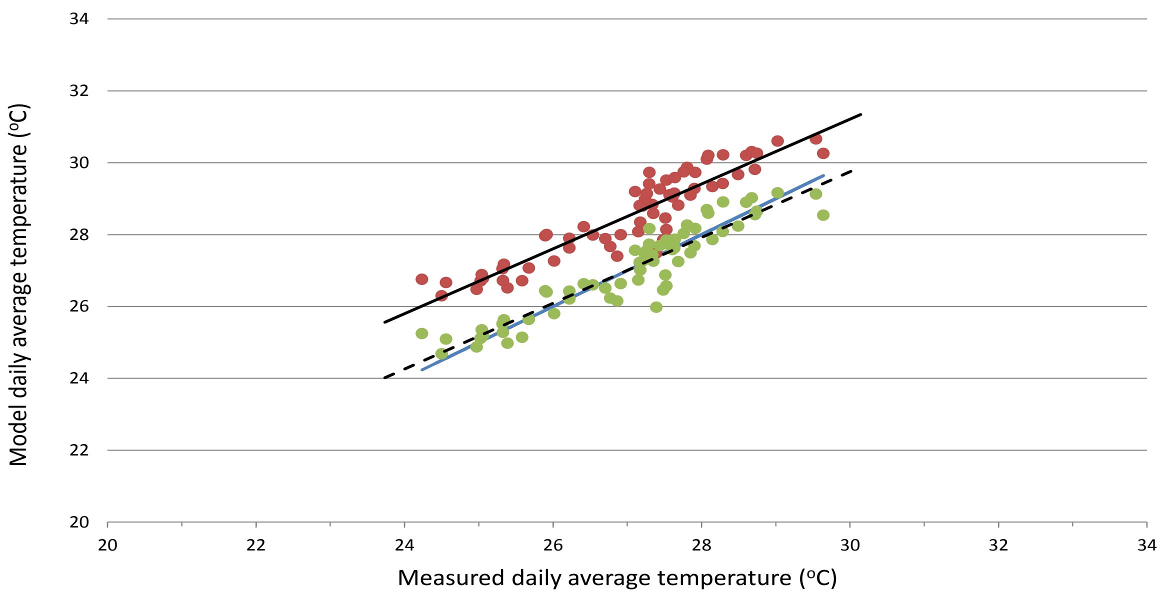


Figure 4.10 Comparison of modelled and measured water temperature in Gilbert catchment waterhole G06. The modelled mean profile water temperature with a wind speed of 2 m/sec is shown by the solid red points and the regression through them (black line) has the form y = 0.90x + 4.2 (R^2 = 0.85). Also shown are the modelled water temperatures with a wind speed of 2.9 m/sec; the regression fitted to these points (dashed black line) has the form y = 0.92x + 2.3 (R^2 = 0.87). The 1:1 line is shown in blue

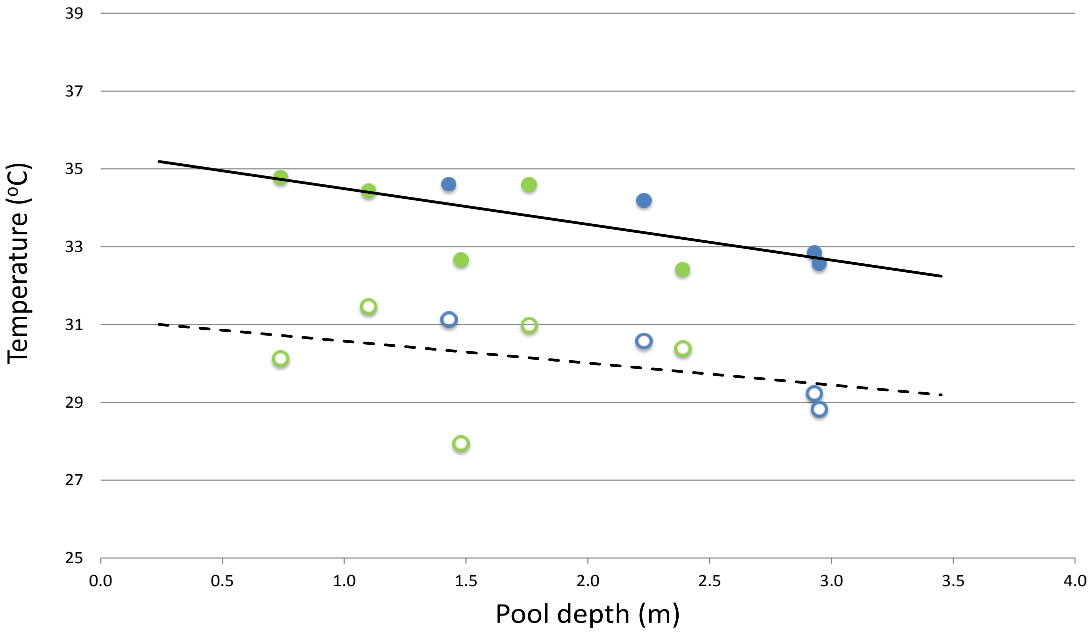


Figure 4.11 The relationship between waterhole profile mean (solid dots) and surface maximum (open circles) water temperature and waterhole depth for Flinders catchment waterholes (green) and Gilbert catchment waterholes (blue). Each data point is the mean of 30 daily values between 15 November and 14 December 2012

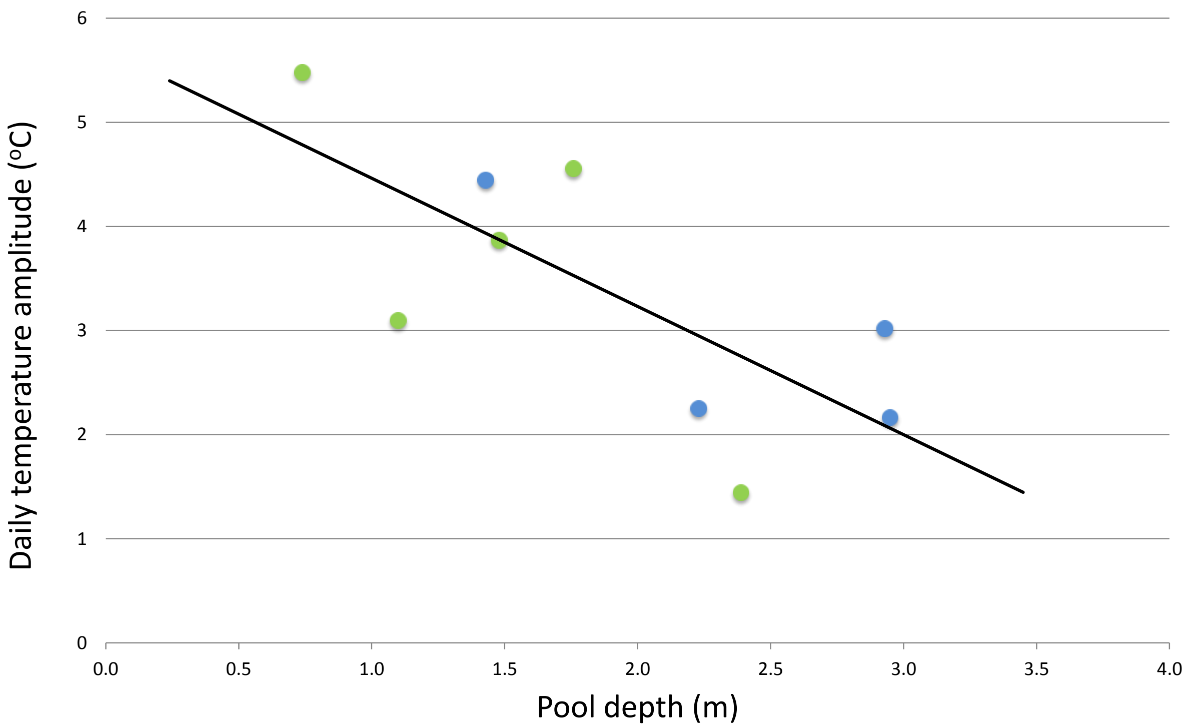


Figure 4.12 The relationship between waterhole daily profile mean temperature amplitude and waterhole depth for Flinders catchment waterholes (green) and Gilbert waterholes (blue). Each data point is the mean of 30 daily values between 15 November and 14 December 2012

4.4.3 WATERHOLE TEMPERATURE THRESHOLDS

The thermal environment around aquatic organisms such as fish directly controls their metabolic rate and therefore influences growth, resource allocation for reproduction and ultimately population size (Jobling, 1995). Growth rates in fish tend to increase with temperature up to an optimum provided there is sufficient food available to sustain growth (McCauley and Casselman, 1981). Hence many species of fish have a preference for water temperatures, T_{pref}, close to their temperature optimum for growth (Pusey and Arthington, 2003). As temperatures increase beyond T_{pref} , growth rates decline and fish become more susceptible to environmental stresses such as low concentrations of dissolved oxygen (Butler et al., 2007; Butler and Burrows, 2007) and, ultimately, fish can experience lethal effects. This lethal threshold has been defined as the '*critical thermal maximum*', CT_{max}, (Lutterschmidt and Hutchinson, 1997). There are therefore two key water temperature thresholds that are important for fish, their preferred temperature, T_{pref} , and their critical thermal maximum, CT_{max}.

Most of the evidence for water temperature thresholds for tropical Australian fish comes from studies that have recorded water temperature along with the presence of various fish species (e.g. Pusey et al., 2004). These data have their drawbacks, in that they are usually spot measurements made near the surface at the location where the fish were observed. Nevertheless, they can be used to give guidelines to what thermal thresholds might exist for tropical species. For example, Pusey et al. (2004) reported that in the Burdekin River the commonly occurring bony bream (*Nematalosa erebi*) were not usually found in waters above 31 ^{o}C and, although they can tolerate higher temperatures, they clearly prefer habitats cooler than this. Similarly, Casselman (2002) reported preferred water temperatures from 27 to 31 ^{o}C for warmwater fish in Lake Ontario, north America; a temperate climate which is substantially cooler than the northern Australian tropics.

Unfortunately, there are no systematic chronic lethal temperature exposure data for most tropical fish and the best that is available are the acute thermal tolerance tests performed by Burrows and Butler (2012). They exposed 7 fish and 4 crustacean species to water with temperatures from 28 to 42^{o}C in order to determine their critical thermal maximum (CT_{max}). This involved raising the temperature of the test water over a defined period (15 mins to 2.5 hrs) and recording the temperature at which the fish lost their ability to stay upright (further details of the test methods are given by Burrows and Butler (2012)). They found that CT_{max} values ranged from 33.5 ^{o}C for fly-speckled hardyhead (*Craterocephalus stercusmuscarum*) to 41.8 ^{o}C for barramundi (*Lates calcarifer*). The above studies give two preliminary thresholds (T_{pref} = 31^{o}C and CT_{max} = 33.5 ^{o}C) that can be combined with the waterhole water temperatures of this Assessment to assess how often fish in the Flinders and Gilbert catchments may be exposed to unsuitable thermal regimes. These two thresholds are reasonable starting points based on the limited evidence currently available (Burrows and Butler, 2012), but should be considered as illustrative until further data are obtained on fish exposure to both chronic and acute thermal regimes.

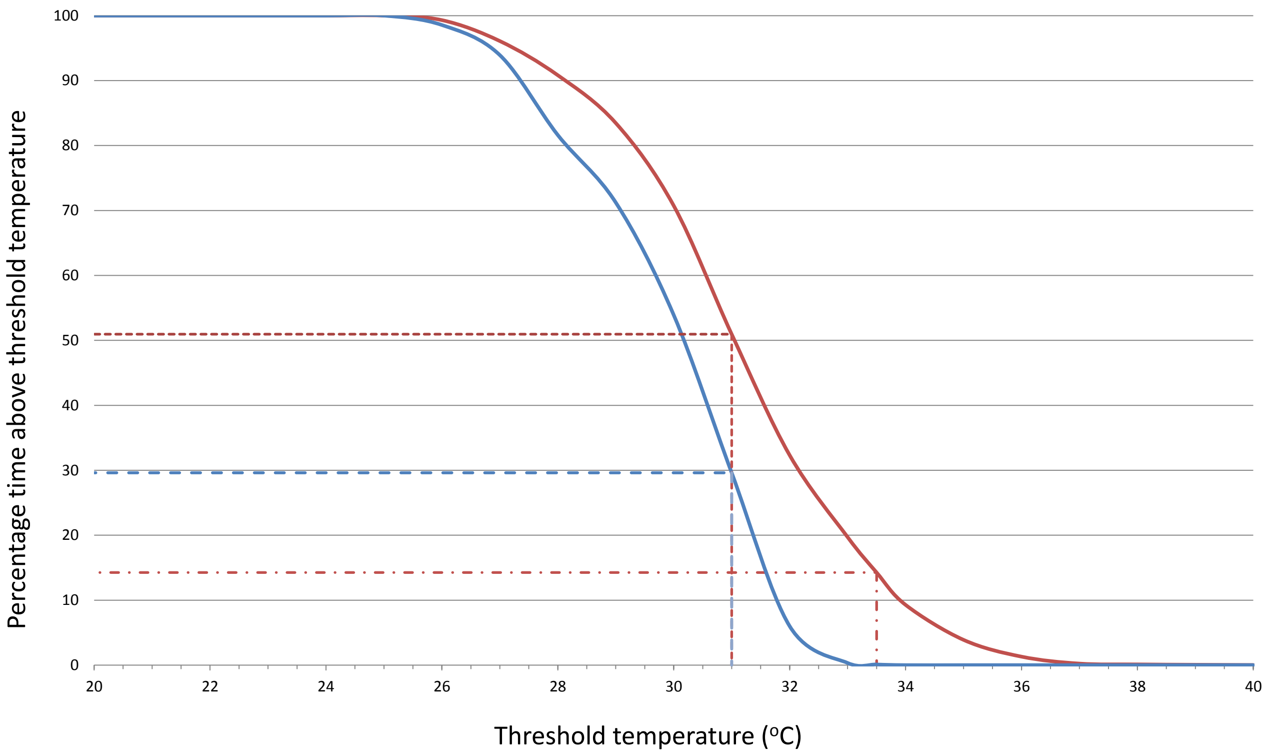


Figure 4.13 The percentage of time surface (red) and bottom (blue) water temperature exceed any given temperature threshold in Gilbert catchment waterhole G10. Dashed line indicate the preferred temperature (T_{pref} = 31.0°C) and critical thermal maximum (CT_{max} = 33.5°C). The frequency curves are compiled from all 20 min recordings made in the 100 day period from 14 October 2012 to 21 January 2013

The amount of time the temperature at the surface and bottom of G10 is above a given temperature is shown in Figure 4.13. The period chosen (14 October 2012 to 21 January 2013), represents the time in the year when waterhole water temperatures rise from near their annual mean to the warmest temperatures recorded during December 2012 and January 2013. As water temperatures decline almost symmetrically in the following 3 months, the percentage times calculated can be taken as representative of the entire summer period (October 2012 to March 2013) in this region. This figure also shows that water temperature at the bottom of waterhole G10 is never above the critical thermal maximum (CT_{max} = 33.5 °C), but the preferred temperature (T_{pref} = 31 °C) is exceeded 30% of the time. Surface water temperatures are higher and in this part of the waterhole T_{pref} is exceeded 51% of the time. Even the CT_{max} threshold is exceeded at the surface for about 14% of the time. Fish may therefore prefer to remain in the cooler thermal environment at the bottom of this waterhole, but may have to move closer to the surface if other factors, such as dissolved oxygen, become limiting in the deeper, often stratified, waters.

The amount of time the temperature at the surface and bottom of Flinders catchment waterhole F07 is above a given temperature is shown in Figure 4.14. This is a slightly cooler waterhole than G10 (Table 4.2) and is quite turbid. The surface water still exceeds T_{pref} (47% of the time) and CT_{max} (10% of the time), but by shorter times than in G10. The effect of the turbidity in waterhole F07 shows up most in the shape of the bottom water frequency curve (Figure 4.14). At this depth in waterhole F07 water temperatures never exceeded CT_{max} or T_{pref}. This compares with an exceedance of T_{pref} in bottom water frequency of waterhole G10 of 30% (Figure 4.14). Fish in waterhole F07 may therefore be able to find a thermal regime close to, or below, their preferred optimum for the entire summer period.

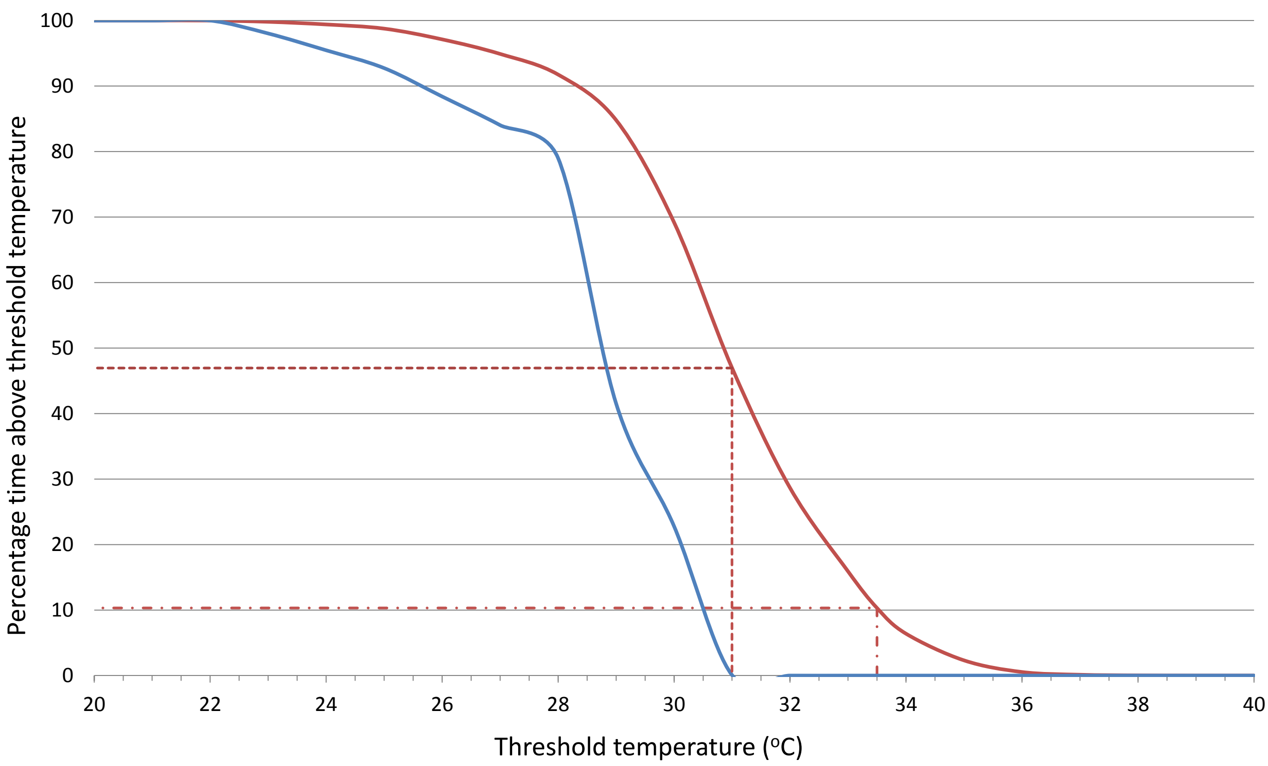


Figure 4.14 The percentage of time surface (red) and bottom (blue) water temperature exceed any given temperature threshold in Flinders catchment waterhole F07. Dashed lines indicate the preferred temperature (T_{pref} = 31.0°C) and critical thermal maximum (CT_{max} = 33.5°C). The frequency curves are compiled from all 20 min recordings made in the 100 day period from 14 October 2012 to 21 January 2013

4.4.4 POTENTIAL IMPACTS OF CLIMATE CHANGE

If the climate in the Flinders and Gilbert catchments were to change in the future, this could have an impact on dry season waterholes and their thermal environment. Climate change in the Flinders and Gilbert catchments has recently been assessed by Petheram and Yang (2013). These authors used an ensemble of 15 Global Climate Models (GCM's) with 5 km x 5 km resolution downscaled using 121 years of historical (SILO) climate data to simulate the future climate associated with a global mean temperature increase of 2 °C (relative to 1990). The main conclusion of their study was that neither mean annual rainfall nor rainfall intensity were likely to change significantly across the Flinders and Gilbert catchments under this future climate scenario. This lack of change in rainfall implies that river flows should also remain as they have been historically. To be consistent with the Petheram and Yang (2013) study, in this Assessment simulations were made of how dry season waterhole water temperature and depth might change under 2 °C warmer air temperatures (Scenario C; see Petheram and Yang (2013)) and assuming that the onset and duration of the period of zero flow does not change.

Zero flow (or cease to flow) conditions in the Flinders and Gilbert catchments have been defined in a companion study of dry season waterholes by McJannet et al. (2013) as when gauged flow is less than 1 ML/day. Using this definition they found that the mean duration of zero flow in the mid-Flinders catchment was 225 days, substantially longer than in the Gilbert catchment, 160 days. Therefore two illustrative examples were made in the Assessment of the potential impact of climate change on waterhole temperature in the period when flow is zero in each of these river reaches. River flow analysis by Lerat et al. (2013) shows that flow in the Flinders catchment typically approaches zero by the end of April and this occurs about a month later in the Gilbert catchment. The start and end of zero flow in mid-reaches of the Flinders and Gilbert rivers were therefore chosen to be from 1 May to 11 December (225 days) and 1 June to 7 November 2012 (160 days) respectively.

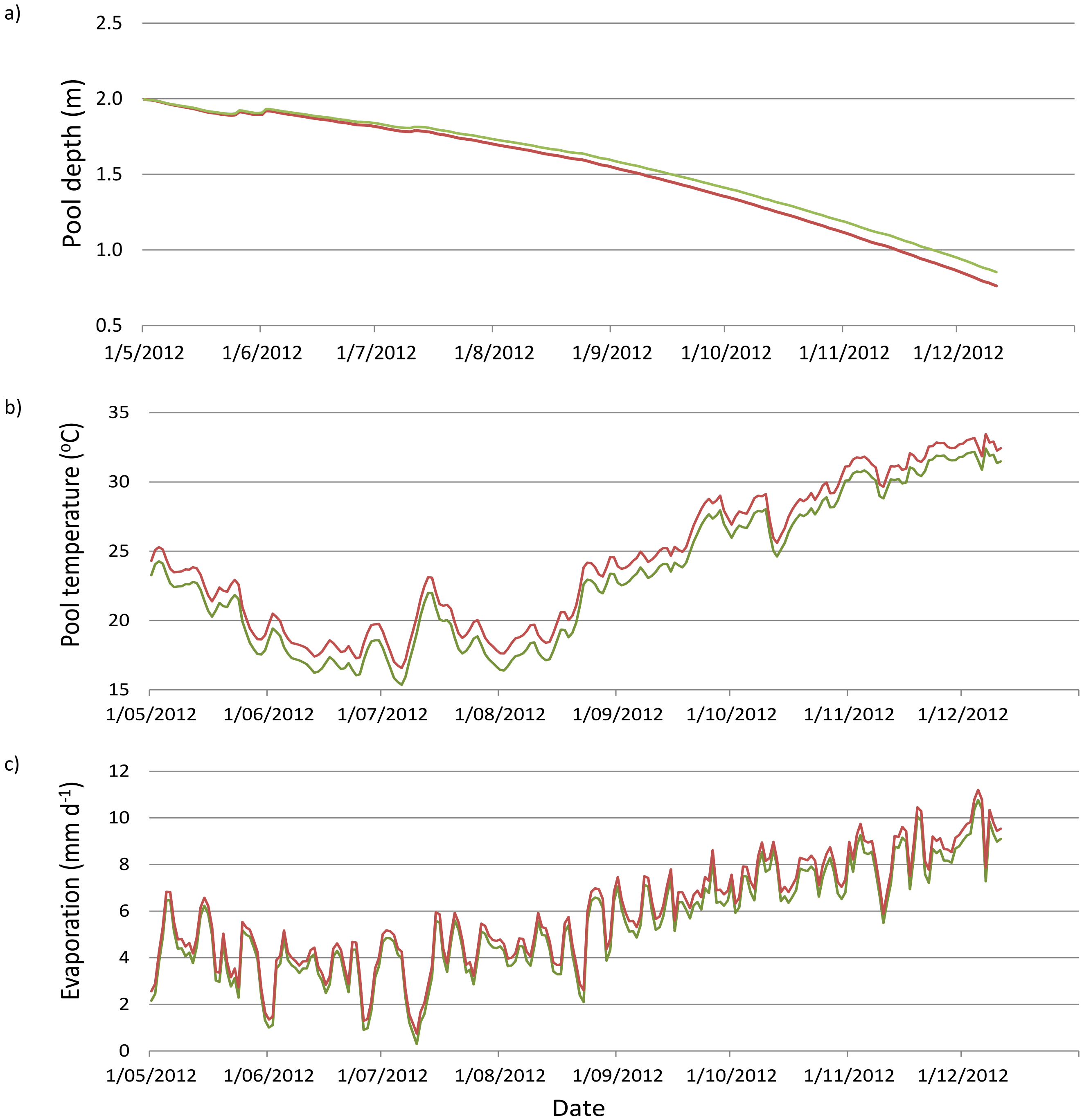


Figure 4.15 A comparison of: a) waterhole depth; b) waterhole temperature; and c) waterhole evaporation rate for a 2 m deep waterhole in the mid-Flinders catchment under current climate (green) and a future climate that is 2°C warmer (Scenario C)

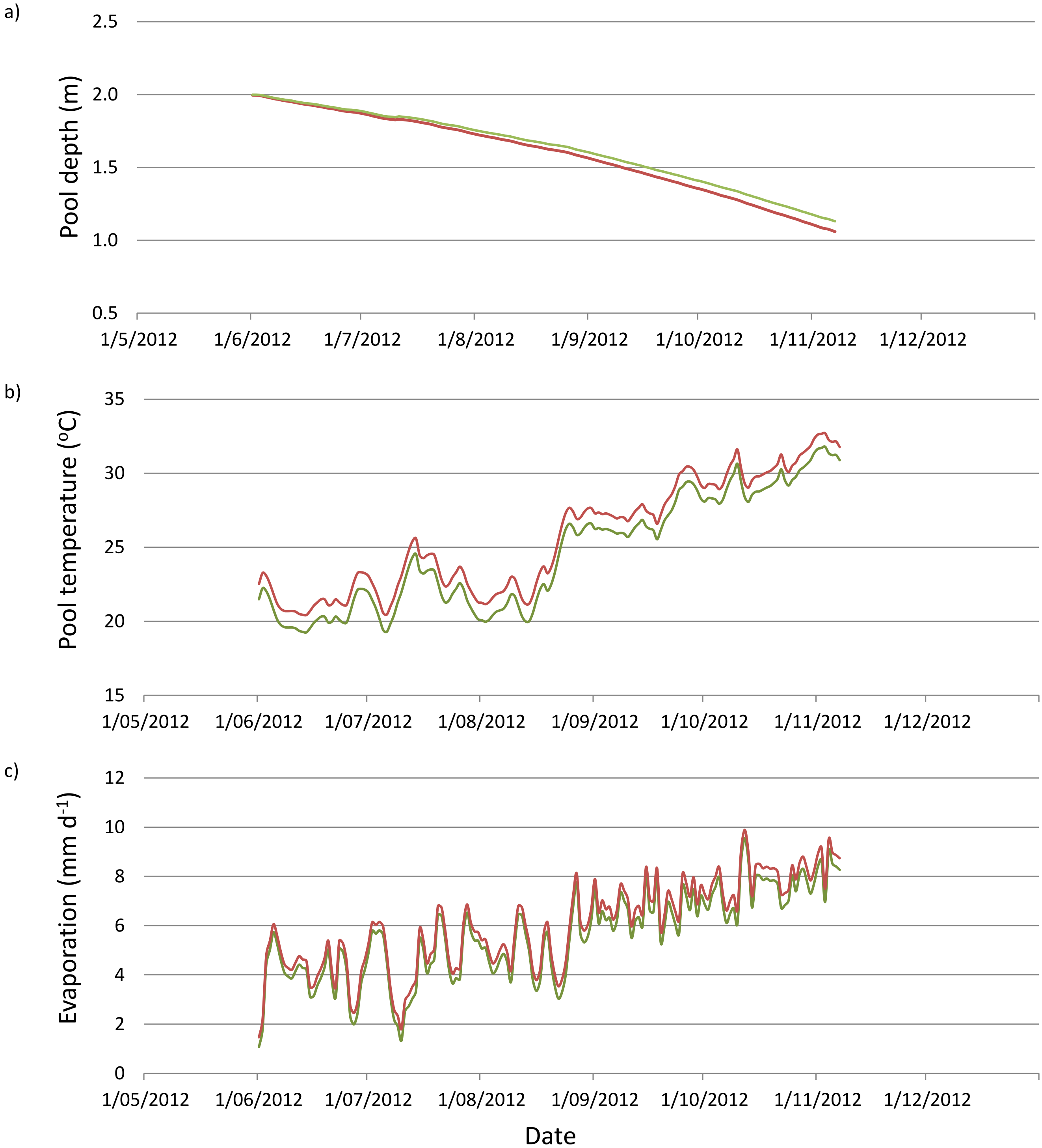


Figure 4.16 A comparison of: a) waterhole depth; b) waterhole temperature; and c) waterhole evaporation rate for a 2 m deep waterhole in the Gilbert catchment under current climate (green) and a future climate that is 2 °C warmer (Scenario C)

The effect of a 2 °C warming on waterhole depth, temperature and evaporation during the zero flow period in the mid-Flinders catchment is shown in Figure 4.15. Under the current climate waterhole depth drops steadily from 2 m on the 1 May 2012 (set in the model) to 0.85 m on 11 December 2012. Under climate Scenario C, waterhole depths decline slightly faster, but are only 90 mm shallower by the end of the simulation period (Figure 4.15a). This is a direct consequence of the higher evaporation rate under Scenario C, which increases by ~ 0.4 mm/day (Figure 4.15c). Simulated waterhole water temperature increases from a minimum of 15 °C in July 2012 to a maximum of 32 °C in December 2012 (Figure 4.15b). Under Scenario C, water temperatures are elevated, but only by 1.1 °C on average. In both the Flinders and Gilbert rivers climate warming has a relatively small effect on the decline in waterhole depth and therefore would not have a major impact on deeper waterholes. The 2 °C warming of the air under Scenario C results in a 1.1 °C waterhole water temperature rise. This 'damping' of the air warming is due to the increased rate of evaporation under Scenario C and demonstrates how water waterholes provide a buffering effect on climate change.

The effect of climate warming on a 2 m deep waterhole in the Gilbert River is shown in Figure 4.16. The period of zero flow is shorter in this river reach (160 days) and waterhole depth under current climate declines from 2 m on 1 June 2012 (again, set in the model) to 1.13 m on 7 November 2012 (Figure 4.16a). Under Scenario C the waterhole is only 70 mm shallower. Again, this is because of the higher evaporation rate in the warmer climate (Figure 4.16c). Waterholes in this river reach start the zero flow period around 19 °C (warmer than in the mid-Flinders catchment), but by the end of the period have reached 32 °C (similar to the mid-Flinders catchment). Again under Scenario C, waterhole water temperatures increase by 1.1 °C.

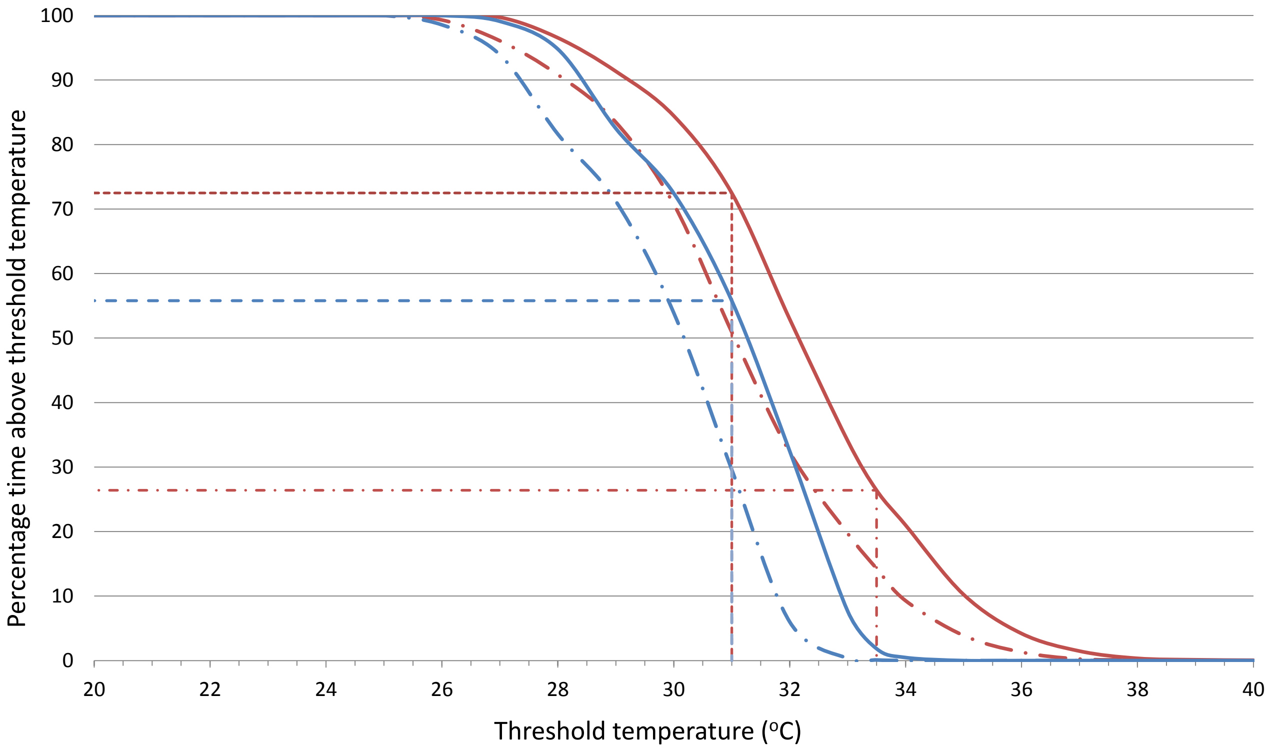


Figure 4.17 The effect of climate change (Scenario C) on the percentage of time surface (red) and bottom (blue) water temperature exceed any given temperature threshold in Gilbert catchment waterhole G10. For comparison the surface and bottom frequency curves for the current climate (as in Figure 4.16) are also shown (dotted lines). Dashed lines indicate the preferred temperature (T_{pref} = 31.0 °C) and critical thermal maximum (CT_{max} = 33.5 °C)

The impact of climate change (Scenario C) on the frequency with which waterhole water exceeds given temperature thresholds is illustrated in Figure 4.17 for Gilbert catchment waterhole G10. Under current climate bottom water temperature never exceeded the critical thermal maximum (CT_{max}) whereas under Scenario C it would exceed it around 2% of the time and the exceedance of the preferred temperature (T_{pref}) increases from 30 to 56%. In the surface water of this waterhole exceedance of T_{pref} and CT_{max} under current climate were 51% and 14% respectively and under Scenario C these increase markedly to 73% and 26%. Hence, although climate change only increases waterhole water temperature by just over 1 °C, this causes substantial increases in the amount of time the water temperature exceeds critical thresholds. This is a consequence of the steep shape of the frequency curves over most of their range and hence substantial increases in threshold exceedance will occur under Scenario C for any critical aquatic thresholds in the range ~ 28 to 37 ^{o}C.

4.4.5 SURFACE TEMPERATURE MEASUREMENTS DURING SATELLITE OVERPASS DAYS

A summary of the comparison of LandSat TM 7 thermal band high gain brightness readings with ground based waterhole water surface temperature readings is shown in Table 4.3.

Table 4.3 Summary of the comparison of LandSat TM 7 brightness readings and ground truth waterhole water surface temperature on six occasions. "point" values are image brightness readings at the exact IR instrument locations and maximum, minimum and mean values are for the entire waterhole either side of the IR instrument locations

Date	Catchment	Waterhole	Surface Temperature * (^{o}C)	LandSat clarity over waterhole	LandSat TM Reading			
					Point	Min	Max	Mean
11 October 2012	Gilbert	G05	26.4	Cloudy	n/a	n/a	n/a	n/a
25 October 2012	Flinders	F08	22.9	clear	174	169	174	172
03 November 2012	Flinders	F05a	28.7	clear	181	178	190	184
03 November 2012	Flinders	F05b	28.4	clear	181	178	190	184
03 November 2012	Flinders	Lake Fred Tritton	26.5	clear	166	166	169	168
03 November 2012	Flinders	F05 a	34	clear	208	-	-	208
12 November 2012	Gilbert	G05 a	26.8	part cloudy	n/a	166	171	168
	Gilbert	G05 b	28.4	part cloudy	n/a	166	171	168
28 November 2012	Gilbert	G05 a	28.2	Cloudy	n/a	n/a	n/a	n/a
	Gilbert	G05 b	27.9	Cloudy	n/a	n/a	n/a	n/a
12 December 2012	Flinders	F08	28.9	cloudy	n/a	n/a	n/a	n/a
			27.4	cloudy	n/a	n/a	n/a	n/a

*at 10:30 EST

As with many applications of satellite data, clouds often obscure the required surface signal and this was the case on three of the six days examined here. However, on the three clear days the LandSat TM 7 brightness readings obtained around the waterholes are shown in Figure 4.18. The screen capture colour scheme is scaled to show the patterns of relative brightness values (blue low, yellow high) based approximately on the ranges of brightness values observed both within each waterhole and over the adjacent land. Missing data due to Landsat TM 7's scan line corrector failure appear as zig-zag dark blue or black lines.

In the Flinders catchment at waterhole F08 (Figure 4.18a), the long waterhole in the river channel can clearly be seen as dark blue (cooler) and green pixels (warmer) within the brighter landscape (yellow). As the river channel is only ~ 70 m wide, pixels (30 m) nearest the bank appear warmer than in the middle of the channel and this is most likely to be caused by 'smearing' of the satellite signal due to pixels overlapping with the river bank. To obtain the best estimate of water brightness temperature a random selection of pixels was therefore chosen along the centre line (darkest blue) of the channel. This gave a range of brightness values within the channel at waterhole F08 on the 25 October 2012 of only 5 units (Table 4.3). Pixel smearing can be more easily seen in Figure 4.18b along the channel at waterhole F05 on 3 November 2012. On this occasion the range of brightness values (again along the centre line of the river) was 12 units. The IR instrument at Lake Fred Tritton is also very close to the edge of the swath (Figure 4.18c), where the satellite signals is more unreliable.

The largest water body studied was Lake Fred Tritton, adjacent to the town of Richmond (~350 x 350 m) and the Landsat TM 7 data for this location on 3 November are shown in Figure 4.18c. Again pixel smearing can be seen around the edge of the Lake, part of which is very close to the swath edge. However, the range of values within this water body is only 3 units (Table 4.3). The final example of satellite brightness data are for the Einasleigh River, in the Gilbert catchment, on 12 November 2012. The ground response is obscured in many places by cloud (the broader patches of dark blue), including one obscuring the IR instrument at waterhole G05, a narrow southeast pointing waterhole. The range of brightness values (5 units) as shown in Table 4.3 represents the range in the waterhole immediately southeast of the instrument at waterhole G05, but northwest of the cloud and its shadow.

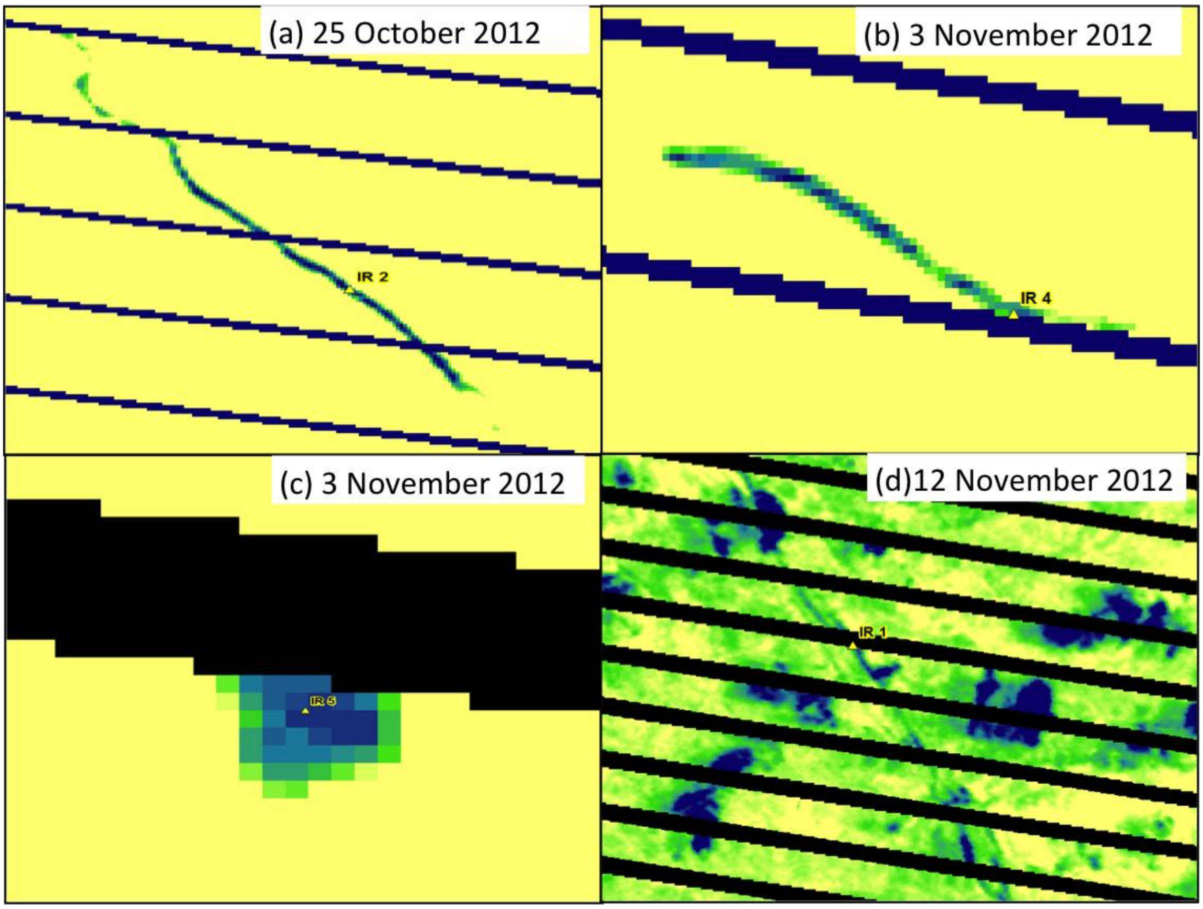


Figure 4.18 LandSat TM 7 brightness scenes at four of the waterhole locations in the Flinders and Gilbert catchments: a) Flinders catchment waterhole F08 (IR2), showing location of deployed IR instrument; b) Flinders Rivers waterhole F05 (IR4), showing location of deployed IR instrument; c) Lake Fred Tritton (IR5) ; and d) Gilbert catchment waterhole G05 (IR1) showing location of deployed IR instrument. Note there are different resolutions in each scene

Ground based surface temperatures on the above satellite overpass dates are shown in Table 4.3. On the four latter occasions two IR temperature sensors were deployed on the same waterhole about < 1 km apart and the recordings at the satellite overpass time (10:30 EST) were quite similar (never more than 1.5 °C different). This implies that the surface temperature along the central axis of these large waterholes is fairly constant at this time. This was confirmed by a manual survey of waterhole F05 made on 3 November 2012 with a hand held IR thermometer deployed from a boat. The range of surface temperature (ground based) of all of the waterholes shown in Table 4.3 was fairly narrow (23 to 29 °C), which implies that these waterholes remained large (i.e. deep) enough during the observation period to maintain relatively moderate temperatures compared to what might happen in smaller (very shallow) waterholes. However, there is some evidence for an increase in surface temperature in waterhole F08 (around 5 °C) in the Flinders catchment between the 25 October and 12 December 2012. This is consistent with the waterhole temperature changes with season presented in Section 5.3.1.

A preliminary examination of the likely uncertainty in waterhole temperature (T_s) estimates using LandSat TM 7 brightness temperatures (L_b) was made using the data shown in Table 4.3. The correlation between T_s and L_b (mean rather than point) for these data is shown in
Figure 4.19. This simple analysis ignores any differences there may be in the atmospheric corrections to the satellite data on different days (which could make the following correlations better or worse). If only waterhole water temperature data are used (the six blue points in
Figure 4.19, the correlation between T_s and L_b is very poor (R^2 = 0.19) and cannot be used to estimate waterhole surface temperature. However, if the T_s and L_b data for the river bank (measured on the 3 November 2012) are added (yellow point in
Figure 4.19) the correlation improves (R^2 = 0.69), however, the uncertainty (one standard error) in any estimate of T_s is still greater than 2 °C.

This analysis demonstrates that future field studies of waterhole temperature should include measurements of the land surface temperature adjacent to the waterholes. These data are needed to expand the observed surface temperature range so that more accurate regressions between T_s and L_b can be obtained. Land based values of T_s may also be useful for addressing the mixed pixel issue, especially if the relative proportion of water and land in any given pixel can be determined.

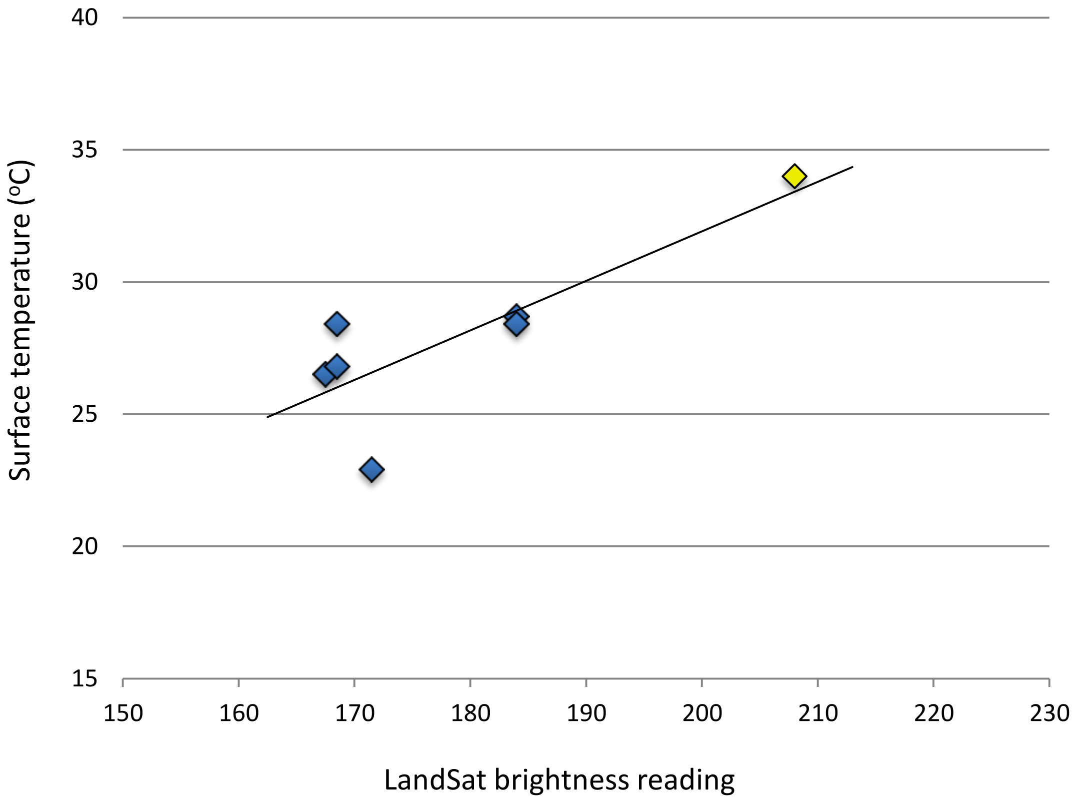


Figure 4.19 Relationship between waterhole water surface temperature (T_s) and LandSat TM 7 brightness temperature (L_b). The linear regression has the form T_s = 0.19 (±0.06) L_b – 6 (±10); R^2 = 0.69

4.5 Discussion

Daily mean profile waterhole water temperatures in the Flinders and Gilbert catchments were found to be quite similar rising from ~ 22 °C in September to ~ 32 °C in December 2012. Waterhole depth had only a small influence on daily mean water temperature, however, shallower waterholes had much larger diurnal temperature fluctuations and this will affect the suitability of these waterholes as aquatic habitats. This illustrates that daily mean water temperature data may mask important aspects of a waterholes thermal regime such as the temperature fluctuations and the maximum conditions that are reached.

This Assessment has demonstrated how high time resolution waterhole water temperature data can be used to determine a number of important aspects of their thermal regime. For example, diurnal fluctuations in surface and bottom water temperature can be used to indicate when thermal stratification occurs in waterholes. This influences the degree of mixing in a waterhole which can affect its suitability as an ecological habitat and also the accuracy with which waterhole water temperature can be modelled. The amplitude of the diurnal change in waterhole water temperature can vary substantially between waterholes and this can be due to differences in waterhole depth and turbidity. For example, Flinders waterhole F05 had much greater amplitude fluctuations than Gilbert waterhole G05. Some of this difference may be due to depth, but it is also possible that this reflects differences in groundwater inputs. If a waterhole is receiving significant groundwater which is cooler than the waterhole water the diurnal amplitude may be reduced. Recent studies in New Zealand by Moridnejad et al. (2013) found that in gaining river reaches that received groundwater this cooler water damped the diurnal amplitude of river temperature. Conversely, in reaches with no groundwater input the diurnal change in river temperature was greater. In the Flinders and Gilbert catchments groundwater inputs to in-stream waterholes were assessed by Jolly et al. (2013) using a combination of radon concentrations, stable isotope and major ions. They found that in the Flinders River the vast majority (~ 90%) of waterholes showed little or no likelihood of being fed by groundwater, whereas in the Gilbert River about half of the waterholes sampled had a high likelihood of being fed by groundwater. It may be that the lack of groundwater inputs in the Flinders River contributes to the larger diurnal temperature fluctuations in this river compared to the Gilbert River where there are significant groundwater inputs.

Water temperature gradients between the surface and bottom of a waterhole also varied between waterholes. Again this may reflect the different depths of waterholes, but there may also be an influence of water clarity. In more turbid waterholes incident light is preferentially absorbed in the surface layers, thereby causing a relatively large increase in the temperature near the surface. Conversely, in clearer waterholes deeper light penetration leads to less difference between the surface and deeper water temperatures. Water body clarity has been estimated in the Flinders and Gilbert catchments by Lymburner and Burrows (2009), using LandSat TM 7 remote sensing. They found that most waterholes in the Flinders River catchment were always turbid, whereas waterholes in the Gilbert River catchment contained much clearer water. Analysis of temperature gradients and diurnal amplitudes in waterholes in these two catchments shows that overall there were slightly larger gradients and smaller diurnal amplitudes in the Flinders compared with the Gilbert, consistent with the clear waterholes that exist in the Gilbert catchment (Chapter 3). However, this picture is confounded by other factors such as waterhole depth.

The high resolution waterhole temperature data have been used to construct frequency curves that show how long either waterhole surface or bottom water temperatures are above any chosen threshold. Two preliminary thresholds for optimum growth (T_{pref}) and the critical thermal maximum (CT_{max}) of tropical Australian fish species have been chosen to illustrate this technique. This indicates that during the warm summer period waterhole surface waters are often in excess of T_{pref} (up to 50% of the time). Water temperatures at the bottom of clear waterholes exceed T_{pref} less often, but still by significant amounts of time (~ 30%). Turbidity in waterholes keeps bottom water temperatures lower than in clear waterholes and in the turbid waterholes examined bottom water temperatures never exceeded T_{pref}. The critical thermal maximum was also never reached in turbid waterholes, but can be exceeded in clear waterholes up to 14% of the time. Fish may therefore prefer to remain in the cooler thermal environment at the bottom of waterholes, but may have to move closer to the surface if other factors, such as dissolved oxygen become limiting in the deeper water layer. In turbid waterholes fish may be able to find a thermal regime close to (or below) their preferred optimum for the entire summer period.

Daily mean profile waterhole water temperature can be adequately estimated using a simple water body energy balance model than uses readily available daily weather data (SILO; solar radiation, air temperature and vapour pressure and rainfall). The model works best in well-mixed waterholes, but thermal stratification can introduce some differences between the model and measured data. In stratified waterholes the model predicts the surface water temperature better than the mean profile temperature. Stratified waterholes have very non-linear temperature profiles and the profile mean temperature can be underestimated by the mean of the surface and bottom temperatures. Under these waterhole conditions it would be necessary to have a greater number of temperature profile measurements to obtain the correct profile mean water temperature. This Assessment also found that at some locations model overestimates of waterhole water temperature could not be ascribed to this profile averaging issue and here the overestimates could be due to these waterholes being windier than assumed in the model (i.e. 2 m/sec). The use of locally measured wind speed may resolve this issue; these data are not currently available in the national SILO weather data base.

This investigation has shown how the model can be used to predict the change in waterhole water temperature during the dry season period with zero flow. The model also predicts how waterhole depth changes during this period and can be used to estimate when a waterhole would approach a critical depth (or dry up completely) towards the end the dry season. The model is not designed to give simulations of temperature and depth into the following wet season, but it may be possible to modify it in future to do so.

Simulations of the impact of climate change (Scenario C) on waterhole water temperature have shown that a 2 ^{o}C warming only increases water temperature by just over 1 ^{o}C. This damping of the air temperature rise is due to the cooling effect of increased evaporation in the warmer climate. The enhanced evaporation increases the rate at which waterhole depths decline during the dry season period of zero flow. By the end of this period in either the Flinders (225 days zero flow) or Gilbert (160 days zero flow) waterhole depths decreased by an extra 70 to 90 mm under Scenario C, equivalent to ~ ten days evaporation at this time. This may not have a major effect of waterholes that are fairly deep towards the end of the dry season, but for shallower waterholes there is a risk that they may go below a critical depth (or dry out) ~ ten days earlier under Scenarios C than they would have done under the current climate.

The investigation here also simulated the impact of climate change (Scenario C) on the frequency with which waterhole water exceeds an illustrative tropical fish preferred temperature (T_{pref}) and critical thermal maximum (CT_{max}). Climate change markedly increased the length of time that waterhole waters exceeded T_{pref} and almost doubled the exceedance of CT_{max}. Hence, although climate change only increases waterhole water temperature by just over 1 degree, this could cause substantial increases in the amount of time the water temperature exceeds critical thresholds. This is a consequence of the steep shape of the frequency curves over most of their range and hence substantial increases in threshold exceedance will occur under Scenario C for any critical aquatic thresholds in the range ~ 28 to 37 ^{o}C.

The current preliminary analysis of LandSat 7 TM data has highlighted some of the difficulties in estimating the surface temperature of channelized river waterholes using satellite data. The main problem is one of resolution. Even the largest river waterholes are only ~ 70m wide and hence LandSat pixels over these waterholes (with an original resolution of 60 m) are more often than not contaminated with signal from the warmer river banks. This issue is exacerbated in the LandSat Level 1 product, which has been resampled to 30 m, potentially making 'smear' effects from the surrounding river banks worse by mixing values from adjacent pixels. Further progress might be made by obtaining the original unsmoothed (60 m) LandSat data, and through careful selection of mid river pixels, which have the lowest brightness temperatures. However, application of such a method over large areas may be difficult unless the method can be robustly automated. Ultimately, it may be necessary to obtain higher resolution thermal band data than are currently possible from satellites using aircraft-mounted systems[1] in order to monitor the surface temperature of river waterholes over large areas. If this could be done it would be possible to construct thermal frequency distributions of numerous waterholes along river reaches and how these evolve as the dry season develops. Thermal tolerance thresholds could then be added to these frequency distributions to identify what proportion of the waterhole is suitable/unsuitable for a given species, and how this changes seasonally and from year to year.

[1] http://www.spatialscientific.com.au/docs/SST_ThermalImaging.pdf

5 Waterhole ecology in the Assessment

5.1 Summary points

- Differences in instream habitat between the catchments are apparent with waterholes in the Gilbert generally characterised by greater amounts of instream woody debris, greater variability in substrates and a higher diversity of aquatic plants compared with those in the Flinders catchment;
- Overall riparian condition was lower for the waterholes in the Flinders catchment due to greater impacts from feral animals compared to the Gilbert catchment waterholes;
- Aquatic invertebrate assemblages differed between catchments and habitats although the greatest differences were found at the habitat scale (e.g. bottom habitat compared to vegetated edges);
- Fish assemblages included many species commonly found throughout the southern Gulf catchments including species targeted by anglers (e.g. barramundi, sooty grunter, or catfish);
- Fish assemblages differed between the catchments and these differences were largely due to the absence of fly-specked hardyheads, and consistently lower numbers of chequered rainbow fish and banded grunter in the Flinders catchment compared to the Gilbert catchment;
- Variables related to waterhole clarity and light penetration accounted for most of the explained variation in biotic assemblage composition between catchments indicating an important role for waterhole clarity and light penetration in structuring aquatic community assemblages;
- A review of existing literature and available databases identified a range of fauna dependent on surface and/or groundwater flows. These include several species of freshwater turtles, frogs, crocodiles, crustaceans and fishes including several species of high conservation value (e.g. the freshwater sawfish and the freshwater whipray).

5.2 Introduction

Dry season river waterholes provide vital aquatic habitats for a range of aquatic birdlife, reptiles, amphibians, invertebrates, fish, and mammals (Balcombe et al., 2006; Horwitz et al., 2009; Kenard, 2010; Pearson et al., 2013; Pusey et al., 2011). The waterholes provide key refugia and are hotspots of aquatic biodiversity (Arthington and Pusey, 2003; Closs et al., 2004; Hermoso et al., 2013; Poff and Zimmerman, 2010). Successful management and conservation is underpinned by provision of specific data focused on biophysical relationships and hydrological connectivity inherent in river systems. To achieve a balance between further development while also protecting ecosystem services provided to local wildlife requires data that link land use change and management, water resource planning and climate change to water quality and ecosystem targets (Arthington et al., 2006; Pearson et al., 2013).

Freshwater fauna of the Flinders and Gilbert catchments must deal with the vagaries of dry season water quality conditions and habitat availability. A great deal of ecological information, for example, species distribution/assemblage details and tolerances, can be obtained from examining the composition of species for a study area, and this is particularly necessary for assessing proposed agricultural water resource developments. Biological communities are commonly used in freshwater ecological health investigations as they offer an integrated (over time and cumulative effects) summary of environmental conditions for the preceding period. Among the range of biological indicators available, the two most commonly used for freshwaters are fish and aquatic invertebrates because: 1) they are abundant, and easy to identify and process; 2) a single survey can represent a range of species and tropic feeding modes; 3) some species are more sedentary and provide a direct and continuing biological response to local environmental (and contaminant) conditions; 4) many common species have usually been well studied so data are available on biology, ecology and tolerances (in terms of water quality thresholds); 5) particularly for fish, many have a high public awareness as they are economically and recreationally targeted; and 6) their loss can be equated to societal costs (Arthington et al., 2010; Brooks et al., 2011; Gehrke and Harris, 2001; Poff and Zimmerman, 2010; Sheldon et al., 2010).

Only a few studies are available within the Assessment area that focus on freshwater fish distribution, aquatic habitat and conservation risks and water quality in the southern Gulf catchments (e.g. see DERM, 2011; Faggotter et al., 2013; Kennard, 2010). In one of the most comprehensive assessments of the implications to biological communities resulting from irrigation developments completed to date, the Burdekin catchment Water Resource Plan included assessment of both fish and aquatic invertebrates. That water resources assessment, however, had access to several decades of collected data. Despite the availability of extensive data, compared to other regions in north Queensland, a key recommendation was still to implement an ongoing monitoring program to assess the diversity, composition of aquatic fauna, and whether the underlying functional ecology (e.g. food webs) shifted following development (DNRMW, 2006). The extent of data available for other irrigation development schemes in north Queensland is substantially less than for the Burdekin catchment, hence a major aim of these investigation here is to prepare a preliminary database of aquatic ecology in the Flinders and Gilbert catchments.

The chapter concentrates on:

1) Generating a comprehensive list of aquatic species known from the Assessment area, from available databases and reports; and
2) Collection of new biological data from within the Assessment areas, along with collection of environmental variables to examine underlying processes.

5.3 Methods

5.3.1 INSTREAM AND RIPARIAN SURVEY

Instream habitat was assessed along a 100 m reach at each waterhole during all sampling trips. Instream aquatic plants (% cover and species present), benthic microalgae (% cover), large woody debris (% cover along pool margin), leaf litter (% cover of substrate), sediment substrate characteristics (% cover based upon Wentworth grain size classifications (Wentworth, 1922)), and riparian shading (expressed as the % cover over the waterhole) were estimated. The extent (%) of habitat type (dry, silty, sandy, rocky, riffle or run) within the waterhole reach was also estimated. In addition, climate conditions (cloud cover, wind), and hydrological stage (swift flow, recent flow, baseflow or no flow) were recorded.

Riparian vegetation condition was assessed once per waterhole, with field data collected during the October/November 2012. Three riparian condition descriptors (Table 5.1) were assessed based on the method described by Werren and Arthington (2002). The width of the riparian zone as a proportion of the mean stream width was calculated from the most recent available Google Earth imagery. Riparian vegetation condition was assessed along a 100 m transect parallel to the waterhole extending to the full width of the riparian zone. Within the transect, data relating to vegetation linear continuity and the degree of bank protection offered by riparian vegetation were collected. Data were used to generate a score from 1 (poor) to 5 (very good), as outlined in Table 5.1. A total riparian condition score for each waterhole was then generated by summing the three scores to give a maximum possible score of 15 and a minimum score of 3.

Table 5.1 Riparian zone condition assessment scores

WIDTH OF RIPARIAN ZONE (AS PROPORTION OF MEAN STREAM WIDTH)	SCORE	LINEAR CONTINUITY (% OF NATURALLY VEGETATED BANK LENGTH, 100 M SAMPLE)	SCORE
1. > 3 x wetted width	5	91–100% vegetated with expected riparian vegetation (e.g. native forest, tall shrubs, etc.) without significant discontinuities	5
> 2 x wetted width	4	75–90% vegetated (see above) with significant discontinuities	4
1–2 x wetted width	3	50–74% vegetated (see above) with significant discontinuities	3
< 1 x wetted width	2	25–50% vegetated (see above) with significant discontinuities	2
vegetated verge absent/severely depleted	1	0–24% vegetated (see above) with significant discontinuities	1

DEGREE OF BANK VEGETATIVE PROTECTION	SCORE
> 90% of streambank surfaces and immediate riparian zones covered by native vegetation	5
70–89% of native vegetation present; disruption evident but not affecting full plant growth potential.	4
50–69% native vegetation coverage but disruption obvious with patches of bare soil or closely cropped vegetation	3
25–49% native vegetation coverage with disruption obvious, patches of bare soil or closely cropped vegetation, and some soil erosion/compaction evident	2
0–24% native vegetation coverage, mostly bare soil with obvious soil erosion/compaction	1

5.3.2 AQUATIC INVERTEBRATES

Aquatic invertebrate communities were sampled at each waterhole using a standard dip net (triangular frame: 0.3 m x 0.3 m x 0.3 m, 0.65 m bag depth, mesh size 250 µm). Sampling was stratified across different habitat types (bank edges, pool bottom, macrophytes) where available, with three replicates completed in each habitat type. ‘Kick samples’ of benthic habitat within waterhole environments were collected at all waterholes (over an area of 2 m^2). Benthic pool habitats occupied the main stream channel and comprised relatively deep, stationary or very slow flowing water over silty, sandy, stony or rocky beds. Edge and macrophyte samples were collected by sweeping the dip net through and along each habitat over an area of approximately 2 m^2. ‘Sweeps’ of edge habitat were conducted at all waterholes where appropriate structure (root masses, trailing vegetation, undercut banks) was present. On site live picking of aquatic invertebrates were conducted for 45 min in total for each habitat type (15 min for each of the three replicates). Specimens were stored in vials and preserved in 70% ethanol before detailed laboratory processing. Specimens were identified to family level where possible, although some of the more taxonomically challenging groups were identified to higher taxonomic levels.

5.3.3 FISH

Freshwater fish assemblages were sampled predominantly using a backpack electrofisher (Smith Root Model 12-B and an ETS unit). An electrofisher provides an electronic current to the water to temporarily stun fish within the small electrical field generated, rendering them easy to scoop up with a small hand net.

Fish quickly recover from this effect and are released shortly after capture. Typically the entire waterhole was walked (at least along the margins) in a single pass, so that most or in some cases, the entire waterhole was surveyed. In deep and long waterholes (F05, F07, F08, F09, G02, G05, G08, G09, G10), a 50 m reach of the waterhole was walked with the electrofisher to a maximum depth of approximately 1 m. Where feasible, a gill net (30 x 2 x 0.075 m stretch mesh) was deployed for approximately two hrs soak time. Bait traps (0.2 x 0.2 x 0.4 m) were set at waterholes for approximately two hrs soak time, though on several occasions traps were set overnight in an attempt to capture more nocturnal species. Captured specimens were identified and released immediately. A summary of the sampling program is shown in Table 2.4 and Table 2.5. Electrofishing and gill net catch were analysed separately and standardised to number of number of fish per 100 seconds operation (electrofishing), and number of fish per hour soak time (gill net).

5.3.4 DATA ANALYSIS

A subset of metrics was utilised to assess the status of the invertebrate communities at each waterhole. These include taxonomic richness (number of taxa), Evenness (J'), Shannon diversity (H'), and SIGNAL (Stream Invertebrate Grade Number Average Level) index (Appendix B). The SIGNAL index is currently recommended in the Queensland Water Guidelines (DERM, 2009a) because it is one of the most sensitive metrics for discriminating anthropogenic impacts (Metzeling et al., 2003). The SIGNAL index values were calculated in accordance with Chessman (1995), by assigning pollution sensitivity grade numbers from one (most tolerant) to ten (most sensitive) to each taxon and then averaging the pollution sensitivity grade numbers of all taxa present. The sensitivity grades utilised here were derived from Chessman (2003).

Non-metric multidimensional scaling (NMDS) was used to ordinate catchments from biotic similarity matrices using the Bray-Curtis index, on presence/absence transformation. Both presence/absence and 4th root transformation was performed on biotic data to check whether relative abundances rather than taxonomic composition were driving the ordination results. Little differences in the ordinations were apparent (RELATE routine in PRIMER; Clarke and Gorley, 2001; electrofish data $\rho = 0.577$, $P = 0.1$; gill net fish $\rho = 0.747$, $P = 0.1$; aquatic invertebrates $\rho = 0.708$, $P = 0.1$), therefore presence/absence transformation was used throughout. Sample methods in waterholes could not be pooled (e.g. electrofishing and gill nets) due to logistical problems using gill nets in small waterholes (e.g. F03 and F04). To examine the hypothesis that biotic similarities varied between catchments and surveys PERMANOVA using the Bray-Curtis dissimilarity measure was used with the terms catchment and surveys both fixed, and an interaction term (catchment x survey) (Anderson, 2001). Similarity Percentages (SIMPER) identified which species contributed most to the difference (i.e. high mean/sd ratio; Clarke (1993)). BIOENV (rho) was used to assess relationships for single or combinations of environmental factors (see Appendix D) using the weighted Spearman coefficient (ρw) (Clarke and Ainsworth, 1993).

5.4 Results

5.4.1 RIPARIAN AND INSTREAM CONDITION

The results of the instream and riparian assessment for the waterholes investigated are presented in Table 5.2 and Table 5.3. Few pieces of woody debris were present in the waterholes along the Flinders catchment which contrasts with the Gilbert catchment waterholes. The latter had small patches of woody debris present at waterholes, with the highest extent of woody debris present at G08 (along 50% or more of the waterhole margin). Similar data relating to the presence of detritus within the pools were collected, with G02 the only waterhole to have a 50% or greater covering of detritus on the waterhole bottom.

Coverage and the number of aquatic plant species were highest in the off-channel, shallow waterholes (F03 and F10) of the Flinders catchment. Generally, however, aquatic plants were more common and exhibited greater species diversity in Gilbert catchment waterholes compared with Flinders catchment waterholes. This is possibly a function of the differences in turbidity between catchments (Chapter 3) but may also reflect differences in other factors such as substrate mobility and water permanence. The substrate of the waterholes in the Flinders catchment was dominated by silt and sand with little differences among waterholes examined. In comparison, the Gilbert catchment had more variable waterhole substrates, in particular, bottom habitats including bed rock, gravel/rocky and sandy substrates, or a combination of these features (Table 5.2 and Table 5.3).

Impact from cattle grazing on riparian vegetation was evident at all waterholes. Nine waterholes exhibited low levels of vegetative protection giving them a protection score of two or less (Table 5.1). Only four waterholes with 70% vegetative protection or more were identified (F02, F03, F05 and G08). Both percentage of naturally vegetated bank length and the width of the riparian zone varied between waterholes, however, overall riparian condition was slightly lower in the waterholes in the Flinders catchment compared to Gilbert catchment waterholes (mean riparian score of 8 in the Flinders catchment compared to 9.5 in the Gilbert catchment). Prickly acacia (*Acacia nilotica*) was common at waterholes in the Flinders catchment, while rubber vine (*Cryptostegia grandiflora*) was more common at the Gilbert catchment waterholes (Appendix E and Appendix F). Neem trees (*Azadirachta indica*) are found in the Gilbert catchment, but were not observed at waterholes investigated.

Table 5.2 Flinders catchment aquatic and riparian ecology details. [1] Groundwater influence determined from Jolly et al. (2013). NA = not sampled. [2] Substrate classifications based on broad groupings from the Wentworth grain size classification (Wentworth, 1922). [3] Score from a total of 15 based upon riparian zone width (low = 1, high = 5), continuity (low = 1, high = 5) and vegetative protection (low = 1, high = 5) within 100 m reach during Nov 2012, modified from Werren and Arthington (2002). [4] Woody debris cover as proportion of pool margin. [5] Habitat type offered within 100 m reach during Oct/Nov 2012

WATER-HOLE	RIVER	CONNECTIV-ITY	FLOW REGIME	GROUND-WATER INFLUENCE [1]	SUBSTRATE TYPE [2]	RIPARIAN SCORE [3]	WOODY DEBRIS COVER [4]	DETRITUS COVER	AQUATIC PLANT COVER / NO. SPP.	HABITAT [5]
F01	Fairlight Creek	Channel	Permanent waterhole / seasonally intermittent flow	High	70% silt, 30% sand	9	10–50%	1–10%	0% / 0	20% sandy waterhole, 70% silty waterhole, 10% dry
F02	Flinders River	Channel	Seasonal	Nil	65% silt, 30% sand, 5% boulder	13	1–10%	10–50%	0% / 0	90% sandy waterhole, 5% rocky waterhole, 5% silty waterhole
F03	Flinders River	Off-channel	Seasonal	Low	100% silt	10	1–10%	1–10%	75% / 3 spp.	55% silty waterhole, 45% dry
F04	Flinders River	Off-channel	Seasonal	Nil	100% silt	7	1–10%	10–50%	0% / 0	50% silty waterhole, 50% dry
F05	Flinders River	Channel	Permanent waterhole / seasonally intermittent flow	Nil	70% silt, 30% sand	10	1–10%	1–10%	10% / 1 spp.	10% sandy waterhole, 90% silty waterhole
F06	Flinders River	Off-channel	Seasonal	Nil	100% silt	4	0%	0%	0% / 0	100% dry
F07	Flinders River	Channel	Permanent waterhole / seasonally intermittent flow	Nil	100% silt	9	1–10%	1–10%	2% / 1 spp.	85% silty waterhole, 15% dry
F08	Julia Creek	Channel	Permanent waterhole above weir / seasonally intermittent flow	Nil	100% silt	7	1–10%	1–10%	10% / 1 spp.	100% silty waterhole
F09	Cloncurry River	Channel	Permanent waterhole / seasonally intermittent flow	Low	90% sand, 10% bedrock	7	10–50%	1–10%	0% / 0	70% sandy waterhole, 5% rocky waterhole, 25% dry
F10	Alick Creek	Channel	Seasonal	Nil	100% silt	4	1–10%	1–10%	90% / 1 spp.	100% dry

Table 5.3 Gilbert catchment aquatic and riparian ecology details. [1]Groundwater influence determined from Jolly et al. (2013), [2]Substrate classifications based on broad groupings from the Wentworth grain size classification (Wentworth 1922). [3]Riparian score based on riparian zone width (low =1, high =5), continuity (low =1, high = 5) and vegetative protection (low = 1, high = 5) within 100 m reach during Nov 2012, modified from Werren and Arthington (2002). [4] Woody debris cover as proportion of pool margin. [5]Habitat type offered within 100 m reach during Oct/Nov 2012

WATER-HOLE	RIVER	CONNECTIV-ITY	FLOW REGIME	GROUND-WATER INFLUENCE[1]	SUBSTRATE TYPE[2]	RIPARIAN SCORE[3]	WOODY DEBRIS COVER [4]	DETRITUS COVER	AQUATIC PLANT COVER / NO. SPP.	HABITAT[5]
G01	Bundock Creek	Channel	Permanent waterhole above causeway / seasonally intermittent flow	High	5% bedrock 5% boulder 20% gravel, 60% sand, 10% silt	8	10–50%	1–10%	20% / 3 spp.	90% sandy waterhole, 10% rocky waterhole
G02	McKinnons Creek	Channel	Permanent waterhole / seasonally intermittent flow	Nil	40% sand, 30% gravel, 10% pebble, 10% boulder, 10% bedrock	9	1–10%	50–75%	20% / 1 spp.	80% sandy waterhole, 10% rocky waterhole, 10% silty waterhole
G03	Einasleigh River	Channel	Permanent waterhole / seasonally intermittent flow	Low	50% sand, 10% gravel, 10% boulder, 30% bedrock	9	1–10%	1–10%	60% / 5 spp.	70% sandy waterhole, 30% rocky waterhole
G04	Einasleigh River	Channel	Permanent waterhole / seasonally intermittent flow	Nil	70% sand, 5% pebble, 5% cobble, 10% boulder, 10% bedrock	7	1–10%	1–10%	40% / 3 spp.	60% sandy waterhole, 15% rocky waterhole, 25% dry
G05	Einasleigh River	Channel	Permanent waterhole / seasonally intermittent flow	Nil	65% sand, 5% cobble, 10% boulder, 20% bedrock	11	1–10%	1–10%	25% / 4 spp.	70% sandy waterhole, 30% rocky waterhole
G06	Elizabeth Creek	Channel	Perennial flow	High	70% sand, 5% gravel, 10% pebble, 10% cobble, 5% boulder	12	10–50%	10–50%	70% / 5 spp.	90% sandy waterhole, 10% riffle
G07	Junction Creek	Channel	Perennial flow	Low	95% sand, 5% boulder	11	1–10%	1–10%	50% / 5 spp.	90% sandy waterhole,10% rocky waterhole
G08	Langlovale Creek	Channel	Permanent waterhole / seasonally intermittent flow	Low	70% sand, 20% gravel, 10% pebble	13	50–75%	10–50%	5% / 3 spp.	100% sandy waterhole
G09	Pleasant Creek	Channel	Permanent waterhole / seasonally intermittent flow	Nil	60% sand, 20% gravel, 20 bedrock	8	10–50%	10–50%	2% / 1 spp.	80% sandy waterhole, 20% rocky waterhole,
G10	Gilbert River	Channel	Permanent waterhole / seasonally intermittent flow	High	20% silt, 50% sand, 30% bedrock	7	1–10%	1–10%	0% / 0 spp.	60% sandy waterhole, 20% rocky waterhole, 20% dry

5.4.2 AQUATIC INVERTEBRATES

Sixty-six (66) invertebrate taxa were recorded from investigation waterholes in the Assessment, with fewer taxa recorded in the Flinders catchment (50 taxa) compared to Gilbert catchment (64 taxa). Species within the family Cladocera (22%), Ostracoda (17%) and Corixidae (13%) dominated the catch in Flinders catchment waterholes, while Copepoda (12%), Corixidae (12%), Caenidae (8%), and Chironominae, Tanypodinae and Baetidae (all 7%) dominated in the Gilbert catchment. Full details of the invertebrate data are provided in Appendix B.

Most waterhole sampling included collection of invertebrates from bottom habitats, with samples from edge habitats the next most common, while only a few samples were collected from macrophyte habitats (only in the Flinders catchment at off-channel waterholes - F03 and F10). Total abundance and species richness was variable across catchments, surveys, waterholes and habitats. The Shannon diversity, evenness and SIGNAL scores were similar among waterholes in both catchments. There were also slight reductions in these scores when pooling data in catchments in the second survey compared to the first survey (Figure 5.1). The exception was macrophyte habitats in the Flinders catchment where a marginal increase was observed. More data are necessary to statistically examine this pattern.

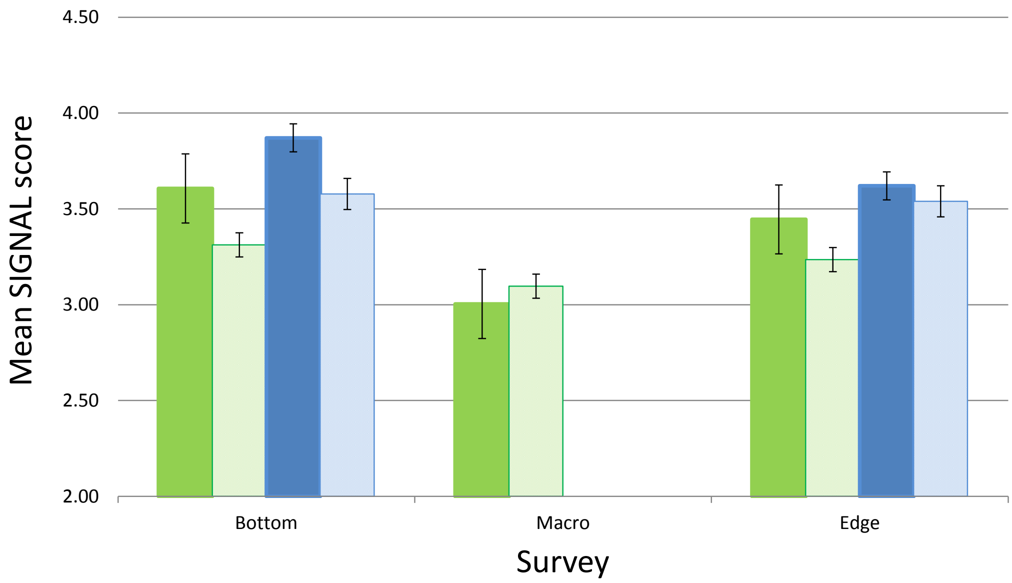


Figure 5.1 Mean (SE) SIGNAL scores calculated by pooling waterholes for each habitat in Flinders (green) and Gilbert (blue) catchments during survey 1 (solid bar) and survey 2 (hatched bar), showing a slight reduction in score over time

PERMANOVA indicated a significant interaction between catchment and habitat (F_1 = 2.76, P = 0.006), though catchments and habitats also differed (catchments: F_1 = 3.5, P = 0.01; habitats: F_2 = 10.9, P = 0.001). This interaction relationship is driven by the consistent pattern of habitat separation, whereby habitats are clustered together regardless of catchment (Figure 5.2a and b). The mean turbidity value accounted for most of the variation in assemblage composition between catchments (BIOENV, ρ_w = 0.209). With the addition of NoRS, TSS, TFAP in the analysis, the explanatory power increases, though only slightly (BIOENV, ρ_w = 0.294; Table 5.4).

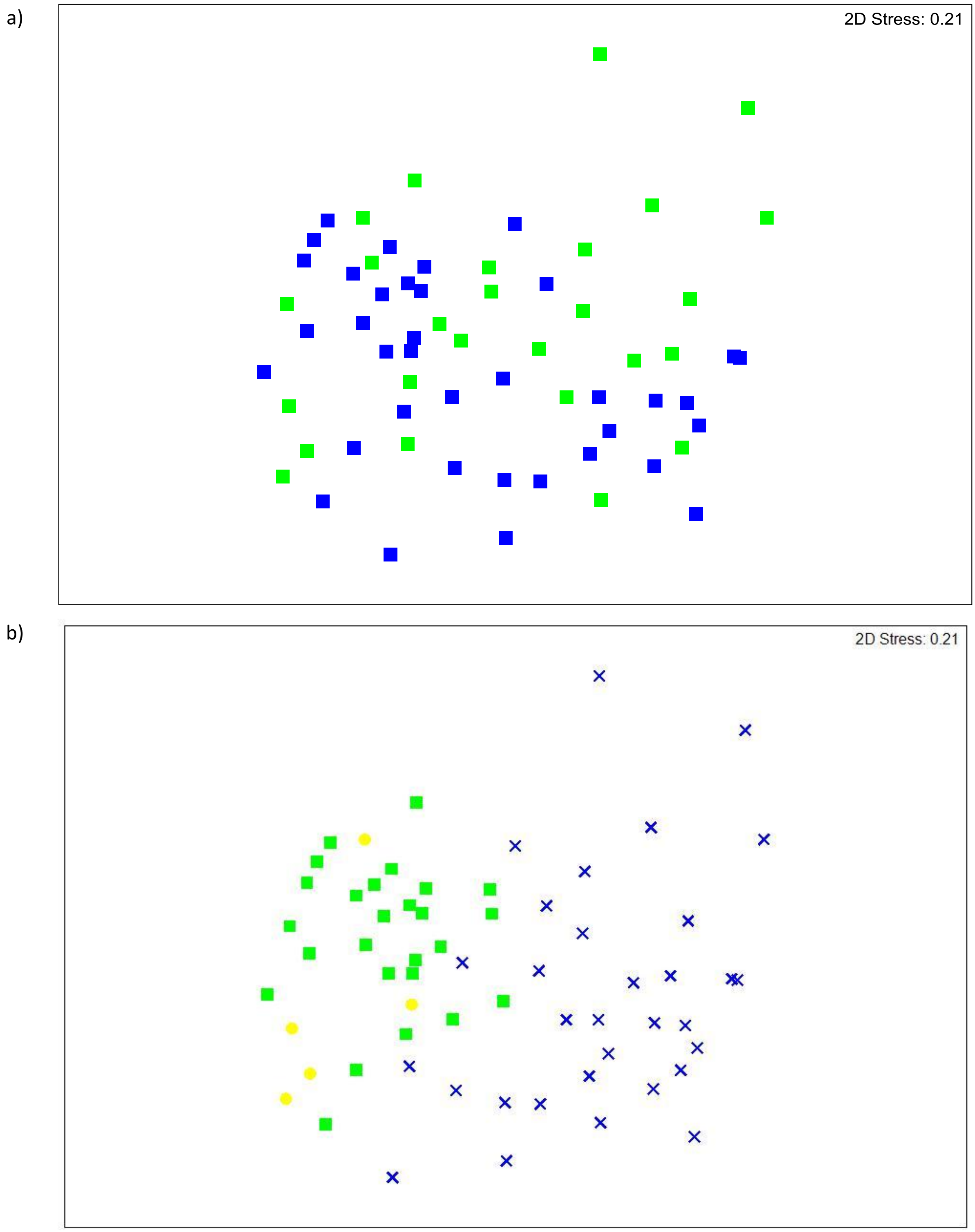


Figure 5.2 NMDS of aquatic invertebrate assemblages for catchments: a) Flinders (green) and Gilbert (blue) catchments; and b) edge (green squares); bottom (dark blue crosses); and macrophytes (yellow circles)

Table 5.4 Correlations between the composition of aquatic invertebrate assemblage and combination of environmental variables (BIOENV results) for the Assessment. NTU; turbidity, NoRS; no riparian species; TSS, total suspended sediments, TFAP; total filterable aqueous phosphorus

VARIABLE SET	TAXONOMIC COMPOSITION: BEST VARIABLE (RHO)			
	1 variable	2 variables	3 variables	4 variables
All	Mean NTU (0.209)	Mean NTU, NoRS (0.242)	Mean NTU, NoRS, TSS (0.270)	Mean NTU, NoRS, TSS, TFAP (0.294)

5.4.3 FISH

Community

During this investigation, a total of 6844 fish were caught, comprising 23 species from 15 families, with fewer species recorded in the Flinders catchment (18 species) compared to the Gilbert catchment (22 species). The five species contributing more than 80% of the total combined catch by number were chequered rainbowfish (*Melanotaenia splendida inornata*) (49%), fly-specked hardyhead (*Craterocephalus stercusmuscarum*) (12%), banded grunter (*Amniataba percoides*) (8.2%), glassfish (*Ambassis* sp.) (7.4%) and bony bream (*Nematalosa erebi*) (6.2%) By far, more fish were recorded in the Gilbert catchment (6092 individuals) compared to the Flinders catchment (752 individuals). Large numbers of *M. splendida inornata*, *Ambassis* sp., *C. stercusmuscarum* and *A. percoides* contributed to the higher number of fish in the Gilbert catchment waterholes. All fish species recorded in the Flinders catchment were also recorded in the Gilbert catchment (with the exception of the freshwater anchovy; *Thryssa scratchleyi*). Species caught only in the Gilbert catchment waterholes included freshwater longtom (*Strongylura krefftii*), giant gudgeon (*Oxyeleotris selheimi*), freshwater sole (*Brachirus selheimi*), *C. stercusmuscarum*, and northern trout gudgeon (*Mogurnda mogurnda*).

Patterns in fish assemblages

Electrofishing

Ordinations revealed clear differences in fish assemblage structure between catchments (Figure 5.3). PERMANOVA indicated a significant difference in fish assemblages between catchments (F_1 = 3.56, P < 0.001). No differences, however, were found between surveys (F_1 = 1.07, P = 0.39) and no interaction was detected between catchment and survey (F_1 = 0.238, P = 0.93). Fish species contributing most (51%) to the separation between catchments included: chequered rainbowfish (27.6%), fly-specked hardyhead (13.8%) and banded grunter (10.2%).

The maximum secchi depth to depth ratio ($MaxZ_{sec}$:Z) accounted for most of the explained variation in assemblage composition between catchments, with the Gilbert catchment having a greater maximum secchi depth to depth ratio compared with waterholes in the Flinders catchment (BIOENV, ρw = 0.283; Figure 5.4). With the addition of TFPN, NoRS, TCa, and NTU in the analysis, the explanatory power explaining the fish assemblage pattern improved (BIOENV, ρw = 0.346; Table 5.5).

No regression relationships were found between individual fish abundances, total abundance or species richness and environmental factors. Differences in the catch of fly-specked hardyhead, *Craterocephalus stercusmuscarum*, between waterholes on the basis of water clarity were, however, found (Figure 5.5).

Gill net

Gill net sampling increased the fish species list caught in both catchments, especially larger, more mobile, species that are capable of escaping the electrical field of the electrofisher. Additional fish species captured using this method included: fork-tailed catfish (*Neoarius graeffei*), toothless catfish (*Anodontiglanis dahli*), black catfish (*Neosilurus ater*), seven spot archerfish (*Toxotes chatareus*), barramundi (*Lates calcarifer*), oxeye herring (*Megalops cyprinoides*), and freshwater anchovy (*Thryssa scratchleyi*). PERMANOVA indicated no differences in assemblages for all comparisons.

No regression relationships were found between individual fish abundances, total abundance and species richness and environmental factors. At the community level, calculated minimum surface temperature for a defined period prior to fish sampling accounted for most of the variation between catchments (BIOENV, ρw = 0.576). With the addition of EC, AUN, APN and ADON in the analysis, the explanatory power explaining the fish assemblage pattern improved (0.917; Table 5.5).

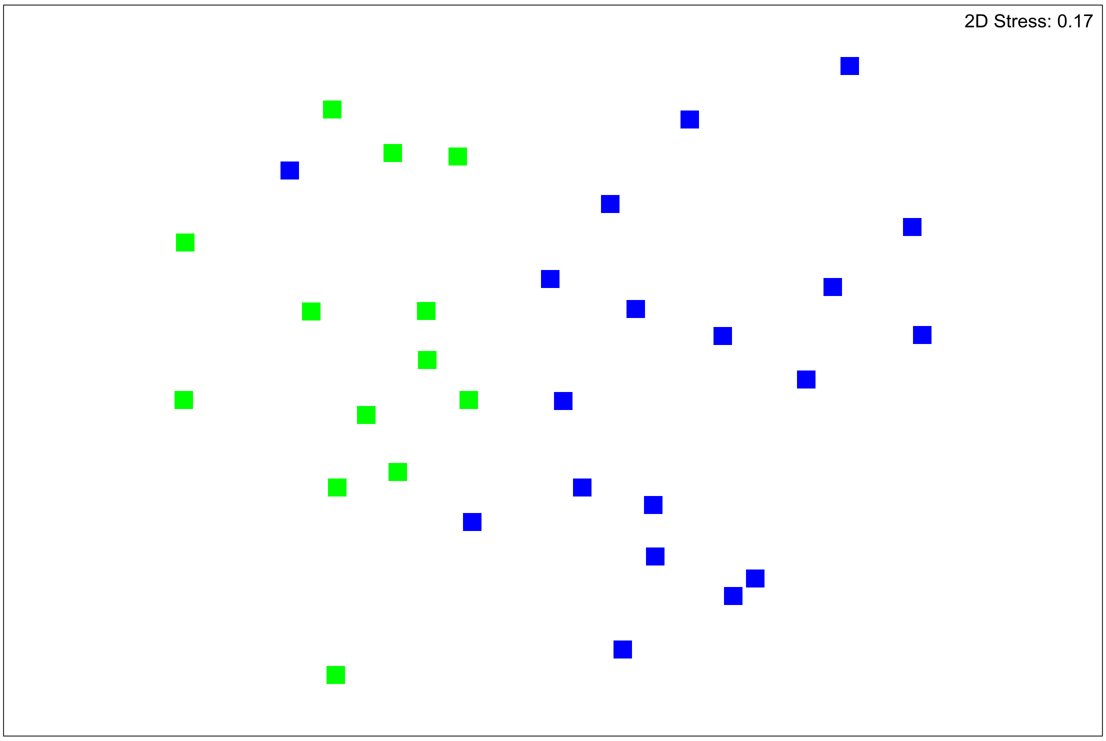


Figure 5.3 NMDS (presence/absence transformation) of fish assemblages using electrofishing for waterholes in Flinders (green) and Gilbert (blue) catchments

Table 5.5 Correlations between fish composition captured using both electrofishing and gillnets, and environmental variables (BIOENV results) for the Assessment. Max Zsec:Z; maximum secchi disc depth to water column depth ration, TSS, total suspended sediments, NTU; turbidity, NoRS; no riparian species; TFAP; total filterable aqueous phosphorus, TCa; total chlorophyll-*a*, EC; electrical conductivity, MinSurfTemp; minimum surface temperature recorded with continuous loggers, AUN; Aqueous urea, APN; aqueous particulate nitrogen, ADON; aqueous dissolved oxidised nitrogen

SAMPLING METHOD	TAXONOMIC COMPOSITION: BEST VARIABLE (RHO)			
	1 variable	2 variables	3 variables	4 variables
Electrofishing	Max Zsec:Z (0.283)	TSS, TCa (0.314)	NoRS, TSS, TCa (0.337)	NoRS, NTU, TSS, TCa (0.346)
Gillnet	MinSurfTemp (0.576)	EC, AU (0.785)	EC, APN, AU (0.859)	EC, APN, ADON, AU (0.917)

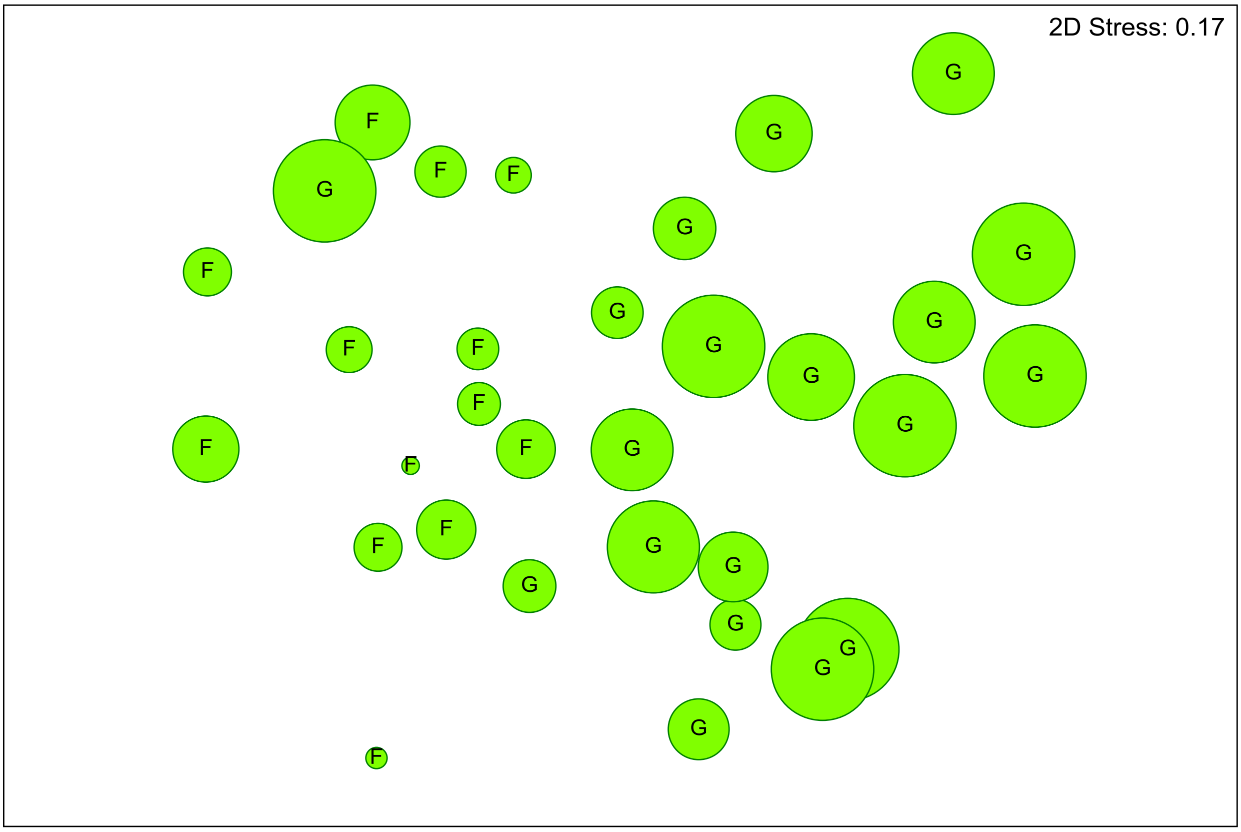


Figure 5.4 Same NMDS ordination plot in Figure 5.3 with superimposed circles of increasing secchi depth to depth ratio (%). Smallest circle = 10%, largest circle = 100% or greater. F, Flinders catchment; G, Gilbert catchment

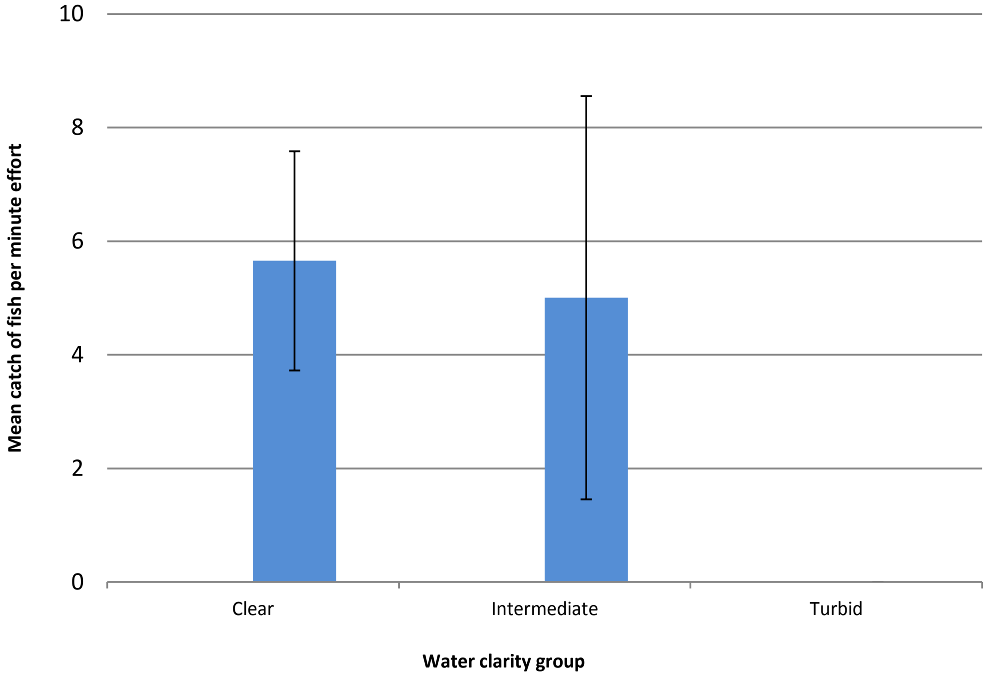


Figure 5.5 Mean (SE) catch (electrofisher) per waterhole for each minute of effort to catch *Craterocephalus stercusmuscarum* in Gilbert catchment in clear (100%), intermediate (50-100%), turbid (0-50%) secchi depth to water depth ratio. *C. stercusmuscarum* was not caught in the Flinders catchment

Catchment wide fish assemblage

A review of the published literature, museum records and expert local knowledge was completed, and along with data collected during the Assessment, revealed a total of 50 fish species recorded from the Flinders catchment and 42 species from the Gilbert catchment (Table 5.6). Generally, the number of fish species in Australian rivers decreases from downstream to upstream reaches. This is attributable to the marine ancestry of many Australian freshwater fish species and the number of estuarine-dwelling species that are occasionally found in lower reaches of freshwater systems. This highlights the importance of maintaining connectivity between estuarine and lower freshwater reaches and also demonstrates the importance of protecting coastal wetland habitats that support fish, prawns and crabs (Burrows and Perna, 2006).

All species captured during the Assessment in both catchments have been recorded previously. No new species or range extensions were recorded during the Assessment. In adjacent catchments the discovery of fish species outside their known range and possibly entirely new species, has occurred. For example, in the Norman River catchment Burrows and Perna (2006) discovered seven fish species that had not been previously reported in that catchment, one of which (*Neosilurus sp*.) may represent a new species of eel-tailed catfish.

Table 5.6 Fish species in Flinders (F) and Gilbert (G) catchments. (E) exotic species, (*) commercially/recreationally targeted. Sourced literature: 1) Hogan and Vallance (2005); 2) EcoWise (2007); 3) Faggotter et al. (2011) ; 4) Vallance et al. (2000); 5) Pearce et al. (2000a); 6) Pearce et al. (2000b); 7) M. Pearce DAFF unpublished data, Pers. Comm.; 8) Barlow (1987); 9) Thorburn, et al., (2004); and 10) Wildnet website (http://www.ehp.qld.gov.au/wildlife/wildlife-online). No Authority given for species not identified (i.e.. spp.) and therefore some caution is necessary with interpretation

FAMILY	COMMON NAME	SPECIES	STOCKED LAKES	LITERATURE SOURCE	QLD MUSEUM RECORD	THIS ASSESSMENT
Ambassidae	Sailfin perchlet	*Ambassis agrammus* Günther, 1867		4 (G)	G	
	Elongate glassfish	*Ambassis elongata* (Castelnau, 1878)		2 (G)		
	Reticulated glassfish	*Ambassis macleayi* (Castelnau, 1878)	Lake Corella (6)	1, 2 (F, G)		F, G
	Glassfish	*Ambassis spp.*	Chinaman Dam (5)	1, 2 (F, G)		
	Giant glassfish	*Parambassis gulliveri* (Castelnau, 1878)	Lake Tritton, Chinaman Creek Dam (5, 7)	1, 2, 3 (F, G)	F, G	
Apogonidae	Mouth almighty	*Glossamia aprion* (Richardson, 1842)		1, 2, 3 (F, G)	G	F, G
Ariidae	Berney's catfish	*Neoarius berneyi*		1, 2, 3(F, G)	F	
	Fork-tailed Catfish	*Neoarius graeffei*		1, 2, 3 (F, G)	F	F, G
	Lesser salmon	*Sciades leptaspis*	Chinaman Creek Dam (5)	1, 2 (F, G)		
	Carpentaria catfish	*Neoarius paucus*		1, 2 (F, G)	F, G	
	Silver cobbler	*Neoarius midgleyi*	Chinaman Creek Dam (5)	3 (F)		
	Small-mouthed catfish	*Cinetodus froggatti* (Ramsay & Ogilby, 1886)		1 (F, G)	F	
Atherinidae	Fly-speckled hardyhead	*Craterocephalus stercusmuscarum* (Günther, 1867)		2 (G)	G	G
Belonidae	Freshwater long tom	*Strongylura krefftii* (Günther, 1866)		1, 2 (F, G)	G	G

FAMILY	COMMON NAME	SPECIES	STOCKED LAKES	LITERATURE SOURCE	QLD MUSEUM RECORD	THIS ASSESSMENT
Centropomidae	Barramundi*	*Lates calcarifer* (Bloch, 1790)	Lake Tritton, Chinaman Creek Dam (5, 7)	1, 2, 3 (F, G)		F, G
Clupeidae	Bony bream	*Nematalosa erebi* (Günther, 1868)	Chinaman Creek Dam, Lake Corella, Lake Tritton, Kidston Dam (5, 6, 7, 8)	1, 2, 3 (F, G)	F	F, G
	Papuan river sprat	*Clupeoides cf. papuensis*		1, 2 (F, G)		
Dasyatidae	Freshwater whipray	*Himantura dalyensis* Last & Manjaji-Matsumoto, 2008		1, 3, 10 (F, G)		
Eleotridae	Crimson-tipped flathead gudgeon	*Butis butis* (Hamilton, 1822)		1 (F)		
	Gilbert gudgeon	*Hypseleotris sp.*		2 (G)		
	Northern trout gudgeon	*Mogurnda mogurnda* (Richardson, 1844)	Kidston Dam (8)	1, 2 (F, G)	F	G
	Sleepy cod*	*Oxyeleotris lineolatus* (Steindachner, 1867)	Chinaman Creek Dam, Lake Tritton, Kidston Dam, Lake Corella (5, 6, 7, 8)	1, 2, 3 (F, G)	F	F, G
	Giant gudgeon*	*Oxyeleotris selheimi* (Macleay, 1884)	Chinaman Creek Dam, Lake Corella, Lake Tritton, Kidston Dam (5, 6, 7, 8)	1, 2, 3 (F, G)	F	G
	Small-eyed sleeper	*Prionobutis microps* (Weber, 1907)		1 (F)		
Engraulidae	Freshwater anchovy	*Thryssa scratchleyi* (Ramsay & Ogilby, 1886)		1, 3 (G)		F
Gobiidae	Tadpole goby	*Chlamydogobius ranunculus* Larson, 1995		1 (F)	F	
	Golden goby	*Glossogobius aureus* Akihito & Meguro, 1975	Lake Tritton, Chinaman Creek Dam (5, 7)	1, 2 (F, G)	F	F, G
	Flathead goby	*Glossogobius giuris* (Hamilton, 1822)	Lake Corella (6)	2 (F, G)	F, G	
	Square-blotched goby	*Glossogobius sp. C*	Kidston Dam (8)	1, 2 (F, G)		
	Unidentified goby	*Glossogobius sp.*		2 (G)		
	Goby Un Id.	*Pseudogobius sp.*		1 (F)		
	Speckled goby	*Redigobius bikolanus* (Herre, 1927)		1 (F)		
Hemiramphidae	Snub-nosed garfish	*Arrhamphus sclerolepis* Günther, 1866		2 (F, G)	G	
	River garfish	*Zenarchopterus spp.*		1 (F)		
Kurtidae	Nursery fish	*Kurtus gulliveri* Castelnau, 1878		1, 3 (F)	F	
Megalopidae	Tarpon	*Megalops cyprinoides* (Broussonet, 1782)		2, 3 (F, G)		F, G
Melanotaeniidae	Chequered rainbowfish	*Melanotaenia splendida inornata* (Castelnau, 1875)	Chinaman Creek Dam, Lake Corella, Lake Tritton, Kidston Dam (5, 6, 7, 8)	1, 2, 3 (F, G)	F, G	F, G

FAMILY	COMMON NAME	SPECIES	STOCKED LAKES	LITERATURE SOURCE	QLD MUSEUM RECORD	THIS ASSESSMENT
Mugilidae	Diamond mullet	*Liza ordensis* (Whitley 1945)		1 (F)		
Poeciliidae	Mosquitofish (E)	*Gambusia holbrooki* Girard, 1859		1 (F)	F	
Plotosidae	Toothless catfish	*Anodontiglanis dahli* Rendahl, 1922	Chinaman Creek Dam (5)	1, 2, 3 (F, G)	F	F, G
	Black catfish	*Neosilurus ater* (Perugia, 1894)		1, 2, 3 (F, G)	F, G	F, G
	Hyrtl's tandan	*Neosilurus hyrtlii* Steindachner, 1867	Lake Tritton, Kidson Dam (7, 8)	1, 2, 3 (F, G)	F	F, G
	Silver tandan	*Porochilus argenteus* (Zietz, 1896)			F	
	Rendahl's catfish	*Porochilus rendahli* (Whitley, 1928)		1, 2 (F, G)	F	
	Catfish Un Id.	*Porochilus sp.*		1 (F)		
Pristidae	Giant freshwater sawfish	*Pristis pristis* (Linnaeus, 1758)		3, 9 (F, G)		
Terapontidae	Barred grunter	*Amniataba percoides* (Günther, 1864)	Lake Corella, Chinaman Creek Dam, Lake Tritton, Kidston Dam (5, 6, 7, 8)	1, 2, 3 (F, G)	F, G	F, G
	Sooty grunter*	*Hephaestus fuliginosus* (Macleay, 1883)	Chinaman Creek Dam, Lake Tritton, Kidston Dam, Lake Corella (5, 6, 7, 8)	2 (F, G)		F, G
	Spangled perch	*Leiopotherapon unicolor* (Günther, 1859)	Chinaman Creek Dam, Lake Corella, Lake Tritton, Kidston Dam (5, 6, 7, 8)	1, 2, 3 (F, G)	F	F, G
	Gilbert's grunter*	*Pingalla gilberti* Whitley, 1955		2, 4 (F, G)	F, G	
	Gulf grunter*	*Scortum ogilbyi* (Castelnau, 1878)	Lake Tritton, Chinaman Creek Dam (5, 7)	1, 2, 3 (F, G)	F, G	F, G
Scatophagidae	Spotted scat	*Scatophagus argus* (Linnaeus, 1766)		1 (G)		
Soleidae	Saltpan sole	*Brachirus salinarum* (Ogilby, 1910)		1, 2 (G)	F	
	Freshwater sole	*Brachirus selheimi* (Macleay, 1882)		1, 2, 3 (G)	F	G
Toxotidae	Seven-spot archerfish	*Toxotes chatareus* (Hamilton, 1822)	Lake Tritton, Kidston Dam (7, 8)	1, 2, 3 (F, G)	F	F, G

1. Vallance et al. (2000) reports *Scortum neili* in the Gilbert River, however, this is outside known range and therefore removed here
2. Family Ariidae and inclusion of *Neoarius paucus* and *N. midgleyi* separately (despite being closely related) follows advice from J. Johnson, Queensland Museum

The distribution of fish species throughout the Flinders and Gilbert catchments is not known with precision, owing mostly to limited studies in many tributaries (Figure 5.6). This partial distributional knowledge may become relevant with respect to the location of water resource and other development infrastructure as the dams and weirs become barriers for fish passage. The installation of water storage structures low in catchments or on main river channels effectively reduces opportunities for the upstream return migration of fish. Fish movement across instream barriers can be aided by the installation of a fish passage device, although such devices are generally regarded as variable in their success (Marsden and Stewart, 2005). While positioning of water storage facilities on tributaries might therefore be viewed more favourably, important freshwater refuge habitat may still exist in upper tributaries and therefore a full survey of tributaries is warranted.

A small number of freshwater fish species recorded in the Flinders and Gilbert catchments are targeted by anglers, in particular barramundi, sleepy cod, giant gudgeon, sooty grunter as well as some catfish species. The number of these species caught in the region is unknown, though recreational fishing in both catchments is popular and provides at least some contribution towards socio-economic values for the region (see Crossman et al. 2013). In addition to their value of these species as food for humans, a wider set of cultural associations with these species (and maybe other aquatic animals) is covered in Barber (2013).

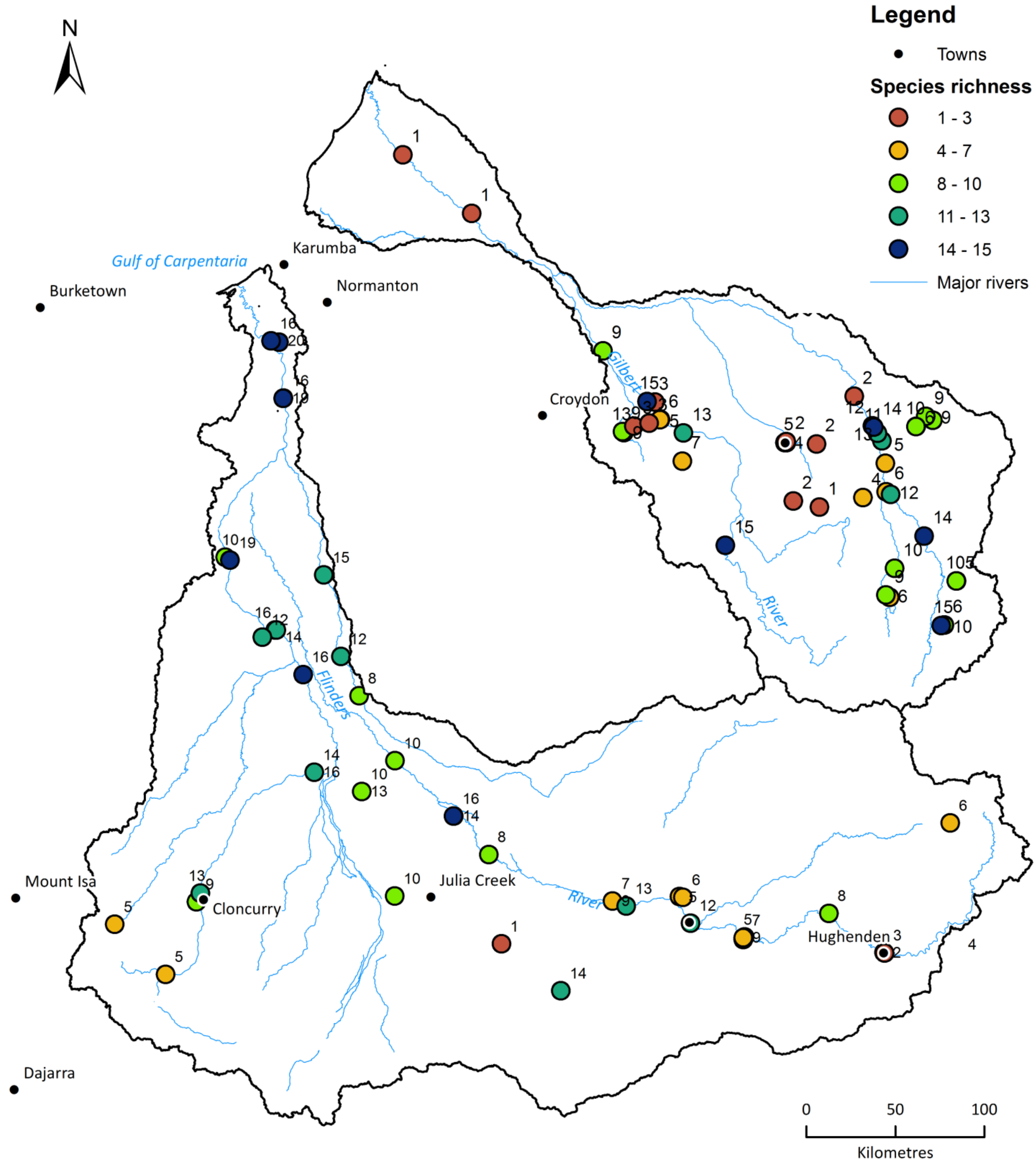


Figure 5.6 Spatial representation of freshwater fish investigations across the Flinders and Gilbert catchments, including total number of species captured in this investigation. Note that at several locations only a single species has been recorded which represents a spot recording and is typically freshwater sawfish and freshwater whipray; see Figure 5.7

5.5 Discussion

5.5.1 INSTREAM AND RIPARIAN CONDITION

The riverine waterholes investigated in the Assessment had a substrate consisting mostly of sand and silt material with variable habitat characteristics including riparian vegetation, wood debris and flow. The waterholes examined in the Flinders River were typically more turbid (see Chapter 3), and this probably contributes to a distinct lack of aquatic macrophytes. Minimal fallen timber providing shelter and protection for aquatic fauna exists in the Flinders catchment waterholes. Off-channel waterholes had aquatic macrophyte beds of low species diversity (see Appendix E), which were quickly lost as they dried. In contrast, the Gilbert catchment waterholes were generally sandier, with many containing exposed bedrock outcrops, a reflection of the catchment geology. Several waterholes had aquatic macrophytes present, however, high densities only became obvious later during the investigation, particularly at G03 and G04 (January – May 2013).

The number of plant species that occurs strictly within the riparian zone in seasonal dry tropical rivers of northern Australia is low (23 obligate riparian species), though another 126 species have been recorded in riparian zones (Dowe, 2008). Riparian vegetation communities at the waterholes investigated ranged between sparse through to intact vegetation communities. Riparian vegetation improves the ability of riverbanks to withstand high flows and bank erosion (Pettit et al., 2001). A recent examination of the sources of river sediments in the Mitchell River and Cloncurry River (Queensland) and Daly River (Northern Territory) determined that more than 90% of sediment transported along the main stem of rivers comes from gully and channel bank erosion (Caitcheon et al., 2012). The removal or loss of riparian vegetation exacerbates the transport of sediment, not to mention reduces shading across waterways and prevents large woody debris from reaching river channels providing habitat for aquatic fauna (Pettit and Naiman, 2005). Reduced shading increases the period of direct sunlight leading to increased water temperature and potentially increased algal productivity. At excessive levels, oxygen consuming algal blooms can contribute to fish kills and may also make water unpalatable or toxic to cattle. Further, riverbank vegetation has been shown to provide habitat and food sources for a range of animal species, and the fallen timber provides habitat structure for animals and plants (Jardine et al., 2012; Pusey and Arthington, 2003).

Two studies have examined riparian communities in the Gilbert catchment. Dowe (2004) assessed riparian communities, using the TRARC method (see Dixon et al., 2006) developed specifically for the Australian dry tropics, at 19 sites in the upper Einasleigh sub-catchment. Twenty-six tree and shrub species were recorded at these sites with *Melaleuca fluviatilis* the most common along the lower bank margins while *Eucalyptus camaldulensis* dominated higher parts of the stream bank. Brooks et al. (2008) assessed riparian vegetation extent and condition across the entire Gilbert catchment using remote sensing analysis. Those authors found an overall 19% net increase of in-channel vegetation, from 1988-2005, as well as a net increase in channel sand bar formation, which is in contrast to the adjacent Mitchell catchment where instream channel vegetation has decreased while channel sand bar formation increased but not to the extent determined in the Gilbert catchment. Factors contributing to these between catchment differences include differences in land use activities, fire management, scouring, and also differences in rainfall and base flow patterns. During the study of Brooks et al. (2008), the condition and ecological status of riparian communities were assessed using the TRARC method, at an additional 72 sites across in the upper Einasleigh catchment. As with Dowe (2008), the condition of sites was variable and the data provide a baseline condition assessment for future comparisons.

Many of the waterholes investigated had obvious impacts from stock access and there are major stream side impacts associated with extensive numbers of feral pigs (*Sus scrofa*). Providing access to river systems for cattle not only had direct water quality impacts through the addition of fecal material and nutrients, but the access tracks themselves concentrate sheet flow during rainfall and contribute high loads of sediments. Trampling vegetation and soil compaction also reduces the extent and quality of riparian vegetation. Several invasive environmental weeds were obvious at most waterholes in both catchments, including rubber vine (*Cryptostegia grandiflora*), and prickly acacia (*Acacia nilotica*). Along with invasive plants, invasive animal species including rabbits (*Oryctolagus cuniculatus*), foxes (*Vulpes vulpes*), cats (*Felis catus*) were observed.

5.5.2 AQUATIC INVERTEBRATES

Emerging evidence in north Queensland river systems show a pattern of variability in aquatic invertebrates across habitats, sites, reaches, catchments and seasons, with differences at the scale of individual waterhole habitats more evident than across catchment comparisons (Blanchette and Pearson, 2012; Leigh, 2012). This variability is thought to be related to biophysical variables (e.g. water temperature, dissolved oxygen, turbidity) and other local scale habitat patterns (e.g. riparian shading, waterhole depth, groundwater influences, and variability in flow for example riffle stretches). It is this variability at the local scale, particularly habitat scale (e.g. bottom habitat compared to vegetated edges), that contributes to the greatest differences in aquatic invertebrate assemblages. This means that sites within the same habitat are more tightly grouped together regardless of river reach or catchment (Blanchette and Pearson, 2013). Sheldon (2005) suggested that after waterholes become isolated they operate as mesocosms with assemblages reflecting the taxa present at the time of hydrological separation. During prolonged disconnection and increasing hash conditions, Sheldon (2005) predicts that assemblages become more similar as the dominance of tolerant generalists increases. However, Blanchette and Pearson (2013) present contrary data showing that both biophysical variables and aquatic invertebrate assemblages differ between dryland river waterholes, and these differences persist during periods of hydrological isolation. The reason for this divergence over time is thought to be associated with different local environmental conditions, geomorphology, aquatic assemblage (i.e. dominated by large fish or small fish), source nutrients (i.e. affected by grazing stock), groundwater and riparian shading/aspect.

The absence of significant flushing flows in either catchment during the Assessment prevented examination of the key influence of first flush events on aquatic invertebrate communities. However, some changes were able to be detected due to decreasing water levels in the dry season. Though only a six week period occurred between sampling, data from this Assessment provide some evidence of a reduction in both species richness and SIGNAL scores between the first and second surveys (see Appendix B). This is consistent with the seasonal conceptual model which predicts a decrease in water quality and habitat availability as water levels decline and instream temperature increases (Figure 3.1). Water quality in the Assessment declined during the dry season to a level that was probably becoming stressful to some invertebrate species. Receding water level during the dry season can result in a loss of habitats, especially edge habitat from waterholes and bottom pool habitats can also become smothered in sediment. As aquatic invertebrate assemblages are closely linked to habitat type, it is probable that assemblages will vary with changes in habitat diversity and persistence throughout the dry season (Blanchette and Pearson, 2013). Reductions in the biodiversity of aquatic invertebrates may have broader implications for tropical river food webs as invertebrates are important primary and secondary consumers in these systems (Bunn et al., 1997; Douglas et al., 2005). Water resource development that results in reduced flushing of waterholes and stream reaches in the wet season and/or lower dry season water levels in remnant waterholes, are likely to diminish the integrity of invertebrate communities. However, due to the drought conditions experienced during the Assessment, these processes were not fully examined. Water resource and agricultural developments can also increase turbidity and nutrient loadings to waterholes and these have been shown to have significant effects on water quality within waterholes, especially the clear waterholes located in the Gilbert catchment (see Chapter 3).

5.5.3 FISH

The relatively flat relief of the floodplain provides opportunities for fish to move overland between basins (Unmack, 2001), and probably as a result of this many fish species occur in both catchments. There was, however, a distinct difference in the fish assemblage between catchments (when examining the standardised data collected using the electrofisher). This pattern was most obvious for the fly-specked hardyhead (*Craterocephalus stercusmuscarum*) which was only recorded in the Gilbert catchment. This species is small, commonly 5 to 6 cm, and is usually captured over still or slow flowing river sections, small waterholes, through to faster flowing creeks (Pusey et al., 2004). Pusey et al. (2004) reviewed the literature on this species and draws attention to the fact that despite its widespread distribution across the Burdekin catchment, for example, this species seems to be absent from subcatchments there where turbidity is greater than 100 NTU. While all river reaches in the Flinders catchment have not been examined to confidently conclude a complete absence of this species, it is remarkable that it has not been recorded to date, yet it occurs in adjacent catchments (e.g. Norman and Gilbert catchment) with higher clarity (Burrows and Perna, 2006; EcoWise, 2007; Vallance et al., 2000). Sooty grunter (also known as black bream) also favour water of higher clarity and were common in the Gilbert catchment but rare in the Flinders catchment. Turbidity is not just a matter of presence or absence for certain species. Although the list of species found in the two catchments was similar, the assemblage of the fish communities between the Flinders (turbid waterholes) and Gilbert (clear waterholes) catchments were significantly different and the main driver, among the parameters measured, of these differences were turbidity and related water clarity variables such as euphotic depth and water light climate. As was shown for invertebrates, water clarity is a main driver of fish community assemblages and any changes in water clarity due to catchment developments can be expected to alter the fish community structure.

The total species richness of fish in both catchments during the Assessment is lower compared to previous studies (Table 5.7). This is probably a function of differences in sampling techniques used (backpack versus boat mounted electrofishing), effort (number of sites/surveys), and also that previous studies sometimes included sites lower in the catchments which contain additional estuarine-dependent species that are occasionally found in lower freshwater reaches (e.g. Diamond mullet; *Liza ordensis*). The overall fish community in both catchments appears to be consistent with expected species for the Gulf and western Cape catchments for the level of catch effort expended (number of sites surveyed).

Table 5.7 Number of sites surveyed and species found in fish surveys (excluding individual literature and museum records) in Gulf of Carpentaria and western Cape York Peninsula catchments (Burrows, 2008; Burrows and Perna, 2006; EcoWise, 2007)

REGION	CATCHMENT	NUMBER OF SITES	NUMBER OF SPECIES
Western Cape York	Holroyd River	9	34
	Jardine River	26	42
	Wenlock River	26	57
	Archer River	37	40
	Edward River	8	35
	Coleman River	11	33
Southern Gulf	Mitchell River	53	57
	Nicholson River	31	46
	Staaten River	21	42
	Norman River	18	46
	Leichhardt River	10	30
	Flinders River	19	41
	Gilbert River	20	38

5.5.4 FISH OF CONSERVATION VALUE

In general, most freshwater fish species in northern Australia have wide distributions and broad habitat tolerances. There are, however, several fish species with recognised conservation values. These are the freshwater sawfish, *Pristis pristis* and the giant freshwater whipray, *Himantura dalyensis*; note that *H. dalyensis* has recently been split from *H. chaophraya* which is recognised as endangered on the IUCN Red List.

The sawfish is listed as Vulnerable under the Commonwealth EPBC Act, Endangered on the 2000 IUCN Red List of Threatened Species and Critically Endangered in south east Asia. It has been nominated for listing as 'Vulnerable' under the Queensland Nature Conservation Act (1992). Due to their saw-shaped rostrum, sawfish are easily identified by non-experts, although there are a number of sawfish species and the taxonomy of individual species is more challenging. The freshwater sawfish is known from at least 15 rivers across northern Australia, as well as south east Asia and India (Peverell, 2005; Thorburn et al., 2003).

The freshwater sawfish is the most freshwater adapted of the sawfish species and may even be able to breed in freshwater (Pogonoski et al., 2002). Although often caught in estuaries, only a few specimens are reported from offshore areas. Freshwater sawfish can grow up to 7m in length, though Australian specimens are usually only up to 2 m long (Last and Stevens, 1994). Freshwater sawfish may occur up to 500 km upstream from the river mouth (e.g. Lynd River, Mitchell catchment, Queensland; (Allen et al., 2002). Given their length and the saw-shaped rostrum, it is unlikely that sawfish would be able to negotiate instream passage barriers. However, given that they are common in both freshwaters and estuaries and are found long distances upstream, movements between those environments may be important and any passage barriers could reduce available habitat to complete lifecycle stages. Being large predators, they may also be subject to declining habitat condition and affected by droughts or reduced waterhole size. Relatively little is known of their biology or habitat requirements, though they are known to feed on benthic animals such as crustaceans and molluscs and also upon fish. Because of their large size and slow reproductive rate, populations will recover more slowly than other fish species (Pogonoski et al., 2002).

All sawfish species are susceptible to fishing pressures being targeted for their rostrum and getting caught in nets and line fishing. They are caught in the commercial bycatch of the Gulf of Carpentaria and northeast Queensland, the Northern Territory shark fishery and in beach protective shark nets in the Qld Shark Control Program (Pogonoski et al., 2002). Stobutski et al. (2000) considered the bycatch of sawfishes in the northern prawn trawl fishery (but not including the freshwater sawfish) as least likely to be sustainable, due to their benthic nature making them more susceptible to capture. All known populations of freshwater sawfish and indeed all sawfish species worldwide have undergone serious population declines (Pogonoski et al., 2002). Research into this species has been ongoing with a management plan prepared recently (SEWPaC, 2012b).

The giant freshwater whipray is also poorly known, only being recognised as present in Australian freshwaters in 1989 (Taniuchi et al., 1991). Prior to that, all long-tailed sting rays from tropical Australian freshwaters were incorrectly referred to as an estuarine sting ray species (Last and Stevens, 1994; Thorburn et al., 2003). The giant freshwater whipray can grow up to 2 m disc width and weigh up to 600 kg, although the largest recorded Australian specimen was 1 m disc width and 120 kg (Last, 2002). In Australia, it is known from the Daly, Alligator and Roper rivers (Northern Territory), the Pentecost and Ord, Fitzroy and Pentecost rivers (Western Australia) and the Flinders, Gilbert, Mitchell, Wenlock and Normanby rivers in Queensland (Peverell et al., 2005; Thorburn et al., 2003), but as it also occurs in Papua New Guinea and south east Asia, so it may, with further survey, be found in more northern Australian rivers (Pogonoski et al., 2002). Like the freshwater sawfish, this species is vulnerable to fishing as prey and bycatch, drought and fish passage barriers.

The known distribution of both the freshwater sawfish and the giant freshwater whipray in the Flinders and Gilbert rivers is drawn from only a few studies and reliable sources (Figure 5.7). Both species have been recorded higher upstream along the Flinders River, compared to the Gilbert River, though their distribution is poorly known in both catchments and is undoubtedly much broader than is represented here. Both species are rarely caught using standard fish survey techniques and specialist techniques are required.

Given their conservation status, vulnerability to fish passage barriers and poorly known distribution and ecology, specific dedicated studies of these species are required before any large-scale development occurs. These studies should utilise methods and approaches specifically targeting these two species.

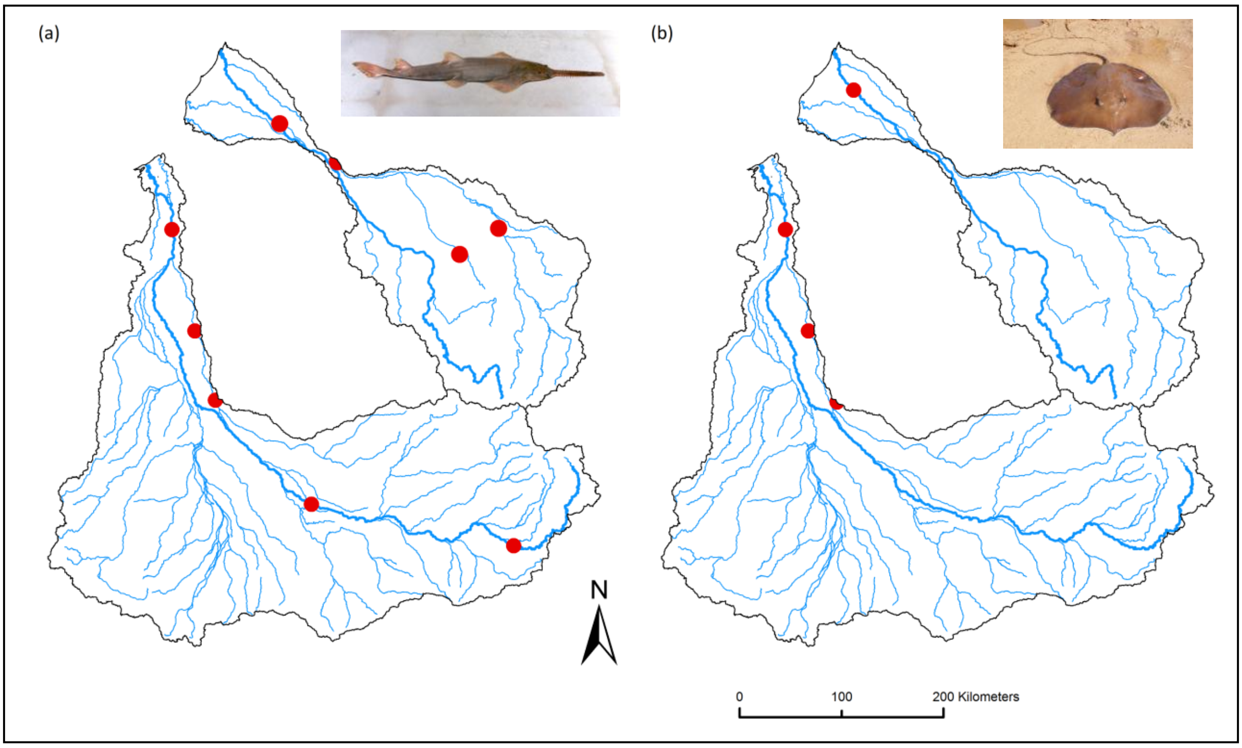


Figure 5.7 Captures or sightings across the Flinders and Gilbert catchments (from Table 5.6 and discussion with community). (a) freshwater sawfish (*Pristis pristis*), photo sourced S. Peverell; b) freshwater whipray (*Himantura dalyensis*), photo sourced B. Pusey

Exotic and translocated native fish

Only a few records exist for exotic fish species in the Gulf of Carpentaria catchments. Guppies (*Poecilia reticulata*) are common in the upper Mitchell River (Ryan et al., 2002), mosquitofish (*Gambusia holbrooki*) have been recorded in the Flinders and Gregory-Nicholson system (Burrows, 2008), though they are not common, and the Queensland Museum has a 1914 record of a goldfish (*Carassius auratus*) in the Norman River, though this species did not establish there.

Even the intentional release of native Australian fish species to new areas can have consequences similar to those arising from the introduction of fishes from other countries (Burrows, 2004b; Pusey et al., 2006). Fish stocking is common in impoundments in Queensland (Hollaway and Hamlyn, 2001; Moore, 2007), and is regulated by Queensland fisheries authorities under the Fisheries Act (1994), and the Fisheries (Freshwater) Management Plan (1999). Several water storage facilities in the Flinders catchment have been stocked with local freshwater fish species in an attempt to create a local fishery and for tourism. For example, Lake Fred Tritton in Richmond as well as Lake Corella and Chinaman Creek Dam near Cloncurry have been stocked with barramundi and sooty grunter and this may have extended the range of each species within this catchment. No such stocking has occurred in the Gilbert catchment, although stocking has been proposed for Kidston Dam (Vallance et al., 2000).

5.5.5 OTHER AQUATIC FAUNA

Along with fish, the waterholes within the Flinders and Gilbert catchments provide important refugia for a range of other aquatic birds, reptiles and amphibians (Rollason and Howell, 2010). As part of the AquaBAMM values workshop held by Queensland Government, a panel of freshwater flora and fauna experts was formed to identify priority fauna species requiring protection and conservation across the southern Gulf catchments (Rollason and Howell, 2010). Among the extensive list of aquatic fauna known to occur across the region, the species considered most vulnerable to habitat (water and terrestrial land) loss included: magpie goose (*Anseranas semipalmata*), sharp-tailed sandpiper (*Calidris acuminate*), red knot (*Calidris canutus*), red-necked stint (*Calidris ruficollis*), great knot (*Calidris tenuirostris*), sarus crane (*Grus antigone*), brolga (*Grus rubicunda*), black-tailed godwit (*Limosa limosa*), little curlew (*Numenius minutus*), desert shovelfoot (*Notaden nichollsi*), freshwater whipray (*Himantura dalyensis*), nurseryfish (*Kurtus gulliveri*), papuan sprat (*Clupeoides sp. cf. papuensis*, Gilbert's grunter (*Pingalla gilberti*), Flinders River catfish sp. (*Porochilus sp*. Flinders), blueback blue eye (*Pseudomugil cyanodorsalis*) and delicate blue eye (*Pseudomugil tenellus*).

Freshwater turtles

Freshwater turtles are an important component of the freshwater fauna in northern Australia. Research over the last ten years has uncovered that Australia has a number of unique, highly aquatic, long-lived freshwater turtle species that are particularly abundant in some regions. Conservation of freshwater turtles is challenging for managers given the paucity of data available when making decisions relating to new developments. Many turtle species place their nests in sand and gravel beds adjacent to main river channels, and hatchling emergence is timed to coincide with benign flow conditions. Fluctuating water levels as a result of water resource developments can inundate or cause egg mortality (Cann, 1998). Further, recent studies have shown that flow regimes affect turtle diets. Tucker et al. (2012) found turtles living within flowing rivers have different, and narrower diets (depleted of aquatic plants and aquatic invertebrates) than the same species collected from nearby impoundments.

The distribution and extent of freshwater turtles within the Flinders and Gilbert catchments is not known. Discussions with experts in this field suggest that 5 species are likely to occur, including yellow-faced turtle (*Emydura tanybaraga*), diamond-headed turtle (*Emydura subglobosa worrelli*), saw-shelled turtle (*Wollumbinia latisternum*), Cann's long-necked turtle (*Chelodina canni*), and northern long-necked turtle (*Macrochelodina rugosa*) (J. Schaffer, TropWATER, James Cook University, Pers. Comm., 2013). During the Assessment, a single saw-shelled turtle was captured in Elizabeth Creek, Einasleigh River catchment (Figure 5.8). The local community report that this species is widespread in this section of the catchment, and upstream to the Lynd. No freshwater turtles were observed or captured in the Flinders catchment during the Assessment, though *E. subglobosa worrelli* is known to occur at least in the Dugald River, a tributary of the Cloncurry River (TropWATER, James Cook University, unpublished data).

Figure 5.8 Saw-shelled turtle captured in Elizabeth Creek, Gilbert catchment

Instream frogs

Thirty species of frogs have been recorded in the Flinders catchment and 30 species have been recorded in the Gilbert catchment (

Table 5.8). Range maps indicate that a couple more species may be present within the Assessment area (Vanderduys, 2012). Most are generalist species, with non-specific requirements in terms of breeding and general habitat. Many are especially common along watercourses in the Flinders catchment, but not entirely dependent on the riverine system (i.e. they are able to breed and survive in natural and artificial waterbodies such as dams, springs, soaks and seasonally inundated clay pans; E. Vanderduys, CSIRO, Pers. Comm., 2013). A few species are burrowing frogs and are generally restricted to areas with sandy substrates. These species rarely breed in river courses, preferring temporary water bodies such as flooded clay pans (Long et al., 1995). The sandstone frog (*Litoria coplandi*) is exceptional in that it is restricted to rocky waterholes and outcrops adjacent to permanent water (Long et al., 1995). In the Flinders catchment, this species has a very restricted distribution in the vicinity of Kynuna. The exotic cane toad (*Rhinella marina)* is widespread through the region and poses a major conservation management challenge. Cane toad populations increase when access to water increases, and their spread and survival is strongly aided by artificial waterpoints in the seasonally dry tropics (Rollason and Howell, 2010). Their population can increase quickly around the margins of dams after construction (E. Vanderduys, CSIRO, Pers. Comm., 2013). This species has become a considerable ecological problem elsewhere in northern Australia (Doody et al., 2006; Urban et al., 2008).

Table 5.8 Instream frog species in Flinders catchment (data from E. Vanderduys with permission, CSIRO 2013)

FAMILY	COMMON NAME	SPECIES	CATCHMENT
Bufonidae	Cane toad	*Rhinella marina*	F, G
Hylidae	Greenstripe Frog	*Litoria alboguttata*	F, G
	Northern sedgefrog	*Litoria australis*	F
	Superb collared frog	*Litoria bicolor*	F, G
	Northern sedgefrog	*Litoria brevipes*	F, G
	Common green treefrog	*Litoria caerulea*	F, G
	Sandstone frog	*Litoria coplandi*	F
	Earless frog	*Litoria cryptotis*	F
	Grassland collared frog	*Litoria cultripes*	F
	Northern waterfrog	*Litoria dahlii*	F, G
	Buzzing treefrog	*Litoria electrica*	F, G
	Eastern sedgefrog	*Litoria fallax*	G
	Graceful treefrog	*Litoria gracilenta*	F, G
	Bumpy rocketfrog	*Litoria inermis*	F, G
	Broad-palmed rocketfrog	*Litoria latopalmata*	F, G
	Little collared frog	*Litoria manya*	G
	Striped rocketfrog	*Litoria nasuta*	G
	Eastern snapping frog	*Litoria novaehollandiae*	F, G
	Pallid rocketfrog	*Litoria pallida*	F, G
	Northern laughing treefrog	*Litoria rothii*	F, G
	Ruddy treefrog	*Litoria rubella*	F, G
	Black-shinned rocketfrog	*Litoria tornieri*	G
Limnodynastidae	Marbled frog	*Limnodynastes convexiusculus*	F
	Spotted grassfrog	*Limnodynastes tasmaniensis*	F, G
	Scarlet sided pobblebonk	*Limnodynastes terraereginae*	F, G
	Brown shovelfoot	*Notaden melanoscaphus*	F, G
	Desert shovelfoot	*Notaden nichollsi*	F
	Ornate burrowing frog	*Platyplectrum ornatum*	F, G
Myobatrachidae	Chirping froglet	*Crinia deserticola*	F, G
	Northern froglet	*Crinia remota*	F, G
		Crinia sp	F
	Great brown broodfrog	*Pseudophryne major*	F
	Stonemason gungan	*Uperoleia lithomoda*	F, G
	Einasleigh gungan	*Uperoleia littlejohni*	F, G
	Mimicking gungan	*Uperoleia mimula*	F
	Chubby gungan	*Uperoleia rugosa*	G
	Orange shouldered gungan	*Uperoleia trachyderma*	F
		Uperoleia sp	G

Freshwater crabs

Freshwater crabs (Parathelphusidae) are another important, but understudied fauna present in both catchments (Figure 5.9). These crabs are highly adapted to deal with the ephemeral nature of streams, digging holes into streambanks in search of the watertable. Their survival is particularly vulnerable in situations where flow modification creates longer dry seasons or lowers the watertable such that crabs need to dig much deeper burrows. Many crab species have low fecundity with no real dispersal stage during reproduction, which means that river reach populations are more likely to be isolated (Yeo et al., 2007). In addition, many reptiles are thought to predate on freshwater crabs, including lizards and snakes, along with invasive species such as feral pigs (*Sus scrofa*). Damage by feral pigs to waterhole banks in the Gilbert catchment, presumably in search for crabs, was noted in the current investigation.

a)  b) 

Figure 5.9 Example of inland freshwater crab (*Austrothelphusa transversa*) and exoskeleton from a moulting crab found in dry river channel in Flinders catchment

Freshwater crocodiles

Crocodiles are a feature of the waterways and coastal regions of tropical Australia. The freshwater crocodile (*Crocodylus johnsoni*) is resident in the both the Flinders and Gilbert catchments and was observed in many of the waterholes investigated in the Assessment. However, their full distribution is not known. The local community suggest that the number of freshwater crocodiles near Mount Surprise and the Lynd junction region has increased in recent years, with individual crocodiles reaching approximately 3 m in length. The estuarine crocodile (*Crocodylus porosus*) is resident in lower reaches of the catchments, although they are also known to migrate into freshwater regions. Their upstream extent is not known. There is little information available on the implications of flow alteration on crocodile populations.

6 Nutrient, sediment and pesticide loads

6.1 Summary points

- Quantitative modelling shows that agricultural development has the potential to elevate sediment, nutrient and pesticide inputs into streams of the Assessment area;
- Delivery of large sediment loads to adjacent waters are predicted in cotton cropping when stubble retention and minimum tillage practices are not employed;
- Similar to sediments, large phosphorus, nitrogen and herbicide loads to adjacent waters are predicted from sugarcane with a potential yield management approach in which water, nutrients and pesticides are supplied to guarantee nutrient limitation and pest damage does not occur;
- For rice, pesticide losses are also potentially substantial but the lack of data about the likely management practices and usage rates precludes a reliable estimate of these losses;
- Cotton losses of pesticides are predicted to be low as both BT cotton and glyphosate resistant cotton use is planned, hence reducing herbicide and insecticide use;
- Increases in sediment, nutrients and pesticides loadings have serious negative implications for aquatic receiving environments including rivers, estuary and coastal systems;
- Adoption of best management practices and other recently-introduced means of reducing chemical losses from agriculture, however, make a significant difference to ecological outcomes.

6.2 Introduction

The proposed development includes introduction of new dams, irrigation channels and roads. Decisions about what, where and how agriculture is produced (e.g. beef vs. rice, high vs. low soil quality, efficient vs. potential yield approaches) will affect downstream environmental values. Globally, the benefits of agricultural development also accrue environmental costs. In other tropical systems, deleterious changes to water quality have been observed consequent to agricultural development. While the benefits of agricultural development are obvious, the potential for negative effects upon downstream ecosystems such as freshwater wetlands, mangroves, seagrass meadows and coral reefs must be afforded equal importance.

Along the eastern coast of Queensland, introduction of agriculture has increased concentrations of suspended sediments and nutrients, resulting in eutrophic freshwater, estuarine and marine ecosystems (Brodie and Mitchell, 2005). Eutrophication occurs when nutrients, especially nitrogen and phosphorus, are supplied to water bodies in excess of natural input levels, or in unnatural ratios, resulting in changes to ecosystem functioning.

Elements including nitrogen and phosphorus, in conjunction with light, are the building blocks for primary production in most waterways, driving production of bacteria and microalgae that become the biotic basis of the aquatic food chain (Bunn et al., 1997; Jardine et al., 2012). Disruptions in the supply of elemental nutrients disturb the balance between aquatic primary and higher levels of production. Large or prolonged disruptions can make conditions difficult or intolerable for native aquatic species.

More than half of the global change in the nitrogen cycle comes from increased reliance on synthetic inorganic fertilisers (Vitousek et al., 1997). Nitrogen inputs to tropical marine systems are likely to persist longer and have greater impact than in temperate systems (Downing et al., 1999). Global phosphorus fluxes are dominated by P transported in eroded material and wastewater from land to oceans; the size of these fluxes approximates the amount of phosphorus fertiliser applied to agricultural land annually (Howarth et al., 2002).

Little information is available describing the current or historical water quality of the Flinders and Gilbert Rivers, associated estuaries and coastal areas. The mouth of the river enters the Gulf of Carpentaria and lies in the Important Bird Area (BirdLife International, 2011) – see Chapter 2. The condition of surface water and groundwater is not routinely monitored in the Flinders River catchment (ANRA, 2009; DERM, 2012). The National Water Quality Assessment (SKM, 2011) reports that of 26 monitored sites, only one met data requirements, and water quality at this site was fair to good.

Little high-quality information is available on water quality of the Gilbert River or its tributaries (Butler and Burrows, 2005). The National Water Quality Assessment (SKM, 2011) recently reported monitoring results from thirteen sites, of which two met data requirements. Results indicate 'good' turbidity, 'fair' conductivity and 'poor' pH levels, but nutrient data were insufficient to report upon (SKM, 2011). Given the poor understanding of the basin's surface water quality, it is impossible to make a confident assessment of general condition (Bloedel et al., 2000; Butler and Burrows, 2005).

Increased nutrient inputs and consequent stimulation of primary productivity in estuaries can increase the supply of organic matter to sediments, elevating benthic metabolism and nutrient release, and exacerbating oxygen depletion (hypoxia) rates (Smith et al., 2012). Hypoxia influences biogeochemical controls on water column nutrient concentrations, and is more common where tidal flushing is reduced (Burford et al., 2008). Nutrient loading in north Australian tropical tidal creeks affects biogeochemical processes of denitrification, benthic nutrient fluxes and pelagic primary production (Smith et al., 2012). In creeks with poor flushing, nutrient loading can create hypoxic conditions and significant changes to ecosystem functioning (Smith et al., 2012).

Eutrophication associated with human activity, including changes in salinity but especially increases in phosphorus has resulted in a global increase in harmful algal blooms (O'Neil et al., 2012). Ganf and Rea (2007) report that several rivers in the Northern Territory may have a medium to high hazard potential for developing blue-green algal blooms if they become exposed to the reduced flows and increased nutrient run-off associated with irrigated agriculture.

Problematic cyanobacteria most common to tropical Australian marine waters are *Lyngbya majuscula* and *Trichodesmium* spp. Marine blooms of *Lyngbya majuscula* are increasing in Australia and elsewhere (Capper and Paul, 2008; Osborne et al., 2007; Watkinson et al., 2005). Although most Australian blooms are recorded on the south eastern coast of Queensland, recent reports show that blooms are occurring regularly in Darwin during the dry season (Drewry et al., 2010) and in Broome in the wet season (Estrella et al., 2011).

The blue-green alga *Trichodesmium* spp. form seasonal surface blooms thousands of kilometres wide in nutrient-poor tropical and subtropical regions characterised by clear waters and deep light penetration (Capone et al., 1997; Rubin et al., 2011; Sellner, 1997). *Trichodesmium* spp. is found in the Atlantic, Pacific and Indian Oceans, the Caribbean and South China Seas and all of Australia's northern waters (Capone et al., 1997; Hallegraeff and Jeffrey, 1984). *Trichodesmium erythraeum* and *T. thiebautii* are the most common species in oceanic blooms (Sellner, 1997). These species are most commonly associated with a range of negative effects, however, the degree to which the effects are toxic or that which contribute to poor water quality is unclear (Landsberg, 2002). Additionally, nitrogen fixation by *Trichodesmium* spp. is critical to the global nitrogen and carbon cycles (Capone et al., 1997; Karl et al., 2002).

The marine and estuarine receiving areas for the Flinders and Gilbert catchment supports rich coastal fisheries, including the Northern Prawn Fishery, recreational barramundi and mud crab fisheries (Balston, 2009; Davis, 1985; Dichmont et al., 2003; Hill, 1994; Knuckey, 1996; van Dam et al., 2008), and dugong and sea turtle seagrass foraging grounds (Kennett et al., 2004; Marsh et al., 2008; Moriarty and O'Donohue, 1993; Poiner et al., 1987; Pollard and Moriarty, 1991). The density and functional richness of reef fish in the Gulf of Carpentaria is among the highest in the world, approaching that of Galapagos Islands (Stuart-Smith et al., 2013).

Previous agricultural irrigation developments in tropical Australia have been associated with decreased river and offshore water quality (Brodie et al., 2010; Brodie et al., 2013; Lewis et al., 2009). These reductions in water quality are directly related to the removal of pre-existing ground cover and the application of fertilisers and pesticides. Fertiliser and pesticide applications are in part absorbed and used by crops, however, during rain events quantities of nutrients and pesticides, as well as exposed soils, are washed into adjacent rivers. River flows spread out and slow down as they reach downstream river, estuary and coastal receiving areas. Downstream receiving areas effectively collect this material carried in agricultural runoff. Some of these downstream habitats (e.g. coral reefs, mangrove wetlands) can be sensitive to increased levels of sediments, nutrients and pesticides in agricultural runoff.

Offshore and onshore blooms of *Trichodesmium* spp. have been shown to suppress larval prawn survival in the Gulf of Carpentaria (Preston et al., 1998). Prawn fisheries are sensitive to suspended sediment (Somers, 1987), changes in river discharge and regulation are likely to have substantial effects on coastal fisheries (Loneragan and Bunn, 1999), and flow-related wetland and estuary degradation can reduce barramundi catch (Balston, 2009). Changes to nutrient and light availability (e.g. algal blooms, turbidity) can cause seagrass decline (Waycott et al., 2005) and coral reef degradation (Bartley et al., 2014; De'ath and Fabricius, 2010; Fabricius et al., 2005; Wooldridge, 2009).

This chapter examines the loss of sediments, nutrients and pesticides from cropping lands resulting from the proposed agricultural development for the Flinders and Gilbert catchments. Six crop types including irrigated fodder, cotton, sorghum, aerobic rice, sugarcane, and guar which are proposed as part of the Assessment are focused upon.

6.3 Methods

6.3.1 EXPORT COEFFICIENT MODEL

Potential pollutant loads transported to the end of the catchment were estimated using the Export Coefficient Model (ECM) (Johnes, 1996). The Export Coefficient Model is a simple empirical model that uses sediment and nutrient generation rates and land use to infer export loads (Letcher et al., 1999). It is suitable for assessing and comparing the effects of catchment management options on coarse changes in export loads, rather than detailed process modeling of transport and transformation (Schofield et al., 2007). As such, the model is well-suited as an initial planning tool, but is not particularly accurate (Letcher et al., 1999). The ECM process requires three main inputs: 1) land use; 2) export coefficients for each potential contaminant under each land use type; and 3) nutrient and pesticide application rates. Information on the effect of land management practices on export coefficients is optional. The ECM applies Equation 1 to predict average annual loads (kg/y):

$$L_{ijk} = \sum_{i=1}^{n} E_{ijk}[A_i\,(I_{ijk})] \qquad (1)$$

Where:

L_{ijk} = load of potential contaminant i from land use type j under management approach k (kg/y)

E_{ijk} = export coefficient for potential contaminant i on land use j under management approach k (kg/ha/y)

A_i = area occupied by land use type i (ha)

I_{ijk} = application rate of potential contaminant i on land use type j under management approach k (kg/ha)

TSS was calculated as shown in Equation 2:

$$L_{ijk} = A_i * E_{ij} \quad (2)$$

A number of assumptions are required to support this model.

Assumption 1

Grazing comprises approximately 98% of the current land use in the Assessment area and thus is assumed to provide an adequate representation of land use impacts to river water quality. To this effect, Table 6.3 shows that no land uses other than grazing are accounted for in the baseline scenario.

Assumption 2

Land uses other than grazing make no significant contribution to nutrient, sediment and pesticide export loads. That is, land within the Assessment area which currently supports peanuts, cotton, conservation, horticulture or any land use other than grazing is not considered in baseline scenario models.

Assumption 3

The location of the converted land has no influence upon generation rates. In reality this assumption will be violated however due to a lack of reliable data and high uncertainty around the nature of proposed development, this assumption is necessary and was maintained throughout all model runs.

Assumption 4

The effects of previous land use do not affect nutrient export loads. Converting grassland or permanent pasture to cultivated land can release substantial amounts of soil nitrogen in the first year, with releases declining over the period of about a decade (Worrall and Burt, 1999). Peak loads during the initial decade are not calculated here.

Assumption 5

Transport and transformation processes do not affect export load estimates. The model is not spatially explicit. The influence of geomorphological, hydrological and biogeochemical processes upon the breakdown, complexation, and movement of sediments, nutrients and pesticides between environmental phases of the air, soil, river and sea is not considered in the model. Importantly, this includes processes of reservoir trapping, overbank flow and floodplain trapping.

6.3.2 SCENARIO STRUCTURE

Scenarios examined in the modelling analysis are detailed below in Table 6.3 and Table 6.4. The storylines describe significant potential change in one or more of three major factors: 1) land use type; 2) area of land use; and 3) agricultural management approach. Change in any single one of these factors can influence the water quality of downstream receiving areas. Change across all three is extremely likely to invoke ecosystem change, thus close examination of potential water quality change is warranted, although may present significant analytical challenges.

To simplify the analysis to a level befitting the current paucity of knowledge in this region, the three elements of the storylines of most relevance to water quality change were framed as simple scenarios for subsequent parameterisation and modelling. The model was used to estimate the potential load of suspended sediment, nitrogen, phosphorus and pesticide delivered to the Flinders and Gilbert Rivers as a result of proposed agricultural developments. Three major scenario types were created: 1) baseline scenarios; 2) reference scenarios; and 3) development scenarios as shown in Table 6.3 and

Table 6.4 respectively.

Baseline scenarios provide an estimate of the contribution of current land use to river sediment and nutrient loads. Reference scenarios provide standardised load estimates for theoretical land use areas that are consistent across each combination of land use type and management regime. With the exception of irrigated fodder, which has no variation in management approach, each crop type in each catchment is modelled under at least four different scenarios.

6.3.3 MODEL PARAMETERS

Data on fertiliser and pesticide usage and loss (i.e. generation) rates under each proposed land use scenario were collected from the scientific literature, informal expert interviews and publicly available databases. Information was also collected on the relationships between nutrient, sediment and pesticide runoff losses and land management approaches in comparative systems.

Management approaches

Long term, large-scale irrigated cropping has never occurred in the Assessment Area, for any of the proposed land uses modeled here. Consequently, accurate and reliable data on fertiliser and pesticide application rates, cropping intensity, tillage practices and timing of crop cycles are simply not available. In order to generate initial, plausible, estimates of the range of nutrient, sediment and pesticide loads which may be introduced to downstream water bodies via agricultural activity, proxy data were required. Information on management decisions relevant to the ECM, were based on data from other tropical agricultural areas; namely the Burdekin, Ord, and Emerald Irrigation Areas. The assignation of proxy data to a model scenario was made on the basis of the published literature and expert advice.

Where possible, information on different management approaches was included in model estimates. Two types of management approaches were used; an efficiency and a potential yield approach to agricultural management. Efficiency approaches assume that costs-efficiency is a primary goal of farm management; nutrient and pesticide supply is matched to meet but not exceed crop demand, and topsoil is retained. These practices can lower sediment, nutrient and pesticide runoff. Potential yield approaches assume that yield maximisation is a primary goal of farm management: water, nutrients and pesticides are supplied to guarantee nutrient limitation and pest damage does not occur (van Ittersum and Rabbinge, 1997).

It is expected that further research and development to identify optimal management practices will take place prior to implementation in the Gulf catchments. The additional information provided from such developments should be used to improve the model results presented here.

Application rates

River loads are developed in the ECM as a direct function of fertiliser and pesticide application rates. Information on likely fertiliser and pesticide application rates was sourced from the published literature and discussions with agronomists and growers.

Export coefficients

Export coefficients, also known as generation rates or runoff coefficients, represent the average total amount of pollutant loaded annually into a system from a defined area, and are reported as mass of pollutant exported per unit area per year (e.g. kg/ha/yr) (Lin, 2004). The ECM model multiplies application rates per unit area with export coefficients to determine annual loads. A study of the currently available Australian literature identified definitive data for nutrient export coefficients from proposed land uses under conditions similar to those expected for the Assessment Area. The literature search demonstrated that in general, as previously stated elsewhere (Bartley et al., 2012), “There is also minimal or insufficient data for land uses such as horticulture, cotton and other high intensity crops such as bananas, particularly for large plot/catchment scales”. Given the relative influence of high intensity and large-scale agricultural development on export loads in other areas of northern Queensland (Bartley et al., 2012; Brodie et al., 2009; Brodie et al., 2012), this is a significant concern.

Baseline scenarios

The Gilbert and Flinders River basins have been used for grazing for at least 100 years. In 1889 there were 4.6 million cattle in Queensland, 50% of the national total (Coghlan, 1890). Little is known about pre-settlement or current water quality in the Gulf catchments (Butler and Burrows, 2005; SKM, 2011). The baseline scenario estimates the contribution of the current land use (i.e. grazing) to suspended sediment, nutrient and pesticide river loads. Grazing comprises approximately 98% of the land used in the Northern Gulf Natural Resource Management Region . The Northern Gulf Natural Resource Management Region provides a reasonable estimate of current land use in the Assessment area. Little information is available about current management approaches used in grazing, so different management approaches were not modelled for the baseline scenario. Table 6.2 shows that grazing comprises 98% of the land in the Northern Gulf NRM Region. Consequently, grazing is the only land use modelled in the Flinders Baseline Scenario (FBS) and the Gilbert Baseline Scenario (GBS).

Table 6.1 Baseline water quality scenarios modelled for the Assessment area

LAND USE	CATCHMENT	AREA (HA)	SCENARIO
Grazing	Flinders	10,951,640[1]	FBS
	Gilbert	4,640,680[2]	GBS

Source: 1 = http://wetlandinfo.ehp.qld.gov.au/wetlands/facts-maps/basin- flinders/; 2 = http://wetlandinfo.ehp.qld.gov.au/wetlands/facts-maps/basin- gilbert/

Table 6.2 The relative proportion of the major land uses in the Northern Gulf NRM region 2010-11

LAND USE	AREA (HA)	NUMBER	%
Meat cattle	-	933,284	-
Other livestock	-	8755	-
Grazing on other land	12,078,337	-	86.5
Grazing on improved pastures	1,548,320	-	11.1
Conservation	333,889	-	2.4
Orchard fruit and nut trees	4195	-	< 0.05
Hay and silage	1347	-	< 0.05
Pasture cut for hay	1261	-	< 0.05
Pasture seed production	233	-	< 0.05
Sorghum	205	-	< 0.05
Peanuts	21	-	< 0.05
Total	13,967,808		100

Source: (ABS, 2012)

Reference and development scenarios

With the exception of irrigated fodder, each crop type in each catchment is modelled under at least four development scenarios, some of which are the same as reference scenarios. In Table 6.3 and

Table 6.4 each scenario has been labelled using the naming convention to indicate the catchment, scenario type (B = baseline scenario; RS = reference scenario; DS = development scenario), proposed land use type (IF = irrigated fodder; C = cotton; S = sorghum; AR = aerobic rice; SC = sugarcane; G = guar), management approach (E = efficiency; P = potential; EA/EB = efficiency approach, Class A/Class B; PC/PD = potential approach Class C/Class D) and the size of land use area in thousands of hectares. Thus, reference scenarios will always end in -10 or -20.

Table 6.3 Reference water quality scenarios modelled for the Assessment Area. Classes A – D (shown in Table 6.12)

LAND USE	CATCHMENT	APPROACH	AREA (HA)	SCENARIO
Irrigated fodder	Flinders	n/a	10,000	F-RS-IF-10
			20,000	F-RS-IF-20
	Gilbert	n/a	10,000	G-RS-IF-10
			20,000	G-RS-IF-20
Cotton	Flinders	Efficiency	10,000	F-RS-C-E-10
			20,000	F-RS-C-E-20
		Potential	10,000	F-RS-C-P-10
			20,000	F-RS-C-P-20
	Gilbert	Efficiency	10,000	G-RS-C-E-10
			20,000	G-RS-C-E-20
		Potential	10,000	G-RS-C-P-10
			20,000	G-RS-C-P-20
Sorghum	Flinders	Efficiency	10,000	F-RS-S-E-10
			20,000	F-RS-S-E-20
		Potential	10,000	F-RS-S-P-10
			20,000	F-RS-S-P-20
	Gilbert	Efficiency	10,000	G-RS-S-E-10
			20,000	G-RS-S-E-20
		Potential	10,000	G-RS-S-P-10
			20,000	G-RS-S-P-20
Aerobic rice	Flinders	Efficiency	10,000	F-RS-AR-E-10
			20,000	F-RS-AR-E-20
		Potential	10,000	F-RS-AR-P-10
			20,000	F-RS-AR-P-20
Sugarcane	Gilbert	Efficiency Class A	10,000	G-RS-SC-EA-10
		Efficiency Class B	10,000	G-RS-SC-EB-10
		Potential Class C	10,000	G-RS-SC-EC-10
		Potential Class D	10,000	G-RS-SC-ED-10
		Efficiency Class A	20,000	G-RS-SC-PA-20
		Efficiency Class B	20,000	G-RS-SC-PB-20
		Potential Class C	20,000	G-RS-SC-PC-20
		Potential Class D	20,000	G-RS-SC-PD-20
Guar	Gilbert	n/a	10,000	G-RS-G-10
			20,000	G-RS-G-20

Source: n/a = not applicable

Table 6.4 Development water quality scenarios modelled for the Assessment area

LAND USE	CATCHMENT	APPROACH	AREA (HA)	SCENARIO
Irrigated fodder	Flinders	n/a	10,000	F-DS-IF-10
			20,000	F-DS-IF-20
	Gilbert	n/a	1500	G-DS-IF-1.5
			3000	G-DS-IF-3
Cotton	Flinders	Efficiency	10,000	F-DS-C-E-10
			20,000	F-DS-C-E-20
		Potential	10,000	F-DS-C-P-10
			20,000	F-DS-C-P-20
	Gilbert	Efficiency	10,000	G-DS-C-E-10
			20,000	G-DS-C-E-20
		Potential	10,000	G-DS-C-P-10
			20,000	G-DS-C-P-20
Sorghum	Flinders	Efficiency	10,000	F-DS-S-E-10
			40,000	F-DS-S-E-40
			10,000	F-DS-S-P-10
			40,000	F-DS-S-P-40
	Gilbert	Potential	10,000	G-DS-S-E-10
			40,000	G-DS-S-E-40
			10,000	G-DS-S-P-10
			40,000	G-DS-S-P-40
Aerobic rice	Flinders	Efficiency	5000	F-DS-AR-E-5
			10,000	F-DS-AR-E-10
		Potential	5000	F-DS- AR-P-5
			10,000	F-DS- AR-P-10
Sugarcane	Gilbert	Efficiency Class A	20,000	G-DS-SC-EA-20
		Efficiency Class B	20,000	G-DS-SC-EB-20
		Potential Class C	20,000	G-DS-SC-EC-20
		Potential Class D	20,000	G-DS-SC-ED-20
		Efficiency Class A	50,000	G-DS-SC-PA-50
		Efficiency Class B	50,000	G-DS-SC-PB-50
		Potential Class C	50,000	G-DS-SC-PC-50
		Potential Class D	50,000	G-DS-SC-PD-50
Guar	Gilbert	n/a	20,000	G-DS-G-20
			50,000	G-DS-G-50

Source: n/a = not applicable

Flinders development scenarios

Irrigated fodder

An estimated 10,000 to 20,000 hectares of land is planted for irrigated fodder in the Flinders River catchment. Modeling was undertaken according to the following assumptions:

- Planting along riverbank only;
- Permanent crop, with no replanting;
- Expect minimal change in runoff over life of land use (4-5 years);
- Planting is done in the dry season to have grass stubble by the wet season;
- No cultivation in middle of the wet season;
- Grassed by late December to prevent erosion; and
- Use of overhead irrigation.

The application rate and management regimes used in the mode are presented in Table 6.5.

Table 6.5 Irrigated fodder management approaches for the Flinders catchment

STAGE	IRRIGATION	FERTILISER[1]	HERBICIDE
Pre-plant	Overhead	90 kg N/ha as urea 150 k P/ha muriate of potash	200 g/kg tebuthiuron @ 0.5 g/m^2
Planting		35 kg N/ha 25 kg P/ha	
Pre-harvest		90 kg N/ha as urea fertigation	
Post-harvest[1,2]		90 kg N/ha of urea	

Source: 1 = O'Gara et al., (2003); 2 = fertiliser is applied after each harvest, with four harvests per year

Cotton

An estimated 10,000 to 20,000 hectares of land is planted for cotton in the Flinders River catchment. Modeling was undertaken according to the following assumptions:

- Planting is undertaken in from mid-December to mid-January;
- All crops use Roundup Ready Flex®/Bollgard II® genetically modified (GM) cotton;
- Furrow irrigation is used when targeting potential yield, overhead irrigation is used when targeting efficient yields;
- No-till or conservation tillage is used when targeting efficient yields;
- Nitrogen is always provided in-crop prior to flowering (25 to 45 days after sowing) in splits as Easy-N. ENTEC urea is used at sowing only and on clays only;
- Only glyphosate herbicides are used, and these are only early in crop cycle (January-February) as per label for Titan Cotton and Dry Glyphosate 700 Herbicide for Roundup Ready Flex cotton;
- Insecticide is only applied during flowering and boll growth (March-May), and is not used heavily;
- The Emerald Irrigation Area provides proxy fertiliser use data, and the Ord Irrigation Area provides proxy pesticide use data for the Flinders (based on rainfall and soil type). Nitrogen regime is a blend of Emerald Irrigation Area and Burdekin Irrigation Area usage rates; and
- The remoteness of the proposed development area makes transport of cotton to existing gins prohibitively costly. A viable cotton gin requires a minimum of approximately 50,000 bales of cotton per year (Manson, 2013). The minimum area planted to cotton is assumed to provide a minimum of 50,000 bales.

Bollgard II® and Roundup Ready® cotton was licensed for northern Australia in 2006. The genetically modified component combines herbicide tolerance with insect resistance (Holtzapffel et al., 2008). Roundup Ready® and Roundup Ready Flex® cotton varieties contain either one or two copies respectively of a gene from the soil bacterium *Agrobacterium* sp., which is insensitive to the effect of glyphosate (Holtzapffel et al., 2008). The addition of the extra copy of the gene in Roundup Ready Flex® cotton extends the period during which the plant is tolerant (Holtzapffel et al., 2008). Bollgard II® (also known as 'Bt cotton') contains two protein genes from the *Bacillus thuringiensis* bacterium which are toxic to lepidopteron species (butterflies and moths) including *Helicoverpa* caterpillars, which is a major cotton pest (Holtzapffel et al., 2008). Two Bt genes are used because it is considered that it is less likely that insects will develop resistance to both proteins simultaneously than to just one (Holtzapffel et al., 2008).

Detection of pesticide residues in rivers is reported to have declined since the introduction of Bollgard II® and the cotton Best Management Practices Program (Holtzapffel et al., 2008). For example the herbicide pendimethalin, which has a relatively long half-life in soil and moderate toxicity to fish, is expected to become virtually redundant under glyphosate-tolerant GM varieties (Moulden et al., 2006).

Introduction of Bollgard II® has reduced the amount of insecticide active ingredient by up to 85%, but as control over *Helicoverpa* has increased, mirids have become the most heavily sprayed pest in Bollgard II® cotton, and fipronil and dimethoate are used more heavily on Bollgard II® than conventional cotton (Holtzapffel et al., 2008).

Similarly, adoption of glyphosate-tolerant GM cotton has increased reliance on glyphosate and has increased the occurrence of glyphosate-tolerant weed species in north Australian broadacre cropping areas (Gaines et al., 2012; Holtzapffel et al., 2008; Preston, 2013). For example, in 2003 glyphosate use alone was higher in glyphosate-tolerant cotton fields (2.3 to 3.2 kg a.i. per ha) than in fields planted with conventional cotton (0.5 to 0.8 kg a.i. per ha) (Holtzapffel et al., 2008). Many resistant weed species are well adapted to minimum tillage; such practices allow in-crop weed control by non-selective herbicides such as glyphosate, triazines and glufosinate ammonium, but can also increase weed pressure, and encourage heavier reliance on one or a few herbicides (Holtzapffel et al., 2008).

Despite the benefits of GM cotton for reducing pesticide use, herbicide and insecticide rates can still be reasonably high. The rates presented in Table 6.6 are conservative estimates and management regimes represent plausible minimum and maximum rates of treatment, on the basis of current published research, which is often conducted outside the Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas. Management regimes used in the model are presented in Table 6.6.

Table 6.6 Cotton management approaches for the Flinders catchment

APPROACH	IRRIGATION	STAGE	FERTILISER	HERBICIDE	INSECTICIDE
Efficiency	Overhead	Sowing	150 kg N/ha 20 kg P /ha	360 g a.i./L glyphosate @ 1.25 L/ha	clothianidin 40 g ai/ha
		Flowering	70 kg N/ha	360 g a.i./L glyphosate @ 1.25 L/ha	nil
Potential	Furrow	Sowing	150 kg N/ha	690 g a.i./L glyphosate @ 2.0 L/ha	fipronil 8 g ai /ha
		Flowering	120 kg N/ha 40 kg P/ha	690 g a.i./L glyphosate @ 2.0 L/ha	clothianidin 40 g ai/ha

Source: Moulden et al., (2006), Yeates et al., (2010a,b,c) (Yeates et al., 2010a; 2010b; 2010c), Yeates (2013, pers. comm.)

Sorghum

An estimated 10,000 to 40,000 hectares of land is planted for sorghum in the Flinders River catchment. Modeling was undertaken according to the following assumptions:

- To avoid flowering or grain setting in the wet season, plant in late February;
- Planting occurs up to 1 km in from the riverbank;
- No cattle are let onto the field in the wet season;
- Standing crop is maintained throughout the wet season;
- Centre-pivot irrigation is used; and
- Zero tillage and shielded spraying in efficiency group pre-planting.

Application rate estimates provided in Table 6.7 are conservative. Substantially higher rates of fertiliser and other herbicides have been reported in sorghum in the Daly catchment (O'Gara et al., 2003). These represent plausible minimum and maximum rates of treatment, on the basis of current published research, which is often conducted outside the Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas.

Table 6.7 Sorghum management approaches for the Flinders catchment

TARGET YIELD[A]	CROP STAGE	FERTILISER[B]	HERBICIDE	INSECTICIDE
Efficiency	Pre-emergent	nil	960g/L S-metolachlor @ 1L/ha	nil
	Post wet	80 kg N/ha 30 kg P/ha	nil	
Potential	Pre-emergent	nil	3.2 L/ha @ 370g/L atrazine 1.0 L/ha @ 290g/L S-metolachlor 1.0 L/ha @ 960g/L S-metolachlor	nil
	Post wet	120 kg N/ha 40 kg P/ha	nil	

Source: Kelvin Schwartz pers. comm.

Aerobic Rice

Aerobic rice systems (Figure 6.1) are also known as upland rice (Kao et al., 2011), alternately submerged–non-submerged rice (Belder et al., 2004), alternate wetting and drying (AWD) (Liang et al., 2013; Tan et al., 2013), intermittent flooding (Borrell et al., 1997; Eriksen et al., 1985), and intermittent wet-and-dry (IWD) rice (Linquist et al., 2013).

Figure 6.1 Attendees at a rice field day at Frank Wise Institute take a closer look at aerobic rice

Source: Photo courtesy of S. Sivapalan, Frank Wise Institute, WA. Used with permission.

Rice has not been harvested in the Flinders catchment to date (September 2013). A trial rice crop was sown in 2013 and irrigated once before drought conditions required the crop to be abandoned. No agronomy or best management practices have been developed for growing upland/aerobic rice in the Flinders River catchment and many issues remain unanswered. Weeds are likely to be a bigger issue in aerobic rice (Borrell et al., 1997).

An estimated 5,000 to 10,000 hectares of land is planted for aerobic rice in the Flinders River catchment. Modeling was undertaken according to the following assumptions:

- The assumptions are based on the rice crop being grown on the flat or using a furrow / bed system with intermittent irrigation i.e. no ponding. There would be differences in some agronomy and especially the nitrogen dynamics between a flat system and a furrow / bed system;
- All products identified are registered for use on rice in Queensland; and
- Wet season cropping only.

An efficiency system for aerobic rice assumes that a site-specific nutrient management (SSNM) approach is used. Similar to the concept of N-replacement and Six Easy Steps, SSNM allows farmers to dynamically synchronise nutrient supply to meet but not exceed crop demand, which lowers nutrient runoff concentrations from immediately after application into the remainder of the growing season.

The dry tropics environment presents a shorter growing season, the consequence of this is that high levels of nitrogen fertiliser (200 kg urea/ha) can often reduce yields and increases the susceptibility of the crop to cool nights, further reducing yield (Sivapalan, 2012). Further, high nitrogen combined with cool nights and dews can encourage blast infection (Sivapalan, 2012).

Planthoppers are a looming issue for rice management in Asia (Bottrell and Schoenly, 2012; Gurr et al., 2011). This model assumes that the presented management regimes provide adequate protection against planthoppers in northern Australia. It is assumed that if specific planthopper control became necessary in northern Australia, given the lack of success of massive insecticide spraying in East Asian situations (Bottrell and Schoenly, 2012; Kushwaha et al., 2013), ecological engineering approaches would be adopted (Gurr et al., 2011). Should chemical controls be used, expected insecticide application rates (as active ingredient) are: buprofezin 150 g/ha, chlorpyrifos 600 g/ha, cartap 700 g/ha, fipronil 35 g/ha, triazophos 35 g/ha, and dimehypo 900 g/ha (Wang et al., 2010). Aerobic rice heavily relies on herbicides and other biocides (e.g. nematicides) and adequate supply of plant nutrients including P, Fe, Zn, and others that may become deficient under aerobic conditions (Prasad, 2011). The only relevant data obtained for Australia were for an experiment conducted at Yanco Agricultural College several decades ago on intermittently irrigated rice, which showed that less than 2% of applied nitrogen leaches deeper than 300 mm; however effects of rainfall on nitrogen loss were not assessed (Bacon et al., 1986). The maximum fertiliser rates in Table 6.8 are lower than those recorded for experimental intermittently-flooded rice in the Burdekin Irrigation Area (Borrell et al., 1997) and the Northern Territory (Eastick et al., 2012).

The management regimes presented in Table 6.8 represent plausible minimum and maximum rates of treatment, on the basis of current published research, all of which has been conducted outside the Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas.

Table 6.8 Aerobic rice management approaches for wet season cropping in the Flinders catchment

TARGET YIELD	IRRIGATION	CROP STAGE	FERTILISER	HERBICIDE	INSECTICIDE
Efficiency	Furrow	Pre-plant	15 kg N/ha diammonium phosphate (DAP) 15 kg P/ha DAP	glyphosate 360 g a.i./L @ 3 L/ha = 1080 g/ha	nil
		Tillering	50 kg N/ha ammonium	thiobencarb 800 g a.i./L @ 5 L/ha = 4kg/ha cyhalofop-butyl 285 g a.i./L @ 0.75 L/ha = 214g/ha	nil
		Panicle initiation	60 kg N/ha ammonium	nil	nil
		Flowering	nil	nil	chlorpyrifos 500 g a.i./L @ 1.5 L/ha
		Ripening	nil	nil	nil
Potential	Furrow	Pre-plant	30 kg N/ha basal urea 25 kg P/ha DAP	pendimethalin 330 g a.i./L @ 3L/ha	nil
		Tillering	70 kg N/ha broadcast urea	thiobencarb 800 g a.i./L @ 5 L/ha cyhalofop-butyl 285 g a.i./L @ 1.5 L/ha	nil
		Panicle initiation	70 kg N/ha broadcast urea	nil	nil
		Flowering	nil	nil	chlorpyrifos 500 g a.i./L @ 1.5 L/ha
		Ripening	nil	nil	chlorpyrifos 500 g a.i./L @ 1.5 L/ha

Source: Ockerby and Fukai (2001), Beecher et al. (2006), Eastick et al. (2012), Hussie (2010), Sivapalan et al. (2010), Sivapalan (2010), P. Elliot pers. comm., S. Sivapalan pers. comm. (Beecher et al., 2006; Eastick et al., 2012; Hussie, 2010; Ockerby and Fukai, 2001; Sivapalan et al., 2010)

Gilbert development scenarios

Irrigated fodder

An estimated 1,500 to 3,000 hectares of land is planted for irrigated fodder in the Gilbert River catchment. Modeling was undertaken according to the following assumptions:

- Planting along riverbank only;
- Permanent crop, with no replanting;
- Expect minimal change in runoff over life of land use (4-5 years);
- Planting is done in the dry season to have grass stubble by the wet season;
- No cultivation in middle of the wet season;
- Grassed by late December to prevent erosion;
- Overhead irrigation is used; and
- Very little erosion except the first cultivation and erosion is slight.

The management regimes presented in Table 6.9 represent plausible minimum and maximum rates of treatment, on the basis of current published research, which is often conducted outside the Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas.

Table 6.9 Irrigated fodder management approaches for the Gilbert catchment

STAGE	IRRIGATION	FERTILISER	HERBICIDE
Pre-plant	Overhead	90 kg N/ha as urea	200 g/kg tebuthiuron @ 0.5 g/m^2
Planting		35 kg N/ha	
		25 kg P/ha	
Post-harvest		90 kg N/ha of urea	

Source: O'Gara et al. (2003)

Cotton

An estimated 10,000 to 20,000 hectares of land is planted for cotton in the Gilbert River catchment. Modeling was undertaken according to the following assumptions:

- Planting is undertaken in late December to mid-January;
- All crops use Roundup Ready Flex®/Bollgard II® cotton;
- Furrow irrigation is used when targeting potential yield, overhead irrigation is used when targeting efficient yields;
- No-till or conservation tillage is used when targeting efficient yields;
- Nitrogen is always provided in-crop prior to flowering (25 to 45 days after sowing) in splits as Easy-N. ENTEC urea is used at sowing only and on clays only;
- Only use glyphosate herbicide, and only early in crop cycle (January to February for wet season crops;) as per label for Titan Cotton and Dry Glyphosate 700 Herbicide for Roundup Ready Flex cotton;
- Insecticide is only applied during flowering and boll growth (March to May), and is not used heavily;
- The Burdekin Irrigation Area and the Ord Irrigation Area provides proxy fertiliser and pesticide use data for the Gilbert (based on rainfall and soil type); and
- The remoteness of the proposed development area makes transport of cotton to existing gins prohibitively costly. A viable cotton gin requires a minimum of approximately 50,000 bales of cotton per year (Manson, 2013). The minimum area planted to cotton is assumed to provide a minimum of 50,000 bales.

The management regimes presented in Table 6.10 represent plausible minimum and maximum rates of treatment, on the basis of current published research, which is often conducted outside the Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas.

Table 6.10 Cotton management approaches for the Gilbert catchment

APPROACH	IRRIGATION	STAGE	FERTILISER	HERBICIDE	INSECTICIDE
Efficiency	Overhead	Sowing	55 kg N/ha 20 kg P /ha	360 g a.i./L glyphosate @ 1.25 L/ha	clothianidin 40 g ai/ha
		Flowering	115 kg N/ha	360 g a.i./L glyphosate @ 1.25 L/ha	nil
Potential	Furrow	Sowing	55 kg N/ha	690 g a.i./L glyphosate @ 2.0 L/ha	fipronil 8 g ai /ha
		Flowering	120 kg N/ha 40 kg P/ha	690 g a.i./L glyphosate @ 2.0 L/ha	clothianidin 40 g ai/ha

Source: Moulden et al. (2006), Yeates et al. (2010), Yeates (2013, pers. comm.)

Sorghum

An estimated 10,000 to 40,000 hectares of land is planted for sorghum in the Gilbert River catchment. Modeling was undertaken according to the following assumptions:

- The GDS3 Sorghum scenario is not tuned for catchment-specific factors, owing to a lack of data; and
- All parameters and assumptions are the same as provided in Table 6.7.

Management regimes presented in Table 6.11 represent plausible minimum and maximum rates of treatment, on the basis of current published research, which is often conducted outside the Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas.

Table 6.11 Sorghum management approaches for the Gilbert catchment

TARGET YIELD[A]	CROP STAGE	FERTILISER[B]	HERBICIDE	INSECTICIDE
Efficiency	Pre-emergent	nil	960g/L S-metolachlor @ 1L/ha	nil
	Post wet	80 kg N/ha 30 kg P/ha	nil	
Potential	Pre-emergent	nil	3.2 L/ha @ 370g/L atrazine 1.0 L/ha @ 290g/L S-metolachlor 1.0 L/ha @ 960g/L S-metolachlor	nil
	Post wet	120 kg N/ha 40 kg P/ha	nil	

Source: Kelvin Schwartz (2013, pers. comm.)

Sugarcane

An estimated 20,000 to 50,000 hectares of land is planted for sugarcane in the Gilbert River catchment. Modeling was undertaken according to the following assumptions:

- Rodenticides and fungicides are typically used in cane management but are not considered here (Goebel and Sallam, 2011); and
- Trap cropping was assumed in A Class practices (Hunt et al., 2012). An example of crop trapping is shown in Figure 6.2.

The management regimes presented in Table 6.12 represent plausible minimum and maximum rates of treatment, on the basis of current published research, all of which has been conducted outside the

Assessment area. Replication of any of these regimes without due consideration of local conditions and requirements is likely to result in poor production outcomes in some areas.

Figure 6.2 Trap cropping in the Burdekin in an unsprayed crop. Non-trap areas are greener

Source: Samson et al. (2012). (Samson et al., 2012)

Table 6.12 Sugarcane management approaches for the Gilbert catchment

CLASS	CROP STAGE	FERTILISER[A]	IRRIGATION	HERBICIDE APPLICATIONS[B,E]	INSECTICIDE APPLICATIONS[C]
A	Legume fallow harvested	nil	drip	1: 540 g a.i./L @ 6.0 L/ha glyphosate and 625 g a.i./L 2,4-D amine @ 0.5 L/ha 2: 540 g a.i./L @ 2.0 L/ha glyphosate and 960 g a.i./L S-metalochlor @ 1.8 L/ha	nil
	Plant	nil 30 kg P/ha[F]	drip	3: 700 g a.i./L 2,4-D amine @ 1.0 L/ha and 900 g a.i./kg @ 1.0 L/ha atrazine and 250 g a.i./L @ 1.3 L/ha paraquat and 700 g a.i./L @ 1.0 L/ha 2,4-D amine and 900 g a.i./kg @ 1.0 L/ha diuron 4: as for (1) + 570 g a.i./L @ 1.5 L/ha glyphosate	imidacloprid 50 g a.i./kg @ 15 kg/ha
	Ratoon 1	100 kg N/ha 15 kg P/ha[F]	drip	5: 700 g a.i./L 2,4-D amine @ 1.0 L/ha and 900 g a.i./kg @ 1.0 L/ha atrazine and 250 g a.i./L @ 1.3 L/ha paraquat and 700 g a.i./L @ 1.0 L/ha 2,4-D amine and 900 g a.i./kg @ 1.0 L/ha diuron and 570 g a.i./L @ 1.5 L/ha glyphosate 6: as for (5)	nil
	Ratoon 2		drip	7, 8: as for Ratoon 1	nil
	Ratoon 3		drip	9, 10: as for Ratoon 1	nil
B	Legume fallow 'catch' crop	nil	overhead spray	1: 540g a.i./L glyphosate @ 6 L/ha and 625 g a.i./L 2,4-D amine @ 0.5 L/ha 2: 540g a.i./L glyphosate @ 3 L/ha and 960 g a.i./L S-metolachlor @ 1.8 L/ha 3: 540g a.i./L glyphosate @ 3 L/ha and 625 g a.i./L 2,4-D amine @ 0.75 L/ha	nil
	Plant	nil 30 kg P/ha[F]	overhead spray	4: 900 g a.i./kg diuron @ 0.3 L/ha and 900 g a.i./kg atrazine @0.3 L/ha and 625 g a.i./L 2,4-D amine @ 0.75 L/ha and 250g a.i./L paraquat @ 1.0 L/ha 5: as above 6: 2,4-D Amine 0.75 L/ha + 250g a.i./L paraquat @ 1.0 L/ha	imidacloprid 50 g a.i./kg @ 10 kg/ha
	Ratoon 1	130 kg N/ha 20 kg P/ha[F]	overhead spray	7: 900 g a.i./kg diuron @ 0.3 L/ha and 900 g a.i./kg atrazine @0.3 L/ha and 625 g a.i./L 2,4-D amine @ 0.75 L/ha and 250g a.i./L paraquat @ 1.0 L/ha 8: as for (7)	nil
	Ratoon 2		overhead spray	9, 10: as for Ratoon 1	nil
	Ratoon 3		overhead spray	11, 12: as for Ratoon 1	imidacloprid 50 g a.i./kg @ 10 kg/ha
C	Bare fallow	nil	nil	1: 540g a.i./L glyphosate @ 3 L/ha and 625 g a.i./L 2,4-D amine @ 0.5 L/ha 2: as above	nil
	Plant	180 kg N/ha 50 kg P/ha[F]	furrow	3: 900 g a.i./kg diuron @ 0.5 L/ha + 900 g a.i./kg atrazine @0.5 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 1.5 L/ha 4: as above 5: 900 g a.i./kg diuron @ 0.5 L/ha and 900 g a.i./kg atrazine @2.0 L/ha and 625 g a.i./L 2,4-D amine @ 1.5 L/ha and 250g a.i./L paraquat @ 1.5 L/ha	imidacloprid 50 g a.i./kg @ 15 kg/ha imidacloprid 350 g a.i./L @ 0.72 L/ha
	Ratoon 1	180 kg N/ha 40 kg P/ha[F]	furrow	6: 900 g a.i./kg diuron @ 0.5 L/ha and 900 g a.i./kg atrazine @0.5 L/ha and 625 g a.i./L 2,4-D amine @ 1.5 L/ha and 250g a.i./L paraquat @ 2.0 L/ha 7: as above 8: 2,4-D Amine 1.5 L/ha	imidacloprid 350 g a.i./L @ 1.05 L/ha
	Ratoon 2		furrow	9, 10, 11: as for Ratoon 1	imidacloprid 350 g a.i./L @ 1.05 L/ha
	Ratoon 3		furrow	12, 13, 14: as for Ratoon 1	imidacloprid 350 g a.i./L @ 1.05 L/ha
D	Bare fallow	nil	nil	Cultivation only	nil
	Plant	240 kg N/ha 80 kg P/ha	furrow	1: 900 g a.i./kg diuron @ 0.5 L/ha + 900 g a.i./kg atrazine @2.0 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 2.0 L/ha 2: 900 g a.i./kg diuron @ 0.5 L/ha + 900 g a.i./kg atrazine @0.5 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 1.5 L/ha 3: 900 g a.i./kg diuron @ 1.0 L/ha + 900 g a.i./kg atrazine @1.3 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 1.5 L/ha	imidacloprid 50 g a.i./kg @ 10 kg/ha imidacloprid 350 g a.i./L @ 1.44 L/ha
	Ratoon 1	240 kg N/ha 40 kg P/ha[F]	furrow	4: 900 g a.i./kg diuron @ 0.5 L/ha + 900 g a.i./kg atrazine @0.8 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 2.0 L/ha 5: 900 g a.i./kg diuron @ 0.5 L/ha + 900 g a.i./kg atrazine @0.5 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 2.0 L/ha 6: 900 g a.i./kg diuron @ 1.0 L/ha + 900 g a.i./kg atrazine @2.0 L/ha + 625 g a.i./L 2,4-D amine @ 1.5 L/ha + 250g a.i./L paraquat @ 1.5 L/ha	imidacloprid 350 g a.i./L @ 1.44 L/ha
	Ratoon 2		furrow	7, 8, 9: as for Ratoon 1	imidacloprid 50 g a.i./kg @ 10 kg/ha imidacloprid 350 g a.i./L @ 1.44 L/ha
	Ratoon 3		furrow	10, 11, 12: as for Ratoon 1	imidacloprid 350 g a.i./L @ 1.44 L/ha

NOTE: each practice scenario is modelled under small (20,000 ha; 160 GL) and large (50,000 ha; 400 GL), as well as reference (10,000 and 20,000) cropping areas. A) Adapted from Biggs et al. (2012 in press); B) Data from Shaw and Silburn (2013). All herbicides applied as directed spray unless indicated otherwise. C) Davis (2013 unpubl. data; D) applied using a shielded sprayer; E) herbicide A practices are adapted from Oliver et al., (2014) based on shielded spray applications. Bifenthrin, metarhizium FI-1045, chlorpyrifos, clothianidin, diazinon, fenamiphos and fipronil are also used in Queensland sugarcane (Samson et al., 2010; Allsopp, 2010; Chandler and Tucker, 2010; Chandler and Tucker, 2011); but have not been included in modelling; F = DERM, (2009), Schroeder et al., (2006) assuming low initial soil P thus highest rates required.(Allsopp, 2010; Biggs et al., 2012; Chandler and Tucker, 2011; Chandler and Tucker, 2010; DERM, 2009b; Oliver et al., 2014; Samson et al., 2010; Schroeder et al., 2006; Shaw and Silburn, 2013)

Guar

An estimated 20,000 to 50,000 hectares of land is planted for guar in the Gilbert River catchment. Modeling was undertaken according to the following assumptions:

- Planting is undertaken on a rolled surface (no furrows) in the optimum window for rain fed guar in northern Queensland, i.e. December-early January, avoiding the need to irrigate and to avoid crop maturity in the wet season (Australian Guar Company, 2013);
- 2,4-D is applied at rates equivalent to the minimum label rate for peanuts but a permit for guar had not been finalised at the time of publication (Australian Guar Company, 2013);
- Gramoxone (paraquat dichloride) is used instead of glyphosate as a pre-harvest desiccant for guar in the USA but has not been permitted for guar in Australia to date. If permitted on Australia guar, the low solubility of this compound would make it a low environmental risk in most circumstances; and
- Guar has few insect pests that warrant chemical control (Australian Guar Company, 2013).

Management regimes presented in Table 6.13 represent plausible rates of treatment, on the basis of current knowledge. This is an emerging crop for northern Australia which is currently under active research. Replication of any of these regimes without due consultation with industry experts is likely to result in poor production outcomes.

Table 6.13 Guar management approaches for the Gilbert catchment

CROP STAGE	IRRIGATION	FERTILISER	HERBICIDE	INSECTICIDE
Pre-plant	nil	15 kg P/ha DAP	480 g a.i./L trifluralin @ 0.9 L/ha = 432 g/ha	nil
Post-sow Pre-emergent	nil	nil	700 g a.i./kg imazethapyr @ 0.1 kg/ha = 70 g/ha	nil
Post-emergent	nil	nil	520 g a.i./L haloxyfop-R-methyl ester @ 0.1 L/ha = 52 g/ha 500 g a.i./L 2,4-D as dimethylamine salt @ 1.3 L/ha =650 g/ha	nil
Pre-harvest	nil	nil	450 g a.i./L glyphosate @ 1.0 L/ha = 450 g/ha	nil

Source: Australian Guar Company (2013), APVMA (2012a; 2012b)

Sediment and nutrient export coefficients

Figures presented do not account for interactions of management variables for example, the effect of rates/timing of applications, placement and forms of fertiliser applied are not considered.

Grazing (baseline)

The Daly catchment has similar climate and rainfall to the current condition of the Gilbert catchment, and similar (low) levels of development. Recent SedNET modelling suggests that sediment export coefficients for the Daly catchment are in the order of 90 kg/ha/yr (Rustomji and Caitcheon, 2010).

The Flinders catchment has experienced more development than the Gilbert, so is more closely represented by more developed northern catchments such as the Mitchell, Burdekin or Herbert. The level of development in those three catchments is higher than that of the Flinders so are likely to over-estimate baseline loads. A better estimate is achieved if the loads occurring in the Daly and Normanby catchments are averaged with those found in the more developed catchments.

Recent SedNET modelling estimates of sediment yields in the Mitchell River catchment suggest current sediment loads from that river are in the order of 460 kg/ha/yr (Rustomji et al., 2010). Similar estimates of sediment loads (approximately 500 kg/ha/yr) are provided in Source Catchments for the Burdekin catchment (adjusted to account for the effects of Burdekin Falls Dam) and the Herbert River. Averaged with the loads occurring in relatively undeveloped GBR catchments produces a sediment load estimate for the Flinders River of 300 kg/ha/yr.

To avoid overestimation of nutrient loads for the baseline scenario, nutrient export rates provided in Source Catchments for the Normanby River and the SedNET nutrient estimates for the Daly River (Rustomji and Caitcheon, 2010) were used to estimate baseline nutrient loads for both the Flinders and the Gilbert catchments.

Table 6.14 Sediment, nitrogen and phosphorus runoff generation rates

PARAMETER	LAND USE	CONDITIONS	GENERATION RATE*	LOCATION	SOURCE
N	Grazing	Baseline	0.15 kg N/ha	Daly and Normanby	1, 2
	Irrigated fodder		10% of applied		3
	Sorghum		10% of applied		3
	Aerobic rice	Efficiency Potential	5.7% of applied 10.5% of applied	China Japan	4 5
	Cotton	Efficiency Potential	2.6% of applied 10.5% of applied	Emerald	6, 7
	Sugarcane[4]	A class B class C class D class	10% of applied 10% of applied 10% of applied 10% of applied	Great Barrier Reef Catchments	3
	Guar		n/a		
P	Grazing	Baseline	0.06 kg P/ha	Daly and Normanby	1, 2
	Irrigated fodder		28% of applied		8
	Sorghum		28% of applied		
	Aerobic rice	Efficiency Potential	0.7% of applied 0.8% of applied	China	4
	Cotton	Efficiency Potential	0.04% of applied 4.0% of applied	Emerald	6, 7
TSS	Grazing	Flinders baseline Gilbert baseline	300 kg/ha 90 kg/ha		
	Irrigated fodder	n/a	negligible		
	Sorghum	n/a	negligible		
	Aerobic rice	Flinders	168 kg/ha	Japan	9
	Cotton	Efficiency Potential	500 kg/ha 20,000 kg/ha	Emerald	6
	Sugarcane	A/B class (controlled traffic) C/D class (conventional till)	19 kg/ha 29 kg/ha	Mackay-Whitsunday	10
	Guar	n/a	n/a		No data

Source: 1 = Rustomji and Caitcheon (2010); 2 = Source Catchments; 3 = Thorburn et al. (2013); 4 = Liang et al. (2013); 5 = Chinh et al. (2008); 6 = Silburn and Hunter (2009); 7 = Waters (2001); 8 = Barlow et al. (2005); 9 = Lee et al. (2013); 10 = Masters et al. (2012). * = total nitrogen and total phosphorus only are reported. (Barlow et al., 2005; Chinh et al., 2008; Lee et al., 2013; Liang et al., 2013; Masters et al., 2012; Silburn and Hunter, 2009; Thorburn et al., 2013; Waters, 2001)

Table 6.15 Nitrogen and phosphorus baseline export coefficients (kg/ha/y)

PROXY	TN	TDN	TP	TDP
Daly	0.15	0.79	0.03	0.13
Normanby	0.63	0.75	0.08	0.04
Average	0.39	0.77	0.06	0.09

Source: Drewry et al. (2006), Rustomji and Caitcheon (2010), Source Catchments (2012) (Drewry et al., 2006; Rustomji and Caitcheon, 2010)

Irrigated fodder

A farm-scale phosphorus export assessment for irrigated dairy farms Victoria suggests that, at lower phosphorus application rates similar to those used here (40 kg/ha), approximately 28% is exported in surface runoff (Barlow et al., 2005).

Cotton

Phosphorus losses were calculated following Silburn and Hunter (2009):

- Total losses as a proportion of phosphorus fertiliser is assumed to be 1.0% for bare plots (potential), reducing to 0.02% with 45–55% cover (efficient yield scenarios) per rainfall event;
- Assume ten rainfall events per year, but to account for runoff load declines that occur later in the season, reduce the estimate to 4% loss of total applied phosphorus as per Waters (2001; cited in Silburn and Hunter (2009)); and
- Multiply phosphorus loss rates by four to get an annual loss estimate:
  - *Potential*: 1% of applied x 4 = 4% of applied;
  - *Efficiency*: 0.02% of applied x 4 = 0.08% of applied phosphorus; then halve to account for overhead irrigation = 0.04% of applied phosphorus.

Nitrogen losses were calculated following Silburn and Hunter (2009):

- Nitrogen losses predominantly occur as sediment nitrogen for plots with lower cover, and decrease with increasing cover and runoff. Total N losses as a proportion of N fertiliser were:
  - *Potential*: 2-4 kg/ha (approximately 1.5% of applied nitrogen)
  - *Efficiency*: 1.2-2.1 kg/ha (approximately 0.75% of applied nitrogen);
- Assume ten rainfall events per year, but to account for runoff load declines that occur later in the season, reduce the estimate to 7% loss of total applied nitrogen as per Waters ((2001); cited in Silburn and Hunter (2009)); and
- Multiply nitrogen loss rates by seven to get annual loss estimate:
  - *Potential*: 1.5% of applied x 7 = 10.5% of applied N;
  - *Efficiency*: 0.75% of applied x 7 = 5.25% of applied N; then halve to account for overhead irrigation = 2.6% of applied nitrogen.

Suspended sediment losses were calculated following Silburn and Hunter (2009):

- Management practices can potentially eliminate runoff from smaller, more frequent, rainfall events. For example, runoff may occur from bare furrows during a 1 in 3 year annual recurrence interval rainfall event, but under high cover and controlled traffic practices, runoff may occur at the 1 in 30 year annual recurrence interval event. To account for this discrepancy, values were calculated on the basis of five rain events per year for efficient yield scenarios, and on the basis of ten events per year for potential yield scenarios;
- *Potential*: 2 t/ha loss per event, at ten events per year = 20 t/ha/yr; and
- *Efficient:* 0.1 t/ha soil loss per event, at five events per year = 0.5 t/ha/yr.

Aerobic rice

Rice growers typically use either ammonium-based fertilisers, or ureas that rapidly convert to ammonium once applied (Linquist et al., 2013). Most nitrogen losses in rice systems are due to the oxidisation of ammonium to nitrate (i.e. nitrification) under aerobic conditions, and the reduction of nitrate to nitrogen gas and nitrous oxide (i.e. denitrification) under anaerobic conditions (Eriksen et al., 1985; Linquist et al., 2013).

Volatilisation of urea occurs rapidly, and may be complete within three days of fertiliser application (Eriksen et al., 1985; Norman et al., 2009), so if fields are not flooded within this period of rapid volatilisation, they are likely to require further fertiliser applications (Griggs et al., 2007). Fluctuation between anaerobic and aerobic conditions also increases losses due to denitrification (Bacon et al., 1986; Belder et al., 2004; Eriksen et al., 1985).

The percentage of fertiliser nitrogen recovered in aboveground plant biomass during the growing season is called the nitrogen fertiliser recovery efficiency (RE_N). Internationally, efficiently managed paddies (i.e. fertilised to meet crop needs) have RE_N values of 40 ± 18%, compared to paddies that are managed less efficiently and which have RE_N values of 31 ± 18% (Cassman et al., 2002). In Australia, flooded systems typically have 60 to 80% nitrogen use efficiency (Vial, 2007). Aerobic and alternate wet and dry (AWD) rice systems often have less than half the nitrogen use efficiency of flooded systems (Borrell et al., 1997; Vial, 2007). For a system managed to realise efficient yields it is assumed that tailwater recycling systems are 100% effective, thus no external losses are incurred to the river system from irrigation events.

Leaching of nutrients to groundwater is usually minimal in rice systems due to low permeability soils and continuous flooding systems. Zhao et al. (2012) report that in conventionally farmed Chinese paddy rice-wheat rotation, runoff contributed up to 85% of total nitrogen exports, compared to a maximum of 18% contribution from leaching. There is reason to believe that leaching may be a more significant export pathway in aerobic systems. Zhu et al. (2000) report that approximately 5.5 kg N/ha was lost through leaching during the aerobic rice phase in a rice-wheat rotation.

Most of the research into nutrient losses to leaching and surface runoff has been conducted in China. These results show that, on Chinese soils, leaching losses from efficient (SSNM) AWD rice systems are approximately 6% and 4% of applied N as TN and NH_4^+ respectively, and 0.8% and 0.5% of applied P as TP and PO_4^{3-} respectively (Liang et al., 2013). By comparison, leaching losses from less efficiently fertilised systems (non-SSNM) were approximately 5% and 3% of applied N as TN and NH_4^+ respectively, and 0.9% and 0.6% of applied P as TP and PO_4^{3-} respectively (Liang et al., 2013). In China it has been found that the effect of bypass or preferential water flow via soil cracking, and strengthened nitrification–denitrification transformation processes in AWD systems, potentially decrease water savings and increase nitrate-N loading to groundwater (Tan et al., 2013). Similar findings in Taiwan indicate that aerobic rice systems may disturb the impermeable soil layer and increase permeability of soil nitrogen into groundwater (Kao et al., 2011). It is unknown how well these results translate to a north Australian context. An experiment conducted at Yanco Agricultural College (NSW) several decades ago using intermittently irrigated rice showed that less than 2% of applied nitrogen leached deeper than 300 mm (Bacon et al., 1986). The potential for groundwater fertiliser contamination in north Australian aerobic rice systems requires further investigation.

Sorghum

As per irrigated fodder.

Sugarcane

The content of phosphorus in sugarcane soils builds up to surplus levels following many years of phosphorus fertilisation (Brodie, 2006), and thereby requires application of much less amounts of phosphorus fertiliser than virgin soils. Thus the highest phosphorus application rates reported by DERM (2009) and Schroeder et al. (2006) were applied in the model.

Atrazine, diuron, 2,4-D, ametryn and paraquat are the most heavily used herbicides on Queensland sugarcane (Davis et al., 2012; Rayment, 2005). Little public information is available on usage rates or environmental effects of newer agrochemicals such as imidacloprid, imazapic and isoxaflutole (Rayment, 2005).

Guar

Guar production is an emerging crop in northern Australia, and little is known about is production. Model parameters were largely derived from the Guar Production Manual for the 2013/14 season (Australian Guar Company, 2013).

Pesticide generation rates

Generation rates were identified for five pesticides of particular environmental concern; atrazine, diuron, paraquat, 2,4-D and imidacloprid. Reliable data describing generation rates under rainfall or irrigation runoff conditions are scarce for north Australian crops and pastures. Local (i.e. northern Queensland) data were available for atrazine, 2,4-D and diuron. In the absence of Australian data, imidacloprid generation rates were estimated from figures published in the international literature. Figures presented in Table 6.16 do not account for interactions of management variables. For example, the effect of rates/timing of applications, placement and formulations of pesticides applied are not considered.

Table 6.16 Pesticide generation rates for sugarcane runoff

			LOSS TO RUNOFF PER RAIN EVENT (% OF APPLIED)		
PRACTICE	ATRAZINE	2,4-D AMINE	PARAQUAT	DIURON	IMIDACLOPRID[3]
A Class	2.4[2]	1.6[2]	negligible	0.44[2]	4
B Class	2.4[2]	1.6[2]	negligible	0.44[2]	4
C Class	4.8[1]	3.4[1]	negligible	0.88[1]	4
D Class	4.8[1]	3.4[1]	negligible	0.88[1]	4

Source: 1 = Davis et al. (2011) for lower Burdekin using furrow irrigation, conventional tillage and broadcast application; 2 = adjusted from Davis et al. (2011) to account for controlled till and banded spray after Masters et al. (2012); 3 = median derived from ranges reported for turf (Thuyet et al., 2012; Armbrust and Peeler, 2002). Significant amounts of paraquat are not expected to be present in runoff. (Armbrust and Peeler, 2002; Davis et al., 2011; Masters et al., 2012; Thuyet et al., 2012)

Atrazine

Values ranging from 0.06-4.8% of applied atrazine were recorded in sugarcane runoff in the Burdekin Irrigation Area (Davis et al., 2011). Controlled traffic practices reduce atrazine losses in runoff by 55% compared with conventionally tilled cane (Masters et al., 2012). Similarly, banded applications reduce atrazine runoff loads by 40% compared with broadcast applications (Masters et al., 2012). Therefore the highest loss rate of 4.8%, reported by Davis et al. (2011), was applied for C and D Class practices, then adjusted downwards by 50% to develop a more realistic value (2.4%) for A and B Class practices.

Diuron

Values ranging from 0.03-0.88% of applied diuron have been recorded in sugarcane runoff in the Burdekin Irrigation Area (Davis et al., 2011). Controlled traffic practices reduce diuron losses in runoff by 47% compared with conventionally tilled cane (Masters et al., 2012). Similarly, banded applications reduce diuron runoff loads by 42% compared with broadcast applications (Masters et al., 2012). Therefore the highest loss rate of 0.88%, reported by Davis et al. (2011), was applied for C and D Class practices, then adjusted downwards by 50% to develop a more realistic value (0.44%) for A and B Class practices.

2,4-D

Values ranging from 0.5-3.4% of applied 2,4-D have been recorded in sugarcane runoff in the Burdekin Irrigation Area (Davis et al., 2011). In keeping with the technique employed for atrazine, but in the absence of similar levels of data, the highest loss rate of 3.4%, reported by Davis et al. (2011), was applied for C and D Class practices, then adjusted downwards by 50% to develop a more realistic value (1.6%) for A and B Class practices.

Paraquat

Paraquat is highly hydrophobic, and thus has a high tendency to partition from water into organic materials such as fish and soil. Hence little paraquat is normally found in runoff from cropping lands such as sugarcane, where it is extensively used.

Imidacloprid

Local data on imidacloprid generation rates from crops to runoff water could not be found. International studies suggest that under simulated rainfall 2.4-6.3% of applied mass is removed from turf in runoff per rainfall event (Thuyet et al., 2012). In contrast, 1.4-1.9% of imidacloprid applied as wettable powder and granules, respectively, was lost to simulated rainfall runoff from turf (Armbrust and Peeler, 2002). Consequently an average value of 4% was applied as the imidacloprid export coefficient for this model.

6.4 Results

Equation 1 was applied using parameters outline in the previous tables to develop annual load estimates for each catchment. In some cases, reliable estimates of either application rates or generation rates were not available (e.g. guar). In these cases results have been indicated as 'no data' in the tables. Results of baseline scenarios for both river systems are presented in Table 6.17. Results of standardised reference scenarios are presented in Table 6.18. The development scenario results for suspended sediment, nitrogen and fertiliser loads are presented in Table 6.19 for land uses delivering runoff to the Flinders River, and Table 6.20 for land uses affecting the Gilbert River. Development scenario results for pesticides are presented for all proposed land uses in Table 6.21.

Due to the relative complexity of the five year sugarcane cropping system, the average value for a full sugarcane cropping cycle (i.e. a fallow year, followed by a plant year, followed by three ratoon years) are reported for sugarcane in Table 6.18, Table 6.19, Table 6.20 and Table 6.21.

Table 6.17 Modelled sediment, nitrogen and phosphorus loads for baseline scenarios

SCENARIO	AREA (HA)	N LOAD (T/Y)	P LOAD (T/Y)	TSS LOAD (T/Y)
FBS	10,950,000	4,300	660	3,300,000
GBS	4,640,000	1,800	280	420,000

Table 6.18 Modelled sediment, nitrogen and phosphorus loads for Flinders and Gilbert catchment reference scenarios

LAND USE TYPE	SCENARIO	N LOAD (T/YR)	P LOAD (T/YR)	TSS LOAD (T/YR)
Irrigated fodder	F-RS-IF-10 G-RS-IF-10	220	70	Negligible
	F-RS-IF-20 G-RS-IF-20	430	140	Negligible
Cotton	F-RS-C-E-10	6	< 1	5,000
	F-RS-C-P-10	280	16	200,000
	F-RS-C-E-20	11	< 1	10,000
	F-RS-C-P-20	570	32	400,000
	G-RS-C-E-10	4	< 1	5,000
	G-RS-C-P-10	180	16	200,000

LAND USE TYPE	SCENARIO	N LOAD (T/YR)	P LOAD (T/YR)	TSS LOAD (T/YR)
	G-RS-C-P-20	9	< 1	10,000
	G-RS-C-P-20	370	32	400,000
Sorghum	F-RS-S-E-10 G-RS-S-E-10	80	84	Negligible
	F-RS-S-P-10 G-RS-S-P-10	120	110	Negligible
	F-RS-S-E-20 G-RS-S-P-20	160	170	Negligible
	F-RS-S-P-20 G-RS-S-P-20	240	220	Negligible
Aerobic rice	F-RS-AR-E-10	71	1	1,700
	F-RS-AR-P-10	320	8	1,700
	F-RS-AR-E-20	140	2	3,400
	F-RS-AR-P-20	630	16	3,400
Sugarcane	G-RS-SC-EA-10	60	15	190
	G-RS-SC-EB-10	78	18	190
	G-RS-SC-PC-10	140	34	290
	G-RS-SC-PD-10	190	40	290
	G-RS-SC-EA-20	80	30	380
	G-RS-SC-EB-20	100	36	380
	G-RS-SC-PC-20	290	68	580
	G-RS-SC-PD-20	380	80	580
Guar	G-RS-G-10	No data	No data	No data
	G-RS-G-20	No data	No data	No data

n/a = not applicable

Table 6.19 Modelled sediment, nitrogen and phosphorus loads for Flinders catchment development scenarios

LAND USE TYPE	SCENARIO	N LOAD (T/YR)	% CHANGE	P LOAD (T/YR)	% CHANGE	TSS LOAD (T/YR)	% CHANGE
Irrigated fodder	F-DS-IF-10 G-DS-IF-10	215	5	70	11	Negligible	Negligible
	F-DS-IF-20 G-DS-IF-20	430	10	140	21	Negligible	Negligible
Cotton	F-DS-C-E-10	57	1	< 1	< 1	5,000	< 1

	F-DS-C-P-10	280	7	16	2	200,000	6
	F-DS-C-E-20	110	3	< 1	< 1	10,000	< 1
	F-DS-C-P-20	570	13	32	5	400,000	12
Sorghum	F-DS-S-E-10	40	1	42	6	Negligible	Negligible
	F-DS-S-P-10	60	1	56	9	Negligible	Negligible
	F-DS-S-E-40	80	2	84	13	Negligible	Negligible
	F-DS-S-P-40	120	3	112	17	Negligible	Negligible
Aerobic rice	F-DS-AR-E-5	36	1	1	< 1	840	< 1
	F-DS-AR-P-5	89	2	1	< 1	840	< 1
	F-DS-AR-E-10	71	2	1	< 1	1680	< 1
	F-DS-AR-P-10	180	4	2	< 1	1680	< 1

Table 6.20 Modelled sediment, nitrogen and phosphorus loads for the Gilbert catchment development scenarios. Figures for sugarcane are averages for a five-year cropping cycle (i.e. one fallow, one plant and three ratoon years)

LAND USE TYPE	SCENARIO	N LOAD (T/YR)	% CHANGE	P LOAD (T/YR)	% CHANGE	TSS LOAD (T/YR)	% CHANGE
Irrigated fodder	G-DS-IF-1.5	220	12	70	25	Negligible	Negligible
	G-DS-IF-3	430	24	140	50	Negligible	Negligible
Sorghum	G-DS-S-E-10	40	2	42	15	Negligible	Negligible
	G-DS-S-E-40	60	3	56	20	Negligible	Negligible
	G-DS-S-P-10	80	4	84	30	Negligible	Negligible
	G-DS-S-P-40	120	7	110	40	Negligible	Negligible
Sugarcane	G-DS-SC-EA-20	80	4	30	11	380	< 1
	G-DS-SC-EB-20	100	6	36	13	380	< 1
	G-DS-SC-PC-20	290	16	68	24	580	< 1
	G-DS-SC-PD-20	380	21	80	29	580	< 1
	G-DS-SC-EA-50	330	18	75	27	950	< 1
	G-DS-SC-EB-50	420	23	90	32	950	< 1
	G-DS-SC-PC-50	590	33	170	61	1,450	< 1
	G-DS-SC-PD-50	800	44	200	71	1,450	< 1
Guar	G-DS-G-20	No data		No data		No data	
	G-DS-G-50	No data		No data		No data	

Cotton	G-DS-C-E-10	4	< 1	< 1	< 1	5,000	1
	G-DS-C-P-10	180	< 1	16	< 1	200,000	48
	G-DS-C-E-20	9	< 1	< 1	< 1	10,000	2
	G-DS-C-P-20	370	< 1	32	< 1	400,000	96

Table 6.21 Modelled loads for selected pesticides in agricultural development scenarios. Figures for sugarcane are averaged over a single five-year cropping cycle (i.e. 1 fallow, 1 plant and 3 ratoon years)

LAND USE TYPE	SCENARIO	2,4-D AMINE (T/YR)	DIURON (T/HA)	ATRAZINE (T/HA)	IMIDACLOPRID (T/HA)
Irrigated fodder	Various	Negligible	Negligible	Negligible	n/a
Aerobic rice	Various	n/a	n/a	n/a	n/a
Sorghum	Various	Negligible	Negligible	Negligible	n/a
Sugarcane	G-DS-SC-EA-20	24	0	0	6
	G-DS-SC-EB-20	32	4	21	8
	G-DS-SC-PC-20	160	19	100	17
	G-DS-SC-PD-20	150	25	240	24
	G-DS-SC-EA-50	61	0	0	12
	G-DS-SC-EB-50	80	10	520	16
	G-DS-SC-PC-50	400	48	260	34
	G-DS-SC-PD-50	380	63	590	48
Guar	G-DS-G-20	Not calculable	Not calculable	Not calculable	n/a
Cotton	various	n/a	n/a	n/a	n/a

n/a = not applicable

6.5 Discussion

Complex biological and chemical processes occur during transport of sediments, nutrients and pesticides from the crop or field to the river and from the river to the sea. Many factors, such as rainfall and soil type, and placement, formulation and timing of agrochemical application can influence the amount of material carried in surface runoff (Liang et al., 2013). These factors are not considered here due to lack of data. Instead the Export Coefficient Model allows us to broadly estimate the amount of sediment, and the proportion of applied agrochemicals, that wash into the river in surface runoff. These load estimates can be broadly categorised as small (1-10%), moderate (10-50%) and large (> 50%) relative to baseline estimates, where a 50% increase in loads is equivalent to a 1.5-fold increase. Experience shows that small (1-10%) load increases are likley to have minimal ecological impact, moderate (10-50%) load increases are likely to have some degree of downstream impact, but without more information accurate prediction of impact is impossible. Large (> 50%) increases in loads are considered likely to have major impacts downstream.

The lack of measurement data for the proposed crops in these systems prevents precise numeric impact estimates, however experience shows that a 50% increase will have a larger effect than a 10% increase. These systems contain complicated ecological interactions and tipping points, and although the relationship between increased loads and ecological impact is unlikely to be linear, relative increases in severity of impact can be expected with large increases in loads. In others words, although a 50% increase in load may not result in exactly a 1.5-fold level of impact, its impact will almost certainly be greater than that experienced from a 1% (1.01-fold) increase in loads.

Reliable information describing likely runoff behaviour of pesticides from the crops proposed for the Flinders catchments could not be found. Consequently pesticides were not modelled for the proposed agricultural development. The effects of likely pesticide regimes associated with any proposed agricultural development will first need to be thoroughly investigated before development takes place.

6.5.1 INCREASED LOADS ASSOCIATED WITH IRRIGATED FODDER

Flinders and Gilbert catchments

The model shows there will be negligible change in suspended sediment loads in both rivers.

Increases in phosphorus loads above baseline are larger in the Gilbert catchment than the Flinders catchment due to the lower natural loads that occur in the Gilbert catchment. The increases range from 11-21% in the Flinders and 25-50% in the Gilbert catchment, depending on the area planted. These increases are considered to be moderate and likely to have some impact downstream.

Increases in nitrogen loads are also larger in the Gilbert catchment than the Flinders catchment, for the same reason. The increases range from 5-10% in the Flinders and 12-25% for the Gilbert catchment. These increases are considered to be small for the Flinders catchment and moderate for the Gilbert catchment. In the Gilbert catchment there may be some impact downstream.

6.5.2 INCREASED LOADS ASSOCIATED WITH COTTON

Flinders catchment

Potentially, poorly managed ground cover (including no retention of stubble) combined with intensive tillage, can lead to substantial erosion in intense rainfall events in dry tropics cotton cultivation. This has been extensively documented in the Fitzroy catchment, Queensland (Silburn and Hunter, 2009). In the Flinders catchment, the model predicts losses of 200,000-400,000 t/yr at a paddock scale in theory when these practices are used. In contrast, when minimum or zero tillage, stubble retention and contour bank practices are employed, suspended sediment loads can be reduced to near natural levels.

The model predicts small increases in phosphorus loads across all scenarios. Increases in nitrogen loads above baseline in the Flinders catchment are typically small, ranging from 1-7% however moderate (13%) increases are predicted for areas of 20,000 ha targeting potential yields.

Gilbert catchment

As shown for the Flinders catchment, poorly managed ground cover and intensive tillage may result in large increases in suspended sediment loads. Large (> 50%) increases in loads are considered likely to have major impacts downstream.

Increases in phosphorus loads above baseline are small except for a moderate (32%) increase predicted for 20,000 ha under the more intensive practices, which may have some ecological impact downstream.

Predicted increases above baseline for nitrogen are smaller than predicted for the Flinders catchment due to a lower baseline.

6.5.3 INCREASED LOADS ASSOCIATED WITH RICE

Predicted increases in suspended sediment, nitrogen and phosphorus loads are small for all scenarios modelled. Downstream impacts are unlikely.

6.5.4 INCREASED LOADS ASSOCIATED WITH SORGHUM

Flinders catchment

Suspended sediment and nitrogen loads are not predicted to increase significantly under sorghum.

Predicted changes in phosphorus loads for the 10,000 ha scenario range from 13-17%, with little difference between practices. This is a moderate increase, which may result in downstream impacts.

It is not possible to model likely losses of pesticides from irrigated sorghum given lack of specific data. There are almost no data from runoff water for irrigated sorghum in Australia, however, some idea of the likely usage of pesticides in this crop is shown from the residues detected in harvested sorghum fodder. It can be expected that some of these pesticides will also be lost from the paddock to the surrounding water bodies.

In sorghum grain, chlorpyrifos-methyl was detected in 19% of analyses, dichlorvos in 6%, and fenitrothion and methoprene in 4%. The only detections above maximum residue limit (MRL) for food safety were three chlorpyrifos-methyl and two dichlorvos results from 1516 analyses (Flynn, 2005). Twelve chemicals were used that do not have an Australian MRL for cereal hay or straw and are therefore classified as 'Nil detect'. These chemicals are trilfuralin, dimethoate, chlorpyrifos, pendimethalin, piperonyl-butoxide, phosmet, cyhalothrin, permethrin, bromoxynil, 2,4-D, MCPA and dicamba. Residues were found for seven of these chemicals (dimethoate, piperonyl-butoxide, permethrin, bromoxynil, 2,4-D, MCPA and dicamba) (Black, 2008). In 131 instances, residues were found for chemicals that were not recorded in spray diary records as having been applied to the crop from which the hay or straw was made (Black 2008). More information is required on the pesticide management practices used in sorghum cropping to allow estimation of likely environmental risks.

Gilbert catchment

Similar to the Flinders River, suspended sediment and nitrogen loads in the Gilbert catchment are not predicted to increase significantly under the modelled sorghum scenarios, and predicted phosphorus loads were moderate (15-40% increases), with little difference between management practices. There is likely to be some downstream impact from increased phosphorus loads.

6.5.5 INCREASED LOADS ASSOCIATED WITH SUGARCANE

The model suggests that sugarcane cropping is unlikely to present substantial increases in suspended sediment loads to the Gilbert River.

Moderate increases in nitrogen ranging from 16 to 44% are predicted in C and D Class practices respectively, and under 50,000 ha A and B Class practices are predicted to result in nitrogen increases of 15 to 23% respectively, with little difference evidence between A and B Class practices. However, it is understood that the increase in N loss will be lost in the form of dissolved inorganic nitrogen (DIN), mainly as nitrate (Thorburn et al., 2013; Webster et al., 2012), whereas natural nitrogen loss will occur in the form of dissolved organic nitrogen (DON) and particulate nitrogen (PN). DIN is 100% bioavailable and consequently a more significant issue for the downstream river and coastal environments.

Moderate to large increases (11-71%) were predicted for phosphorus in all scenarios, and large increases were predicted for C and D Class practices at 50,000 ha planted (61-71%). These losses will be largely in the form of dissolved inorganic phosphorus (DIP), mainly as phosphate (Brodie, 2006; Brodie and Mitchell, 2005). Given that Australian ecosystems are low in phosphorus and that phosphorus is known to be the limiting nutrient for many freshwater ecosystems, increases of this magnitude are likely to have major impacts downstream (Harris, 2001).

For pesticide loads the difference predicted between A and B Class practices compared to C and D Class practices in all cases is dramatic. The reason for this is that herbicides can be managed if desired, even within B Class practices. Under C and D Class practices the loads are large, in the order of hundreds of kilograms per year. This is likely to have significant effects (as yet unknown due to lack of research) on freshwater and estuarine ecosystems.

6.5.6 INCREASED LOADS ASSOCIATED WITH GUAR

There are insufficient data available to reliably predict the likely scale or significance of any downstream impacts from guar cropping in the Gulf catchments. Low fertiliser rates would suggest that the risk of nutrient enrichment of downstream waterways is low, however without sediment, nutrient and pesticide generation rates, or more detailed understanding of crop management, potential risks are difficult to determine even at the coarsest resolution. At minimum, a hazard assessment must be undertaken prior to development of intensive or large-scale guar cropping in the region.

6.6 Conclusions

The three big changes due to irrigated agriculture in the Flinders and/or Gilbert catchment are associated with:

- Large sediment loss in cotton cropping when stubble retention and minimum tillage practices are not employed. This mirrors what has already occurred in the Fitzroy (Queensland) catchment under similar management practices in the irrigated cropping lands;
- Large phosphorus and nitrogen losses from sugarcane with C and D Class practices; and
- Large herbicide losses from sugarcane with C and D Class practices. For rice, pesticide losses are also potentially substantial but given the lack of data about the likely management practices and usage rates a reliable estimate of these losses is not possible. Cotton losses of pesticides are predicted to be low given that both BT cotton and glyphosate resistant cotton use is planned, hence reducing herbicide and insecticide use.

The implications for downstream environments in the river system, estuary and coastal waters of increased sediment loads are:

- Increased turbidity in the river system. Increased turbidity, especially in deep pools, has the effect of reducing light availability to benthic plant communities. This investigation has shown in previous chapters that waterholes in the Flinders catchment are already highly turbid and further increases in turbidity will not decrease their light climate much compared to the high clarity waterholes of the Gilbert catchment, where even slight changes in turbidity will greatly affect the light climate and thus ecological functioning of those waterholes;
- Increased sediment loading in estuarine and coastal waters also increases turbidity (Bartley et al., 2014; Fabricius et al., 2013), potentially creating similar reductions light for phototrophic benthic communities such as seagrass, corals and microphytobenthos;
- Increased sediment loading in all downstream environments may lead to increased sedimentation and in the extreme, burial of benthic communities; and
- Increased sediment loading of coarse sediments may lead to river bed aggradation as has been seen in the rivers of southern Australia (Prosser et al., 2001) leading to changed ecological conditions for aquatic organisms.

The implications for downstream environments in the river system, estuary and coastal waters of increased nitrogen and/or phosphorus loading are:

- Increased algal blooms in the river. Increased nitrogen and phosphorus loading, as well as light availability and temperature, are associated with most of the large-scale algal blooms observed in Australian rivers and estuaries in recent decades (Davis and Koop, 2006). The Flinders River is naturally turbid so algal blooms are less likely to occur there than in the Gilbert River; and
- Increases in macroalgal biomass at the expense of estuarine and marine benthic organisms such as seagrass and corals have been well documented in many Australian systems under conditions of increased nutrient loading. Pertinent examples are: 1) algal proliferation in the Gippsland Lakes (Webster et al., 2001) believed to be driven by increased phosphorus loading from the catchment areas where algal overgrowth of seagrass is common; and 2) macroalgal competition with coral in nutrient-enriched conditions on inner shelf reefs of the Great Barrier Reef (De'ath and Fabricius, 2010).

The implications for downstream environments in the river system, estuary and coastal waters of increased pesticide loads are:

- Photosystem II (PSII) herbicides such as diuron and atrazine reduce photosynthesis in all plants to an almost equal extent. Hence for these herbicides, concentrations above approximately 500 ng/L will reduce photosynthesis for the period that the concentration persists. Persistence of such concentrations for more than a few days will have negative long term effects on plant growth (Davis et al., 2012; Davis et al., 2011; Magnusson, 2012);
- Other, non-PSII herbicides, e.g. glyphosate may also have direct effects on animals. Glyphosate significantly reduces time to metamorphosis for estuarine crabs (Osterberg et al., 2012). Some herbicides, such as atrazine, are known endocrine disrupting chemicals and their presence in Australian north-east coast waters is believed to have deleterious effects on commercially and recreationally important fish species such as barramundi (*Lates calcarifer*) (Kroon and Hook, 2010), and ecologically important species such as frogs (Rohr et al., 2013; Siddiqua et al., 2013); and
- Imidacloprid is now a controversial insecticide for its adverse effects on bees. Imidacloprid has been implicated in disruption to pollinators, especially bees (van der Sluijs et al., 2013), and its use on flowering crops has recently been banned in the EU (Gross, 2013). International data show that low concentrations of imidacloprid (24h LC50 95% CI range of 6.4-15.8 μg/L) significantly increase the frequency of pre-moult juvenile mortality in estuarine crabs (Osterberg et al., 2012). Imidacloprid is also highly toxic to aquatic invertebrates, with 24 h and 96 h LC50s of 2.1 μg/L and 0.65μg/L respectively (Alexander et al., 2007), and repeated exposure has adverse effects on aquatic invertebrates (Mohr et al., 2012).

Downstream ecosystems such as mangroves, freshwater wetlands, salt marshes and seagrass meadows support nationally important commercial and recreational fisheries such as the Northern Prawn Fishery and the Gulf of Carpentaria Barramundi Fishery. Management of increased pollutant loading to river, estuarine and coastal habitats is essential to secure the future of these fisheries, and can only be achieved by the application of regionally appropriate best management practices.

7 Synthesis

7.1 Key observations and conclusions

1. **Due to prevailing drought conditions there was no stage during the 2012-2013 hydrological year when water could have been extracted from either river system without incurring significant risk of adverse impacts on the size and permanence and ecology of waterholes.**

It is apparent from observations conducted at all 17 of the ephemeral sites examined during this study that the 2012-2013 wet season yielded insufficient water to properly replenish the system. This is, for example, evidenced by the behaviour of waterhole F02 on the Flinders River. This waterhole held reasonable quantities of water through the entire 2012 dry season (see Appendix E site photos). No significant rainfall was registered in the immediate vicinity of the waterhole during the 2012-2013 wet season, but a rain event in the upstream catchment area in December 2012 generated a short flow pulse that briefly raised water levels by more than 2 m. However, this flow was not retained and by January 2013 water levels had fallen back to where they had been in September 2012 in this waterhole. The waterhole continued to dry and by the end of February 2013, has remained dry. The decline in water levels in 2013 was too rapid to be explained by evaporation and suggests that seepage losses into the streambed and adjacent alluvium were much more pronounced in 2013 than they had been in 2012. This implies that the waterhole's capacity to retain water during the dry season is contingent on sufficient sustained flow and/or local rainfall to replenish the subsurface water reserves associated with the river.

The quantity of wet season rainfall and stream flow required to recharge waterholes has not been determined and will not be easy to ascertain as it would vary between individual waterholes and river reaches, nor even between the two catchment examined in the Assessment. However, such information would be required in order to be able to accurately predict the ecological impacts of water extraction, especially during dry years.

2. **The current investigation was carried out during the early stages of a drought. There were indications that drought-related stresses were already beginning to develop at a number of waterholes, however, the ultimate impacts of the prolonged dry conditions will not become evident until the drought has run its course.**

At the end of 2013, the region was still drought-affected and rainfall predictions for the next wet season were not particularly optimistic. If the 2013-2014 wet season fails to bring relief the drought has the potential to rank amongst the worst on record. This will present a unique opportunity to evaluate the drought resistance and resilience of the study sites, and ascertain how much water is required to sustain these river ecosystems. It would therefore be highly advisable to implement a supplementary study to continue monitoring changes in water availability and biophysical conditions during both the later stages of the drought and the post-drought recovery period.

3. **Perennial streams such as those which support the Type 3 waterholes in the Gilbert catchment investigation area are regionally rare and ecologically important sites. The springs and groundwater formations which drive baseflow in these streams, and their associated recharge areas, are worthy of special protection.**

Type 3 waterholes are valuable enough to warrant the commissioning of a study to identify and characterise the sources of the perennial baseflows in these streams, and to devise a management plan to ensure that the groundwater formations which drive the baseflow are adequately protected from excessive water extraction and any agricultural developments with the potential to contaminate the aquifers.

4. **Some of the waterholes that serve as vital freshwater drought refugia are small enough to be adversely affected if even modest volumes of water are extracted either directly from the waterhole or (more commonly) from spears and bores situated within the streambed or adjacent alluvium.**

Perennial streams that depend on groundwater to sustain baseflow (i.e. Type 3 in the nomenclature used here) are rare in this study area. Available evidence suggests that surface flows in other parts of the river system are unlikely to be significantly affected by groundwater extraction. However, as discussed above, there is clear evidence that the capacity for waterholes to retain standing water after flows have subsided can be contingent on the existence of localised subsurface water reserves contained within the streambed and/or adjacent alluvium. The role that these "minor" groundwater reserves play in maintaining standing surface water is poorly understood and warrants further study. However, it is clear that at least some waterholes depend on this resource, and until proven otherwise it would be precautionary to assume that extraction of subsurface waters from the bed sands and alluvium proximal to, and upstream of, key waterholes could have substantial localised impact.

7.2 Summary of findings

Agricultural water resource developments have the potential to cause major environmental disturbances, resulting from changes in the hydrology, limnology and water quality of aquatic habitats. Besides the effects of the impoundments themselves and changes in flow regimes, water resource developments are usually accompanied by a host of other ancillary impacts associated with road networks/crossings, invasive species introduction, and contaminants such as fertilisers and pesticides. Water managers are continually faced with the juxtaposition of protecting river systems for the preservation of biodiversity and species protection, but at the same time also allowing development to occur. The effects of developments may be further compounded by climate induced change to rivers and how they are used, the complexities and uncertainties of which present great challenges to effective river management. For example, this study shows climate change will alter water temperature regime in waterholes, increasing frequency that waterholes will reach critical thresholds for local fish species.

Dry season waterholes are particularly vulnerable to changes in both the quality and quantity of water both within but also entering these systems as surface and/or subsurface flows. Discussions in Chapter 3 underline the importance of the first flush in determining the fate of biological communities as flows insufficient to flush water through and refresh the system can lead to life threatening water quality conditions (e.g. severe and potentially lethal oxygen sags). The initial intention of this investigation was to concentrate on these critical dry season aquatic habitats, and monitor water quality and ecological responses to the first flush. The failed wet season prevented any examination of the responses to flushing and instead this investigation has had to focus on water quality and the fate of aquatic communities during the extended dry season. It should be noted, however, that the field monitoring activities associated with this project ceased during the failed wet season (i.e. during the early stages of the 2013 drought), so the full implications of the drought conditions could not be ascertained.

The key findings of this report are summarised as follows.

- **Waterholes examined here fall into one of three waterhole classes.**

Waterholes examined here fall into one of three waterhole classes or typologies (Chapter 3). Shifts in waterhole typology may occur under natural conditions (a result of wetter or drier periods for example) and water resource development as a result of changes in the quality and/or quantity of waters entering the systems. The identified site types comprise:

Type 1 – Persistently turbid, highly ephemeral flow (includes all of the Flinders catchment sites examined in this study, but only a few Gilbert catchment sites);

Type 2 – Seasonally clear, seasonally intermittent flow (includes the majority of non-perennial Gilbert catchment sites); and

Type 3 – Persistently clear, perennial flow (comprises selected tributary streams in the Gilbert catchment).

- **Water clarity is important in determining key chemical, physical and biological properties in waterholes of the Flinders and Gilbert Rivers.**

Waterhole clarity is a key driver of ecosystem processes and was the dominant driver separating the ecology and biotic community composition of waterholes between the Flinders and Gilbert catchments (Chapters 3 and 5). The phototrophic community is particularly vulnerable to changes in turbidity and light availability. Algae are known to drive primary production in many rivers and evidence from northern Australia suggests that benthic algae production provides an important source of energy to higher trophic groups (Jardine et al., 2012; Warfe et al., 2013). Hence, waterholes that currently have relatively clear waters (e.g. Types 2 and 3 in the Gilbert River catchment) are particularly vulnerable to changes in turbidity resulting from development as even minor variations will cause large changes in the depth of light penetration and thus waterhole metabolism (production and consumption of oxygen) among many other effects. Conversely, in the turbid Type 1 waterholes of the Flinders catchment, variations in turbidity will have little effect upon the depth of light penetration through the water column and the associated ecosystem processes that follow.

- **Patterns of water column stratification vary between different waterhole types and this has consequences for how water bodies respond to changes in hydrology.**

Waterhole temperature stratification is an important characteristic of waterholes in the Assessment (Chapter 3). The development of thermal stratification prevents circulation of the whole water body such that the bottom and surface layers may have very different water quality characteristics. Under these conditions, bottom waters, isolated from gas exchange contact with the atmosphere and often receiving less sunlight, are prone to becoming hypoxic. Stratification was most pronounced in the lentic Type 1 waterholes of the Flinders catchment, where the turbidity retained heat within the surface layers, strengthening stratification. Type 2 waterholes (i.e. most of the lentic sites in the Gilbert study area) developed less severe temperature gradients because the water was clear enough to allow sunlight to penetrate deeper into the water column; nevertheless, most sites were still thermally stratified for significant periods during this study. In contrast, Type 3 waterholes (i.e. the perennially flowing sites in the Gilbert River catchment) only stratified for brief periods during daylight hours and the water column generally became mixed each night, indicating that there was sufficient flow to prevent the development of stable stratification. As a result of the overnight mixing of surface and bottom waters, and the increased aeration capacity provided by the flowing water, these waterholes maintained consistently higher dissolved oxygen concentrations than the lentic sites and accordingly were far less susceptible to the development of hypoxia-related problems.

- **Dissolved oxygen concentrations often reach critically low conditions in some waterholes of the Assessment area.**

Dissolved oxygen status is of fundamental importance in freshwater environments and low oxygen concentrations provide a critical and ubiquitous stressor to aquatic fauna, especially in tropical waters with little or no flow. The impacts of periodic acute deoxygenation may be very conspicuous such as major fish kills. However, probably more pervasive is the chronic longer terms effects of frequent or persistent low oxygen levels in reducing fish health, growth rates, reproductive fitness and abundance. Temperature and dissolved oxygen conditions are already at or approaching levels stressful to aquatic biota in many of the waterholes examined in the Assessment (Chapter 3). Further major reductions in flow and waterhole volume could exacerbate already stressful conditions resulting in refuges for aquatic biota within a waterhole becoming fewer and/or less viable.

- **Waterhole temperatures frequently exceed critical thresholds for fish.**

Waterhole surface water temperatures frequently exceed optimal and lethal thresholds for fish (Chapter 4). Due to their heat-trapping ability, surface water temperatures in turbid waterholes were greater than for clear waterholes. Turbid waterholes, however, maintained cooler bottom water temperatures than clear waterholes, hence the temperature differential between surface and bottom layers was generally greater for turbid than for clear waterholes. In stratified waterholes, bottom waters can act as a cool water refuge for biota on the proviso that other water quality conditions (particularly oxygen conditions) are suitable. However, in stratified waterholes, the bottom water layer is often hypoxic, meaning that mobile aquatic species face the challenge of excessively warm surface waters and hypoxic bottom waters. Under a global warming scenario of a 2^{o}C increase in air temperature (relative to 1990), waterhole temperatures in the Assessment area are likely to increase by around 1^{o}C. The increase in water temperature is only half the increase in air temperature (due to the thermal buffering capacity of water), and because surface water temperatures are already at or near stressful thresholds, this 1^{o}C rise markedly increases the amount of time water temperatures exceed optimal and lethal thresholds for fish. Increased water temperatures also greatly increase (non-linearly) the rate of chemical reactions, including the consumption of oxygen, creating a situation of increased respiratory demand but reduced oxygen availability. Reductions in waterhole depths as a result of extraction will result in larger diurnal temperature fluctuations and increases daily maxima that will negatively affect the suitability of these waterholes as aquatic habitat.

- **Waterholes are critical refugia for a range of aquatic biota during the dry season (and even more critical during prolonged droughts.**

Waterholes act as important refugia for freshwater biota during the dry season. Evidence here (Chapter 5) and from previous studies in northern Australia (see TRaCK – www.track.org.au) demonstrate the importance of dry season waterholes in supporting a diverse assemblage of aquatic species that rely on these refugia to survive periods of drought. This accumulated evidence supports the notion that dry season waterholes are critical aquatic habitats in the Assessment area and will require particular management consideration should development proceed. Clear perennial streams are relatively rare in the dry tropics and have particularly high intrinsic ecological value as freshwater refugia during droughts. The biological implications for changes in waterhole persistence and habitat quality depend on numerous factors and it is difficult to predict the effect of altered conditions as it is contingent on the type of development and how it is operated, the nature of hydrological and limnological alterations, species composition and interactions (and their responses to the changes). However, reduced flushing and longer periods of stagnation in waterholes of the Assessment area, and associated deterioration in water quality are likely to have significant consequences for the health, growth and reproduction success of biota that use them. Reduced flow and longer periods between flows are also likely to change the spatial and temporal distribution of waterholes. The study of McJannet et al. (2013) has provided preliminary evidence of a relationship between cease to flow and waterhole size.

- **Quantitative modelling shows that agricultural development has the potential to elevate sediment, nutrient and pesticide inputs into streams of the Assessment area.**

Agricultural water use has significant implications for surface waters. Nutrient, sediment and pesticide load modelling undertaken as part of this Assessment (Chapter 6) suggests that at least small increases in nutrient loadings are expected under most, even modest agricultural development scenarios considered here. Modelling also predicts large sediment loss in cotton cropping when stubble retention and minimum tillage practises are not employed and large phosphorus, nitrogen and herbicide losses from sugarcane with a potential yield management approach in which water, nutrients and pesticides are supplied to guarantee nutrient limitation and pest damage does not occur. For rice, pesticide losses are also potentially substantial but given the lack of data about the likely management practices and usage rates a reliable estimate of these losses was not possible.

- **Conceptual modelling suggests that increased delivery of agricultural contaminants and uninformed use of water resources, both surface and ground water, have the potential to impact on riverine ecosystems of the Flinders and Gilbert Rivers.**

Nutrients are commonly implicated in water quality decline in irrigation districts (Perna, 2003; 2004; Tait and Perna, 2000). Experience in other irrigation districts of north Queensland has shown that this could then be responsible for the proliferation of weeds and the eutrophication of aquatic habitats, resulting in poor water quality and localized extirpation of fish and other aquatic species (Butler and Crossland, 2003; Pearson et al., 2003; Perna, 2003; 2004; Tait and Perna, 2000). Evidence of nutrient limitation to productivity in downstream and estuarine reaches of catchments in north Queensland (Burford et al., 2011; Faggotter et al., 2013; Webster et al., 2005) suggests that elevated nutrients will be a concern.

Chemicals such as pesticides (including herbicides and their derivatives) applied to agricultural lands have serious implications for receiving freshwater and marine environments. Such chemicals are regularly found in existing irrigation districts in north Queensland (Davis et al., 2008; Lewis et al., 2009) and as modelled here, increased pesticide loadings could be expected under the agricultural scenarios considered here. Monitoring of pesticides in the Burdekin River catchment revealed that the majority of residues are exported during major flow events although high levels of some chemical residues were also detected during low flow conditions which persist for most of the year (Davis et al., 2008). There is a lack of knowledge on the effects of potentially harmful concentrations of pesticides on tropical freshwater species. This is compounded by the difficulty in predicting toxicities as they may be modified by water quality and potential interactions between chemicals. Potential effects of herbicides on autotrophic primary productivity require particular consideration given the importance of primary production in supporting food webs in northern catchments. Particularly concerning are the chronic effects of long-term exposure to aquatic biota (Davis et al., 2011) of which we know very little. Agricultural contamination can also have more far reaching effects, impacting upon receiving marine systems (Lewis et al., 2009).

Considerable research aimed at reducing sediment, nutrient and pesticide losses from farms to the Great Barrier Reef has been conducted in recent years. This research demonstrates the high levels of these contaminants are being exported to aquatic receiving environments (Brodie et al., 2013). However, research aimed at reducing such losses has also been promising and modelling conducted here (Chapter 6) and elsewhere shows the adoption (or not) of best management practices and other recently-introduced means of reducing chemical losses make a significant difference to ecological outcomes (Brodie et al., 2013).

- **Impacts associated with increased agricultural activity and water use have the potential to impact on ecosystems far removed from the areas in which these activities are likely to occur e.g. estuaries and near shore coastal systems.**

Near shore regions and their fisheries are highly vulnerable to changes in freshwater flows to estuaries. Reduced freshwater flows have implications for salinity gradients, nutrients and the physical characteristics of estuarine environments. The Gulf of Carpentaria prawn fishery is well known for the strong link between river flow and fishery production, with a higher number of prawn landings following a high wet season flow (Staples and Vance, 1985). In fact, more recently this relationship has been successfully used to develop sophisticated modelling tools to determine the effort combinations of allowable prawn catch across the stock regions each year in an attempt to ensure ongoing sustainable management of this highly valued fishery (Buckworth et al., 2013). The recruitment of other species including barramundi and king threadfin salmon have been linked to characteristics of wet season flows (Halliday et al., 2008; Staunton-Smith et al., 2004). The body of research from temperate and tropical estuaries clearly demonstrates that the positive relationship between river flow and fishery catches is a common theme and should be seriously considered when assessing the economic merits and environmental impacts of water resource developments.

7.3 Other potential impacts of agricultural water resource development

There is a large range of potential impacts from agricultural water resource development. Such effects will depend on the type of proposed development and how it is operated as well as its geographic and biological context. Without specific information regarding the nature of the development, only broad generalisations can be made regarding their potential effects on the ecology of aquatic habitats in the Assessment. Here this investigation has focused on those environmental effects thought, based on experience gather from research on other north Queensland irrigated areas, to be most relevant to potential developments in the Assessment. This does not mean that there are no other effects resulting from development. In fact, unforeseen issues will arise as environmental changes associated with irrigation developments are not easily predicted before or during development, even where the nature of development is better defined than in the current Assessment. For example, the studies conducted prior to construction of the Burdekin Falls Dam and associated irrigation expansion concluded that the impoundment waters would be clear and that this would be of benefit to the aquatic habitats downstream. However, the dam waters have been persistently turbid since the dam was constructed in 1987 (Faithful and Griffiths, 2000) and their release downstream for irrigation has resulted in >100 km of river below the dam, and numerous formerly clear floodplain streams and wetlands, also becoming persistently turbid. This has had significant and widespread negative consequences for the ecology of those aquatic habitats.

Additionally, the environmental harm being caused by exotic weeds, that have found the post-development hydrology of the irrigation area on the Burdekin floodplain (formerly a predominantly seasonal system, but now permanently freshwater) very favourable, was not predicted in advance. Similar, though not as widespread and devastating, effects are seen in the Mareeba-Dimbulah irrigation district (Butler et al. 2007). A key element underlying such profound ecological changes is the conversion of seasonal or ephemeral streams to essentially perennial systems. Dry season conditions restrict the excessive growth of introduced plants, and favour local, native species. Perennial or extended dry season flow, especially where nutrient levels are also elevated (likely in irrigated districts), enables aggressive fast-growing weeds to proliferate, as seen in the Burdekin and Mareeba-Dimbulah irrigation districts. Such increases in flow result where irrigation water is transported using natural stream channels as conduits and where inefficient irrigation methods (e.g. flood irrigation) result in excessive agricultural runoff. Weed growth in these areas can be very dense and the waters within and below these weed infestations severely hypoxic leading to local extirpation of many species and major loss of ecosystem functioning.

A strong understanding of pre-development baseline conditions of aquatic habitats and an adaptive management program that can react proactively to changes in these conditions as they arise, are essential in managing environmental challenges that will inevitably arise during changes in land use to irrigation. Such environmental challenges, even quite significant ones, may not occur for many years post-development. They may gradually develop over time or, for example, may result from the introduction of new weeds that grow vigorously in the modified environment. An adaptive management program is essential to determine the best regime to apply, and it is expected that the required regime will change over time as in-stream habitat changes and adapts to its new landscape paradigm.

Irrigation scheme design is likely to have major consequences for environmental outcomes. In the Burdekin irrigation area furrow/flood irrigation has resulted in substantial alterations to the flow regimes and contributed to poor water quality of the natural creeks receiving the tailwaters (Burrows et al., 2012; Veitch et al., 2008). Mitigation of potential tailwater impacts may be achieved through recycling basins, retention basins and artificial wetlands and more importantly, efficient irrigation systems that use less water. Such mechanisms will need to be incorporated in the design and environmental management planning for the proposed development (Tait and Perna, 2000). More recent irrigation schemes with pressurized supply, trickle feed lines, and minimal tailwater drainage certainly reduce some of the highly damaging effects of flood irrigation systems but are not without their adverse impacts (Hart, 2004).

Salinisation of irrigated land is one of the most widespread and ubiquitous problems associated with irrigation (Ayres and Westcot, 1994). These are usually problems associated with surface irrigation where soils are waterlogged and saline groundwater rises to the surface. This problem is typified by the Burdekin River irrigation area where inadequate sub-surface drainage has led to rising saline groundwaters and 4,000 hectares of irrigated land are in imminent danger of going out of production (DERM, 2013).

Most wetlands and watercourses examined in tropical irrigated districts have dangerously low dissolved oxygen (Butler and Burrows, 2007; Pearson et al., 2003), a critical element for the survival of aquatic fauna. Farm runoff has been conclusively linked to these low dissolved oxygen concentrations (Butler et al., 2007; Butler and Crossland, 2003; Perna and Burrows, 2005; Veitch et al., 2008), especially in sugar cane farming areas where sugar cane juice itself has a high Biological Oxygen Demand (BOD), and can, when washed into adjacent waterways, rapidly consume all the available oxygen (Butler and Crossland, 2003; Pearson et al., 2003). Issues related to high BOD are particularly sensitive to the timing and scale of runoff. The first rainfall event after harvest is usually critical as high levels of organic matter, including cane juice, are washed into receiving waters (Pearson et al., 2003). Organic materials with high oxygen demands entering well flushed systems are less likely to cause problems. However, with reduced flows problems associated with elevated BOD are accentuated and oxygen levels can become depleted rapidly with catastrophic effects on aquatic biota.

Riparian zones in the dry tropics require active management. For graziers, riparian zones are part of their productive landscape and they therefore manage them as best they can. Irrigators do not use riparian zones as part of their productive landscape and thus generally do not apply a similarly active management regime. In the case of the Burdekin and Mareeba-Dimbulah irrigation areas, this lack of management has resulted in significant degradation of riparian zones when the land management changed from grazing to cropping (Tait and Perna, 2000). A visually obvious example is that manner in which para grass (*Urochloa mutica*) has proliferated and dominated riparian zones since the cessation of grazing, when land was converted to cropping. In the Burdekin catchment, this has resulted in recent attempts to reintroduce grazing (and fire management) to riparian zones. Some examples have been quite successful in rehabilitating wetlands (Tait and Perna, 2000), but the biggest impediment is that most riparian corridors are too small for the commercially-viable reintroduction of grazing, fire, or other forms of active management. In new irrigation areas, having cropped areas well away from riparian zones and on flat terrain (reducing sediment runoff) would reduce similar environmental problems. In Barrattas Creek in the Burdekin irrigation area, an undeveloped buffer of varying width, but up to 1km wide, was retained when the area was developed for irrigated sugar cane in the mid 1990s. This has served well for some purposes but with active maintenance and management has gradually declined due to invasive weeds, poor regeneration of riparian trees, lack of an on-going program of maintenance, and an inability to graze and burn key locations along the corridor (Burrows et al., 2012; Veitch et al., 2007).

Under the current Gulf Water Resource Plan (DNRMW, 2006) allocations of 80,000 and 15,000 megalitres of water are available (~ July 2013) for new irrigation developments in the Flinders and Gilbert Catchments respectively. Further increases in allocations that significantly alter flooding and peak wet season flows, however, will impact upon river structure and form and, the ability of rivers to act as conduits for the movement and transport of biota and abiotic material. Movement to access food, for reproduction or to find permanent waters is characteristic of most northern Australian fish species (Pusey et al., 2011). The presence of physical barriers such as impoundment walls and changes in high flow and flood events hinder migration and dispersal and in some cases may prevent species from completing critical life history stages. This will contribute to the decline and even the localised extinction of species that depend on movement within streams and access to inundated floodplain habitats during certain phases of their life cycle. Altering flow in both catchments also requires some consideration on the delivery of nutrient rich flow to the coastal zone, and coastal fisheries production.

Effective management and planning to assess the associated risks and minimise the ecological consequences of water resource development is essential. The list of potential environmental impacts is long, but the options for management to redress many of these also exist, if managers are willing to implement them. The importance of providing sufficient river flows alongside good land management practices (i.e. best practices) cannot be understated. It not only benefits river ecosystem health but also ensures longer term benefits of natural resources to human users.

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Appendix A Water and sediment quality data

Summary of water quality laboratory analysis performed and abbreviated parameter names. See Chapter 3 for reporting limits and analysis methods

PARAMETER	PARAMETER	ABBREVIATED NAME
General water quality	Electrical conductivity	EC
	Temperature	TEMP
	pH	pH
	Dissolved oxygen saturation	DO SAT
	Total Suspended Solids	TSS
	Alkalinity	ALKA
	Hardness	HARD
Nutrients	Total Nitrogen	TAN
	Total Filterable Nitrogen	TFN
	Ammonia	NH3
	Nitrite	NO2-
	Nitrate	NO3-
	Total Phosphorus	TAP
	Total Filterable Phosphorus	TFAP
	Filterable Reactive Phosphorus	FRAP
	Nitrogen oxides	NOx
	Aqueouse Particulate Nitrogen	APN
	Dissolved Organic Nitrogen	ADON
	Urea-Nitrogen	AUN
	Particulate Phosphorus	APP
	Dissolved Organic Phosphorus	ADOP
	Dissolved Inorganic Nitrogen	ADIN
Carbon	Total Organic Carbon	ATOC
	Dissolved Organic Carbon	ADOC
	Dissolved Inorganic Carbon	ADIC
Chlorophyll	Aqueous Surface Chlorophyll 'a'	CHL 'a' SURF
(Acid extraction method 3000B)	Aqueous Integrated Chlorophyll 'a'	CHL 'a' INTEG
	Aqueous Phaeophytin	PHAE SURF
	Aqueous Integrated Phaeophytin	PHAE INTEG
	Total Surface Chlorophyll 'a' (Chloropyll 'a' + Phaeophytin)	TSURF CHL 'a'
	(Total Surface Chlorophyll 'a') – (Total Integrated Chlorophyll 'a')	DIFF CHL 'a'
Isotopes	Aqueous Del ^{13}C	Del ^{13}C
	Aqueous Del ^{15}N	Del ^{15}N
Major ions	Aqueous Calcium	ACa
	Aqueous Magnesium	AMg
	Aqueous Sodium	ANa

Aqueous Potassium	AK
Aqueous Chlorine	ACl
Aqueous Sulfate	ASO4
Calcium	Ca
Magnesium	Mg
Sodium	Na
Potassium	K
Chlorine	Cl
Sulfate	SO4

Flinders catchment water quality laboratory analysis results. (-) no data

WATERHOLE	DATE	TIME	pH	EC µS/cm	TSS mg/L	TDS mg/L	ALKA	HARD	ATOC mg/L	ADOC mg/L	ADIC mg/L	ADIN mg/L	DEL-^{13}C ‰	DEL ^{15}N ‰	CHL 'a' SURF µg/L	CHL 'a' INTEG µg/L	PHAE SURF µg/L	PHAE INTEG µg/L	TSURF CHL 'a' µg/L	DIFF CHL 'a' µg/L
F01	08/09/2012	13:45	-	-	-	415.4	87.0	-	8.9	10.6	10.4	9	-21.30	3.10	4.01	6.23	1.13	1.87	5.14	-
	29/10/2012	9:30	8.4	810	21	491.1	305.0	-	16.1	14.8	36.6	10	-29.31	-1.94	18.16	17.62	3.15	3.31	21.31	0.38
	07/12/2012	13:00	8.41	860	20	529.0	134.2	-	6.5	6.2	16.1	9	-29.87	-1.03	12.97	12.91	1.98	3.60	14.95	-1.56
	19/12/2012	13:40	7.84	292	82	172.0	30.0	84.5	13.6	12.8	3.6	81	-24.70	8.10	0.97	0.53	0.20	0.21	1.17	-
	17/01/2013	9:00	7.93	324	31	198.8	130.8	106.1	6.6	5.9	15.7	23	-26.60	7.60	8.60	8.90	3.23	3.56	11.83	-0.63
	01/06/2013	8:20	-	-	-	253.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F02	07/09/2012	16:00	-	-	10	200.2	107.5	-	4.1	4.6	12.9	10	-	-	9.35	9.01	1.17	1.74	10.52	-0.23
	28/10/2012	15:30	9.45	557	37	338.1	149.2	-	27.4	30.3	17.9	17	-23.50	-	33.11	-	8.01	-	41.12	-
	19/12/2012	17:40	7.76	213	230	125.6	20.0	63.9	10.6	10.3	2.4	93	-26.30	-2.57	1.78	-	0.71	-	2.49	-
	14/01/2013	12:45	7.91	618	810	249.2	422.5	68.9	39.0	33.6	50.7	371	-22.40	19.60	46.99	37.38	12.82	7.48	59.81	14.95
	23/02/2013	16:00	8.37	374	745	207.0	142.7	112.8	21.9	15.7	17.1	12	-24.50	-	185.78	-	61.53	-	247.31	-
F03	07/09/2012	12:30	-	-	5.8	108.1	95.0	-	7.8	9.1	11.4	14	-22.90	11.80	3.67	4.34	1.00	1.74	4.67	-1.41
	29/10/2012	14:00	9.27	229	16	137.0	73.3	-	22.2	23.4	8.8	21	-25.00	3.00	13.68	9.35	0.80	2.34	14.48	2.79
	08/12/2012	16:45	9.2	326	40	203.0	65.0	-	17.9	17.9	7.8	11	-27.72	-4.10	18.69	17.36	2.80	4.14	21.49	-0.01
	19/12/2012	16:50	9.15	366	26	218.7	45.8	42.3	19.0	17.4	5.5	14	-26.29	-7.14	12.97	11.57	3.32	5.87	16.29	-1.15
	14/01/2013	15:15	8.43	405	18	377.6	142.5	140.2	8.5	7.9	17.1	20	-24.80	10.90	62.30	-	47.35	-	109.65	-
F04	08/09/2012	8:00	-	-	-	161.8	125.0	-	10.5	10.9	15.0	14	-27.10	6.50	10.68	7.34	1.00	1.54	11.68	-
	28/10/2012	10:00	8.8	330	100	201.3	70.0	-	30.9	32.9	8.4	19	-26.90	2.50	24.03	-	4.94	-	28.97	-
	08/12/2012	9:00	8.42	561	200	342.2	75.0	-	40.5	38.9	9.0	15	-28.92	-5.18	100.13	-	21.36	-	121.49	-
F05	08/09/2012	9:00	-	-	14	223.5	133.3	-	3.2	3.8	16.0	26	-26.37	-1.84	3.67	3.67	1.00	1.70	4.67	-0.70
	27/10/2012	13:00	8.56	423	22	256.9	101.7	-	10.3	9.8	12.2	17	-28.20	7.90	4.27	4.27	0.96	0.71	5.23	0.25
	09/12/2012	10:00	8.57	480	13	296.9	115.8	-	7.7	6.8	13.9	9	-30.15	-6.41	8.19	8.01	0.53	0.59	8.72	0.12
	20/12/2012	7:15	7.83	270	290	163.4	32.5	88.0	9.5	9.3	3.9	324	-29.04	-3.97	2.00	-	0.33	-	2.33	-
	23/02/2013	13:30	8.83	302	41	173.4	145.3	102.1	6.3	4.7	17.4	11	-23.70	7.40	24.04	17.73	3.05	4.81	27.09	4.55

	31/05/2013	10:20	-	-	-	248.3	-	-	-	-	-	-	-24.40	20.90	-	-	-	-	-	-
F07	09/09/2012	10:30	-	-	18	249.0	160.0	-	4.6	4.8	19.2	8	-	-	7.01	7.01	1.87	1.87	8.88	0.00
	25/10/2012	15:00	8.43	453	12	278.5	137.5	-	11.1	11.8	16.5	21	-29.90	6.30	4.01	6.48	0.43	1.79	4.44	-3.83
	11/12/2012	12:30	8.53	502	21	317.3	123.3	-	8.0	7.4	14.8	9	-29.92	-0.61	9.35	10.15	1.56	2.56	10.91	-1.80
	20/12/2012	11:30	8.49	519	27	316.5	71.7	130.9	6.5	5.9	8.6	14	-29.25	-5.13	9.49	-	2.14	-	11.63	-
	15/01/2013	13:35	8.02	210	260	127.3	90.0	52.3	5.5	3.7	10.8	37	-25.80	3.20	7.57	1.78	2.09	2.21	9.66	-
	22/02/2013	9:00	8.09	254	17	143.9	94.0	68.9	6.4	4.4	11.3	11	-27.30	-1.20	7.43	5.30	2.20	5.02	9.63	-0.69
	30/05/2013	15:15	-	-	-	213.4	-	-	-	-	-	-	-25.60	15.00	-	-	-	-	-	-

WATERHOLE	DATE	TIME	pH	EC µS/cm	TSS mg/L	TDS mg/L	ALKA	HARD	ATOC mg/L	ADOC mg/L	ADIC mg/L	ADIN mg/L	DEL-^{13}C ‰	DEL ^{15}N ‰	CHL ‘a’ SURF µg/L	CHL ‘a’ INTEG µg/L	PHAE SURF µg/L	PHAE INTEG µg/L	TSURF CHL ‘a’ µg/L	DIFF CHL ‘a’ µg/L
F08	09/09/2012	14:00	-	-	12	143.4	91.7	-	3.9	4.7	11	27	-28.80	6.60	5.34	6.01	2.60	1.94	7.94	-0.01
	25/10/2012	9:00	8.1	273	5.4	163.0	81.7	-	8.8	13.4	9.8	19	-29.16	-13.38	6.23	3.56	1.25	2.36	7.48	1.56
	11/12/2012	8:30	8.23	296	19	183.0	86.7	-	8.1	5.8	10.4	13	-28.70	-9.14	6.10	6.48	3.24	3.66	9.34	-0.80
	20/12/2012	8:45	8.39	303	21	183.9	48.3	62.3	4.7	4.6	5.8	15	-24.60	-	6.97	-	1.57	-	8.54	-
	15/01/2013	15:00	8.51	320	46	197.3	183.3	67.3	4.6	3.8	22	24	-26.80	13.40	7.77	6.68	3.79	2.98	11.56	1.90
	22/02/2013	13:30	8.58	359	14	205.6	169.3	73.9	5.3	4.1	20.32	30	-26.70	9.10	7.69	12.22	1.71	2.95	9.40	-5.77
	30/05/2013	17:33	-	-	-	268.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F09	10/09/2012	8:30	-	-	19	153.4	139.2	-	4	3.8	16.7	29	-31.20	5.00	20.03	20.69	5.21	6.41	25.24	-1.86
	25/10/2012	11:30	8.21	301	28	184.4	110.0	-	9.4	10.4	13.2	22	-30.55	-1.04	26.70	20.83	6.63	8.33	33.33	4.17
	10/12/2012	8:30	7.81	341	30	213.0	115.8	-	8.8	6.9	13.9	42	-29.50	-0.55	25.81	29.84	10.95	10.84	36.76	-3.92
	20/12/2012	10:00	8.22	516	30	215.4	115.0	114.5	6.8	6	13.8	29	-28.60	4.00	33.27	-	8.13	-	41.40	-
	15/01/2013	9:00	8.03	218	27	134.6	115.8	83.0	4.1	3.7	13.9	22	-28.90	7.80	22.93	5.65	3.68	5.12	26.61	-
	30/05/2013	11:45	-	-	-	218.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F10	08/09/2012	11:30	-	-	15	468.8	252.5	-	26.8	29.1	30.3	17	-26.80	6.40	-	-	-	-	-	-
	27/10/2012	9:30	9.12	1516	25	931.7	456.7	-	113.3	102.9	54.8	11	-25.44	-5.12	27.29	-	8.84	-	36.13	-

Flinders catchment water quality laboratory analysis results: nutrients

WATERHOLE	DATE	TIME	TAN µgN/L	T-FAN µgN/L	NH3 µgN/L	N02- µgN/L	N03- µgN/L	TAP µgP/L	T-FAP µgP/L	F-RAP µgP/L	NOx µg/L	APN µgN/L	ADON µgN/L	AUN µgN/L	APP µgP/L	ADOP µgN/L
F01	08/09/2012	13:45	829	595	7	1	1	53	11	9	2	234	586	23	42	2
	29/10/2012	9:30	838	433	6	<1	4	69	12	1	4	405	423	19	57	11
	07/12/2012	13:00	711	373	4	1	4	41	12	3	5	338	364	40	29	9
	19/12/2012	13:40	795	762	7	10	64	282	216	209	74	33	681	137	66	7
	17/01/2013	9:00	910	473	2	1	20	70	29	13	21	437	450	-	41	16
F02	07/09/2012	16:00	552	279	6	1	3	39	12	11	4	273	269	20	27	1
	28/10/2012	15:30	1875	1289	11	<1	6	187	53	7	6	586	1272	246	134	46
	19/12/2012	17:40	739	690	13	1	79	323	202	186	80	49	597	117	121	16
	14/01/2013	12:45	6446	4272	353	1	17	525	141	1	18	2174	3901	-	384	140
	23/02/2013	16:00	3449	998	9	1	2	662	57	3	3	2451	986	-	605	54
F03	07/09/2012	12:30	909	647	11	1	2	41	22	9	3	262	633	12	19	13
	29/10/2012	14:00	1288	986	16	<1	5	103	30	5	5	302	965	31	73	25
	08/12/2012	16:45	1785	1309	6	1	4	98	33	1	5	476	1298	1298	65	32
	19/12/2012	16:50	1582	1429	7	1	6	95	34	29	7	153	1415	75	61	5
	14/01/2013	15:15	1191	689	3	1	16	158	20	1	17	502	669	-	138	19
F04	08/09/2012	8:00	1099	733	10	1	3	67	22	8	4	366	719	10	45	14
	28/10/2012	10:00	1951	1262	12	<1	7	225	36	1	7	689	1243	22	189	35
	08/12/2012	9:00	4225	2860	8	1	6	351	86	1	7	1365	2845	2845	265	85
F05	08/09/2012	9:00	369	214	7	1	18	19	6	5	19	155	188	17	13	1
	27/10/2012	13:00	479	305	13	<1	4	45	8	1	4	174	288	3	37	7
	09/12/2012	10:00	505	262	4	<1	5	25	9	4	5	243	253	253	16	5
	20/12/2012	7:15	1023	905	5	2	317	243	94	85	319	118	581	90	149	9
	23/02/2013	13:30	520	307	7	1	3	69	11	2	4	213	296	-	58	9
F07	09/09/2012	10:30	394	236	6	1	1	30	5	5	2	158	228	59	25	1
	25/10/2012	15:00	506	323	16	<1	5	39	8	1	5	183	302	7	31	7
	11/12/2012	12:30	579	377	4	<1	5	36	11	3	5	202	368	368	25	8

	20/12/2012	11:30	585	537	5	<1	9	52	14	13	9	48	523	43	38	1
	15/01/2013	13:35	467	238	3	1	33	199	87	79	34	229	201	-	112	8
	22/02/2013	9:00	297	143	6	1	4	91	37	28	5	154	132	-	54	9

WATERHOLE	DATE	TIME	TAN µgN/L	T-FAN µgN/L	NH3 µgN/L	N02- µgN/L	N03- µgN/L	TAP µgP/L	T-FAP µgP/L	F-RAP µgP/L	NOx µg/L	APN µgN/L	ADON µgN/L	AUN µgN/L	APP µgP/L	ADOP µgN/L
F08	09/09/2012	14:00	438	363	11		15	126	61	53	16	75	336	42	65	8
	25/10/2012	9:00	631	477	13	<1	6	152	39	29	6	154	458	25	113	10
	11/12/2012	8:30	628	291	4	1	8	93	36	26	9	337	278	278	57	10
	20/12/2012	8:45	388	256	4	1	10	84	30	23	11	132	241	25	54	7
	15/01/2013	15:00	638	481	5	1	18	82	33	7	19	157	457	-	49	26
	22/02/2013	13:30	388	244	6	1	23	92	38	25	24	144	214	-	54	13
F09	10/09/2012	8:30	665	233	7	1	1	52	7	3	2	432	224	51	45	4
	25/10/2012	11:30	800	348	13	<1	9	70	14	8	9	452	326	1	56	6
	10/12/2012	8:30	1018	316	31	1	10	82	14	3	11	702	274	274	68	11
	20/12/2012	10:00	972	348	5	1	23	87	16	4	24	624	319	16	71	12
	15/01/2013	9:00	528	243	4	1	17	48	9	3	18	285	221	-	39	6
F10	08/09/2012	11:30	2368	2082	15	1	1	41	30	6	2	286	2065	123	11	24
	27/10/2012	9:30	4411	3772	7	<1	4	169	101	86	4	639	3761	1	68	15

Flinders catchment water quality laboratory analysis results: major ions

WATERHOLE	DATE	TIME	ACa mg/L	AMg mg/L	ANa mg/L	AK mg/L	ACl mg/L	ASO4 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L
F01	19/12/2012	13:40	19	9	24	5	17	22	0.948	0.741	1.044	0.128	0.480	0.458
	17/01/2013	9:00	26	10	25	4	14	20	1.297	0.823	1.088	0.102	0.395	0.416
F02	19/12/2012	17:40	19	4	14	4	8	28	0.948	0.329	0.609	0.102	0.226	0.583
	14/01/2013	12:45	21	4	112	7	40	4	1.048	0.329	4.872	0.179	1.128	0.083
	23/02/2013	16:00	32	8	33	7	10	66	1.597	0.658	1.436	0.179	0.282	1.374
F03	19/12/2012	16:50	12	3	63	6	17	4	0.599	0.247	2.741	0.153	0.480	0.083
	14/01/2013	15:15	38	11	31	6	12	44	1.896	0.905	1.349	0.153	0.339	0.916
F05	20/12/2012	7:15	27	5	18	4	8	43	1.347	0.411	0.783	0.102	0.226	0.895
	23/02/2013	13:30	31	6	24	4	8	32	1.547	0.494	1.044	0.102	0.226	0.666
F07	20/12/2012	11:30	31	13	57	6	32	40	1.547	1.070	2.480	0.153	0.903	0.833
	15/01/2013	13:35	16	3	22	2	6	22	0.798	0.247	0.957	0.051	0.169	0.458
	22/02/2013	9:00	21	4	25	3	6	24	1.048	0.329	1.088	0.077	0.169	0.500
F08	20/12/2012	8:45	20	3	40	4	12	13	0.998	0.247	1.740	0.102	0.339	0.271
	15/01/2013	15:00	22	3	43	5	13	14	1.098	0.247	1.871	0.128	0.367	0.291
	22/02/2013	13:30	23	4	47	5	12	16	1.148	0.329	2.045	0.128	0.339	0.333
F09	20/12/2012	10:00	31	9	30	6	12	6	1.547	0.741	1.305	0.153	0.339	0.125
	15/01/2013	9:00	25	5	12	4	6	5	1.248	0.411	0.522	0.102	0.169	0.104

Flinders catchment sites water quality profiles from field collected data. Results from each survey represent statistics generated from vertical depth profiles of pH, electrical conductivity (EC), temperature, dissolved oxygen (DO) saturation, turbidity (NTU) and secchi disk depth at three random locations across each waterhole using a calibrated hand-held Hydrolab QUANTA (multiprobe) field meter. Depth increments were standardised to 0.1 m, 0.2 m, 0.5 m, 1.0 m and at each 0.5 m increment until the pool bottom was reached

WATERHOLE	DATE	TIME	MEAN NTU	SECCHI m	MIN pH	MAX pH	MEAN pH	MIN TEMP °C	MAX TEMP °C	MEAN TEMP °C	MIN DO %sat	MAX DO %sat	MEAN DO %sat	MEAN EC µS/cm
F01	08/09/2012	13:45	30.0	0.53	8.50	8.81	8.67	20.91	25.92	22.49	24.40	91.40	68.47	692
	29/10/2012	9:30	31.1	0.56	7.80	7.96	7.91	24.52	25.15	24.99	46.70	83.70	64.60	818
	07/12/2012	13:00	39.0	0.57	7.87	8.37	8.22	27.75	31.60	29.74	17.90	97.90	79.84	882
	19/12/2012	13:40	-	0.45	7.53	7.58	7.55	29.04	30.42	29.65	51.30	58.70	53.54	287
	17/01/2013	9:00	-	0.30	7.43	7.80	7.64	28.12	29.93	28.91	22.90	60.70	46.71	331
	01/06/2013	8:20	66.7	0.34	8.34	8.44	8.38	20.22	20.90	20.38	68.60	81.90	74.82	423
F02	07/09/2012	16:00	17.6	0.96	9.24	9.38	9.29	22.60	26.30	24.81	115.90	129.10	120.91	334
	28/10/2012	15:30	76.1	0.32	8.93	9.01	8.98	28.42	30.08	29.47	153.00	166.20	159.88	564
	19/12/2012	17:40	-	0.05	7.41	7.44	7.42	30.41	30.91	30.79	59.10	70.20	66.95	209
	14/01/2013	12:45	-	0.10	8.23	8.46	8.36	31.06	33.13	32.35	51.50	87.10	71.13	415
	23/02/2013	16:00	-	-0.10	8.34	8.34	8.34	31.01	31.01	31.01	102.10	102.10	102.10	345
F03	07/09/2012	12:30	15.4	1.06	9.48	9.77	9.56	22.01	25.28	23.12	107.00	123.70	111.74	180
	29/10/2012	14:00	56.4	0.36	8.29	8.73	8.62	23.64	28.05	25.59	58.40	111.40	93.62	228
	08/12/2012	16:45	150.7	0.20	8.34	9.17	8.80	28.40	34.16	31.55	87.00	149.70	124.51	338
	19/12/2012	16:50	-	0.15	8.42	8.95	8.78	30.59	33.26	32.42	75.30	150.90	125.58	364
	14/01/2013	15:15	-	0.03	7.97	8.32	8.12	36.20	38.26	37.35	51.60	130.20	89.97	629
F04	08/09/2012	8:00	28.8	0.75	9.20	9.26	9.23	20.34	20.91	20.63	78.00	85.90	80.92	270
	28/10/2012	10:00	79.0	0.25	8.37	8.46	8.43	23.00	23.24	23.15	78.20	82.90	80.31	335
	08/12/2012	9:00	155.6	0.10	8.26	8.52	8.41	26.62	27.46	26.92	93.90	100.80	98.28	570
F05	08/09/2012	9:00	23.0	0.67	8.67	8.81	8.72	22.43	22.62	22.54	90.30	95.00	92.23	373
	27/10/2012	13:00	27.5	0.59	8.10	8.15	8.12	27.79	28.36	28.12	91.50	99.40	95.34	428
	09/12/2012	10:00	39.0	0.43	7.86	8.47	8.34	29.25	30.89	30.30	27.40	91.00	77.55	495
	20/12/2012	7:15	-	0.35	7.51	7.59	7.57	28.61	29.91	28.95	50.10	61.90	57.36	272
	23/02/2013	13:30	97.1	0.24	8.12	8.70	8.61	29.66	32.84	31.84	51.30	91.40	77.71	289

31/05/2013	10:20	185.6	0.13	8.50	8.59	8.55	20.03	20.76	20.42	81.70	95.20	91.65	414

WATERHOLE	DATE	TIME	MEAN NTU	SECCHI m	MIN pH	MAX pH	MEAN pH	MIN TEMP °C	MAX TEMP °C	MEAN TEMP °C	MIN DO %sat	MAX DO %sat	MEAN DO %sat	MEAN EC µS/cm
F07	09/09/2012	10:30	32.1	0.54	8.40	8.49	8.45	20.44	22.30	21.49	77.30	86.90	81.25	415
	25/10/2012	15:00	34.8	0.57	7.36	8.02	7.90	25.76	32.38	28.91	31.20	105.60	88.98	464
	11/12/2012	12:30	49.1	0.40	8.21	8.35	8.30	30.00	32.22	31.10	73.80	92.20	85.95	529
	20/12/2012	11:30	-	0.50	8.19	8.30	8.25	29.99	31.49	30.89	67.60	88.60	78.88	528
	15/01/2013	13:35	-	0.10	7.04	7.72	7.38	28.45	32.33	30.15	1.40	77.30	36.30	212
	22/02/2013	9:00	138.2	0.24	7.35	7.99	7.76	28.08	29.41	29.03	27.10	61.30	51.34	240
	30/05/2013	15:15	131.9	0.16	8.06	8.54	8.35	19.63	24.24	21.54	83.20	115.30	96.56	356
F08	09/09/2012	14:00	205.0	0.13	7.94	8.24	8.09	19.19	20.11	19.72	78.80	85.10	81.40	239
	25/10/2012	9:00	214.8	0.11	7.27	7.70	7.59	21.73	24.81	24.31	40.60	84.60	77.78	272
	11/12/2012	8:30	134.2	0.16	7.77	8.17	8.08	27.37	29.05	28.41	58.30	88.10	81.73	305
	20/12/2012	8:45	-	0.25	8.09	8.17	8.12	29.11	29.61	29.28	78.90	84.60	82.43	306
	15/01/2013	15:00	-	0.15	8.31	8.35	8.33	32.11	32.31	32.21	88.30	98.20	93.34	329
	22/02/2013	13:30	126.9	0.20	7.98	8.43	8.31	28.07	32.44	29.32	21.30	92.60	74.77	343
	30/05/2013	17:33	281.6	0.06	8.25	8.59	8.38	18.33	21.75	19.41	86.30	111.40	98.22	447
F09	10/09/2012	8:30	45.1	0.51	7.99	8.43	8.28	19.78	22.14	21.66	59.50	80.10	72.06	256
	25/10/2012	11:30	37.6	0.51	7.35	7.76	7.55	27.73	31.36	28.96	46.20	96.40	72.74	307
	10/12/2012	8:30	45.9	0.35	7.72	8.01	7.88	30.14	31.94	30.76	39.30	77.60	59.99	355
	20/12/2012	10:00	-	0.35	7.86	7.95	7.90	30.73	31.07	30.94	57.70	73.30	65.12	359
	15/01/2013	9:00	-	0.35	6.74	7.84	7.40	30.03	33.27	31.71	0.90	74.10	36.15	224
	30/05/2013	11:45	49.8	0.32	7.81	8.56	8.30	21.13	24.47	22.16	42.90	106.00	80.72	364
F10	08/09/2012	11:30	15.7	-0.35	9.53	9.94	9.75	17.80	20.30	18.67	42.00	78.10	60.47	781
	27/10/2012	9:30	17.6	-0.60	8.18	8.83	8.60	20.60	21.77	21.02	9.20	47.40	24.06	1553

Flinders catchment benthic sediment laboratory analysis results: total nitrogen (TN) and total phosphorus (TP); Delta13C (DEL 13C) and Delta15N (DEL 15N); acid extraction 3000B analysis of chlorophyll-*a* (CHL '*a*') and phaeophytin-*a* (PHAE 'a'); trichromotic method 3020B analysis of chlorophyll-*a* (TCHL 'a'), chlorophyll-*b* (TCHL 'b') and chlorophyll-*c* (TCHL 'a'). Replicates from three individual locations within the pool were taken during each sampling trip

WATERHOLE	DATE	TIME	REPLICATE	TN	TP	CHL 'a'	PHAE 'a'	TCHL 'a'	TCHL 'b'	TCHL 'c'	DEL ^{13}C	DEL ^{15}N
				mg/kg	mg/kg	mg/m^2	mg/m^2	mg/m^2	mg/m^2	mg/m^2	‰	‰
F01	29/10/2012	9:30	A	40	272	65	39	91	<1	2	-24.0	1.5
			B	730	590	68	75	110	27	14	-24.1	3.8
			C	20	34	34	50	65	6	6	-23.6	2.3
F01	07/12/2012	13:00	A	360	335	58	120	130	15	12	-23.5	0.00
			B	770	623	26	52	57	10	2	-21.3	4.8
			C	100	352	65	37	90	<1	3	-22.1	4.0
F02	28/10/2012	15:30	A	160	97	46	84	99	6	4	-25.0	7.8
			B	360	128	64	100	130	7	5	-24.8	2.9
			C	30	36	170	190	230	14	11	-23.6	2.9
F03	29/10/2012	14:00	A	2020	548	110	130	190	12	5	-23	2.8
			B	940	558	130	92	190	27	3	-23.3	3.4
			C	810	464	130	78	180	26	3	-24.3	4.3
F03	08/12/2012	16:45	A	710	500	59	69	100	16	<1	-19.2	6.4
			B	990	307	63	130	140	25	<1	-22.6	5.2
			C	470	496	53	65	93	14	<1	-22.1	7.0
F04	28/10/2012	10:00	A	1760	590	69	100	130	15	6	-24.1	2.5
			B	1670	662	60	42	88	<1	9	-24.9	0.7
			C	1770	634	34	54	68	7	3	-24.3	0.7
F04	08/12/2012	9:00	A	1550	661	65	210	190	25	<1	-23.8	3.9
			B	1620	607	4	68	50	3	<1	-22.2	4.4
			C	1140	506	77	220	220	14	<1	-24.5	4.2
F05	27/10/2012	13:00	A	220	86	14	35	35	2	<1	-24.6	4.5
			B	560	346	61	190	180	7	1	-24.7	5.9
			C	380	298	18	28	36	1	1	-24.7	9.2

F05	09/12/2012	10:00	A	520	254	29	67	70	5	4	-23.3	6.1
			B	530	298	38	70	82	4	3	-26.7	2.8
			C	40	112	41	27	59	<1	3	-23.4	-0.8

SITE	DATE	TIME	REPLICATE	TN	TP	CHL 'a'	PHAE 'a'	TCHL 'a'	TCHL 'b'	TCHL 'c'	DEL ^{13}C	DEL ^{15}N
				mg/kg	mg/kg	mg/m^2	mg/m^2	mg/m^2	mg/m^2	mg/m^2	‰	‰
F06	25/10/2012	15:00	A	150	94	38	48	68	2	4	-27.7	4.9
			B	40	161	38	47	68	3	6	-28.3	10.5
			C	60	190	50	29	69	<1	4	-28.4	3.7
F07	11/12/2012	12:30	A	20	138	12	19	24	1	2	-25.3	1.4
			B	20	103	2	78	50	4	5	-25.7	0.0
			C	20	96	24	21	37	2	4	-26.0	6.2
F08	25/10/2012	09:00	A	700	477	6	29	24	2	1	-21	5.5
			B	590	360	7	38	39	5	1	-19.4	7.9
			C	800	290	8	30	26	4	2	-19.5	12.1
F08	11/12/2012	08:30	A	510	328	33	23	48	1	2	-18.8	5.0
			B	520	374	23	21	36	4	5	-18.2	6.0
			C	680	296	50	53	83	4	2	-21.1	5.9
F09	25/10/2012	11:30	A	510	339	50	130	130	17	5	-25.6	6.0
			B	60	122	24	64	64	9	7	-27.1	2.4
			C	480	196	34	75	80	12	7	-26.2	2.9
F09	10/12/2012	8:30	A	40	127	22	77	68	12	6	-23.9	7.6
			B	20	99	9	17	19	3	2	-24.5	20.2
			C	110	168	17	47	45	7	3	-24.5	4.9

Gilbert catchment water quality laboratory analysis results

WATER-HOLE	DATE	TIME	pH	EC µS/cm	TSS mg/L	TDS mg/L	ALKA	HARD	ATOC mg/L	ADOC mg/L	ADIC mg/L	ADIN mg/L	DEL ^{13}C ‰	DEL ^{15}N ‰	A-CHL SURF µg/L	A-CHL INTEG µg/L	PHAEPHYTIN SURF µg/L	PHAEP INTEG µg/L	TSURF CHL A µg/L	DIFF CHL A µg/L
G01	08/10/2012	13:00	8.47	483	4.6	292.5	304.2	-	4.5	4.3	36.5	8	-27.90	1.80	1.34	1.67	1.00	1.13	2.34	-0.46
	15/11/2012	6:45	8.58	497	8.4	301.1	442.5	-	10.4	9.2	53.1	10	-28.72	-3.97	5.34	4.27	0.96	1.34	6.30	0.69
	01/12/2012	16:30	8.75	486	7.1	295.6	502.5	162.7	11.7	9.2	60.3	6	-29.06	-0.84	2.25	-	0.51	-	2.76	-
	20/01/2013	10:00	8.67	448	16.0	284.8	425.0	186.0	3.9	3.6	51.0	24	-24.90	13.30	9.26	15.49	2.46	2.08	11.72	-
	27/05/2013	10:50	-	-	-	281.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G02	09/10/2012	8:30	7.82	275	8.8	162.3	132.5	-	5.2	5.2	15.9	4	-30.70	4.80	3.67	5.34	2.64	2.94	6.31	-1.97
	14/11/2012	14:30	7.78	312	11.0	189.0	190.8	-	13.5	13.2	22.9	16	-31.02	-1.24	7.34	12.35	1.07	1.20	8.41	-5.14
	01/12/2012	13:00	7.81	332	9.6	203.5	246.7	75.4	15.4	14.2	29.6	5	-31.73	-0.79	5.34	-	0.64	-	5.98	-
	20/01/2013	12:00	7.81	361	14.0	223.4	-	105.2	6.2	-	-	47	-27.00	0.90	6.94	8.90	5.39	10.41	12.33	-
	27/05/2013	13:00	-	-	-	113.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G03	09/10/2012	16:00	8.57	508	2.1	305.6	296.7	-	6.1	5.7	35.6	11	-25.50	0.10	2.34	3.67	0.70	1.47	3.04	-2.10
	14/11/2012	7:30	8.71	478	2.4	290.8	250.8	-	11.2	11.0	30.1	19	-24.76	3.68	2.67	2.67	1.07	1.07	3.74	0.00
	28/11/2012	13:00	8.68	467	1.6	285.0	255.0	107.3	31.6	11.2	30.6	4	-27.42	0.66	2.94	-	0.61	-	3.55	-
	18/01/2013	10:00	9.27	367	8.0	205.9	-	91.7	-	-	-	21	-20.50	-2.80	7.31	7.71	1.35	2.67	8.66	-
	19/02/2013	13:00	7.85	252	5.1	135.4	216.3	83.6	7.9	6.5	25.9	11	-26.50	15.50	2.09	3.52	0.60	0.80	2.69	-1.63
	28/05/2013	8:30	-	-	-	189.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G04	10/10/2012	11:30	8.61	490	19.0	299.3	273.3	-	8.4	7.9	32.8	36	-23.30	-0.50	2.00	3.34	0.20	1.80	2.20	-2.94
	13/11/2012	9:30	8.98	603	3.4	366.4	285.8	-	22.0	21.3	34.3	94	-21.91	-0.76	3.74	-	0.56	-	4.30	-
	28/11/2012	9:00	8.88	634	13.0	383.8	375.0	115.6	25.7	26.1	45.0	5	-22.80	-3.36	11.48	-	2.91	-	14.39	-
	18/01/2013	11:20	8.41	734	150	432.0	364.2	94.2	18.9	16.8	43.7	264	-19.60	9.10	53.99	25.81	10.38	9.08	64.37	-
	28/05/2013	10:20	-	-	-	208.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G05	12/10/2012	11:00	8.71	504	3.6	302.9	272.5	-	4.2	4.6	32.7	13	-26.50	-0.90	3.67	3.67	1.00	0.77	4.67	0.23
	13/11/2012	15:00	8.92	595	4.0	362.2	343.3	-	14.6	12.3	41.2	28	-23.10	-5.33	2.67	2.94	0.51	0.61	3.18	-0.37
	28/11/2012	17:00	8.9	593	2.9	362.8	390.8	142.8	13.7	11.5	46.9	3	-26.85	-5.29	2.94	-	0.24	-	3.18	-
	18/01/2013	14:30	8.94	516	17.0	316.3	375.8	125.6	7.5	7.3	45.1	19	-24.90	9.80	5.64	6.41	0.80	2.19	6.44	-

	28/05/2013	11:45	-	-	-	189.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G06	11/10/2012	9:30	8.23	663	3.4	416.1	479.2	-	4.3	5.4	57.5	23	-29.90	-2.90	1.00	0.33	0.40	0.60	1.40	0.47
	10/11/2012	6:30	8.17	683	1.3	425.6	607.5	-	11.3	8.2	72.9	35	-38.18	-5.21	1.07	1.00	0.20	1.10	1.27	-0.83
	27/11/2012	7:00	8.06	685	2.0	428.4	594.2	307.3	11.6	7.1	71.3	4	-31.73	-2.09	0.53	-	0.40	-	0.93	-
	18/01/2013	11:00	8.15	670	2.0	429.4	657.5	330.5	2.1	1.8	78.9	30	-16.60	-	0.56	7.03	0.62	4.78	1.18	-10.63
	18/02/2013	14:30	7.88	162.3	75	89.8	134.1	57.0	9.6	8.0	16.1	20	-23.40	10.80	2.06	-	1.89	-	3.95	-
	27/05/2013	16:15	-	-	-	431.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-

WATER-HOLE	DATE	TIME	pH	EC µS/cm	TSS mg/L	TDS mg/L	ALKA	HARD	ATOC mg/L	ADOC mg/L	ADIC mg/L	ADIN mg/L	DEL ^{13}C ‰	DEL ^{15}N ‰	A-CHL SURF µg/L	A-CHL INTEG µg/L	PHAEPHYTIN SURF µg/L	PHAEP INTEG µg/L	TSURF CHL A µg/L	DIFF CHL A µg/L
G07	11/10/2012	15:00	8.77	703	2.1	428.5	500.0	-	4.6	6.3	60.0	19	-35.10	-0.50	0.67	0.67	0.20	0.97	0.87	-0.77
	10/11/2012	9:30	8.66	695	3.6	429.5	565.0	-	10.8	8.6	67.8	19	-30.31	-5.30	1.07	-	0.20	-	1.27	-
	27/11/2012	13:00	8.84	672	1.1	415.9	449.2	258.2	9.6	13.4	53.9	4	-27.29	-1.92	1.07	-	0.20	-	1.27	-
	20/01/2013	7:00	8.69	646	3.3	407.2	783.3	273.9	3.1	3.1	94.0	22	-24.50	21.90	1.34	1.07	0.35	0.99	1.69	-0.37
	28/05/2013	6:55	-	-	-	459.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G08	14/10/2012	9:00	7.62	209	8.0	123.5	156.7	-	5.4	3.9	18.8	15	-29.90	-2.60	13.02	13.02	4.51	4.74	17.53	-0.23
	12/11/2012	12:30	7.57	212	6.6	129.0	119.2	-	8.2	8.8	14.3	33	-35.12	1.48	30.37	18.69	2.34	3.18	32.71	10.84
	30/11/2012	13:00	7.64	214	8.5	130.2	155.8	44.7	8.8	9.1	18.7	5	-33.39	1.02	21.00	-	4.17	-	25.17	-
	19/01/2013	14:00	7.2	74.9	67.0	44.8	40.0	15.7	8.9	8.9	4.8	160	-21.60	20.90	4.98	-	0.25	-	5.23	-
	20/02/2013	12:45	7.27	65.3	25.0	36.7	29.7	15.7	8.1	5.6	3.563	72	-23.80	13.00	2.09	-	0.56	-	2.65	-
	29/05/2013	8:35	-	-	-	60.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G09	13/10/2012	17:00	8.04	221	7.4	130.7	138.3	-	7.9	8.1	16.6	12	-34.90	-	14.49	14.69	4.20	6.81	18.69	-2.81
	12/11/2012	6:45	7.33	253	11.1	154.5	114.2	-	20.5	20	13.7	31	-31.63	-0.69	24.03	22.03	8.44	9.51	32.47	0.93
	30/11/2012	8:00	7.62	275	13.0	165.1	129.2	38.1	21.8	21.2	15.5	181	-30.66	0.94	19.58	-	15.93	-	35.51	-
	19/01/2013	10:30	7.36	69.3	22.0	41.2	190.8	18.2	6.7	6.1	22.9	225	-26.50	5.80	5.34	7.34	0.89	18.82	6.23	-
	20/02/2013	13:00	7.1	31.7	26.0	17.3	25.2	5.4	8.1	6.2	3.024	8	-26.50	3.10	9.32	3.52	1.08	0.81	10.40	6.07

	29/05/2013	11:10	-	-	-	45.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G10	13/10/2012	12:00	7.95	193.5	6.5	114.0	118.3	-	3.0	2.8	14.2	11	-32.60	2.70	6.68	7.01	3.14	3.27	9.82	-0.46
	11/11/2012	16:30	8.2	208	6.6	126.1	76.7	-	9.2	8.3	9.2	12	-33.44	1.66	7.48	10.15	0.75	2.00	8.23	-3.92
	29/11/2012	17:00	8.58	215	8.5	130.4	111.7	47.2	9.8	9.3	13.4	6	-30.84	9.05	9.26	-	2.21	-	11.47	-
	19/01/2013	8:45	7.7	111	260	66.5	75.0	29.8	6.9	6.4	9.0	281	-23.10	17.50	2.67	-	0.20	-	2.87	-
	20/02/2013	10:00	7.55	77.8	86.0	43.3	43.5	18.2	9.2	4.3	5.222	58	-25.00	9.10	7.37	-	0.66	-	8.03	-
	29/05/2013	14:25	-	-	-	80.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Gilbert catchment water quality laboratory analysis results: nutrients

WATERHOLE	DATE	TIME	TAN µgN/L	T-FAN µgN/L	NH3 µgN/L	N02- µgN/L	N03- µgN/L	TAP µgP/L	T-FAP µgP/L	F-RAP µgP/L	NOx µg/L	APN µgN/L	ADON µgN/L	AUN µgN/L	APP µgP/L	ADOP µgN/L
G01	08/10/2012	13:00	212	197	6	1	1	49	39	9	2	15	189	2	10	30
	15/11/2012	6:45	388	281	6	<1	4	48	29	23	4	107	271	10	19	6
	01/12/2012	16:30	401	373	4	<1	2	34	20	5	2	28	367	24	14	15
	20/01/2013	10:00	404	317	6	1	17	34	20	9	18	87	293	-	14	11
G02	09/10/2012	8:30	307	267	1	<1	3	23	11	1	3	40	263	1	12	10
	14/11/2012	14:30	500	365	6	<1	10	21	6	3	10	135	349	19	15	3
	01/12/2012	13:00	416	403	4	<1	1	20	6	5	1	13	398	18	14	1
	20/01/2013	12:00	711	368	23	1	23	25	8	3	24	343	321	-	17	5
G03	09/10/2012	16:00	394	308	7	1	3	28	13	2	4	86	297	7	15	11
	14/11/2012	7:30	495	377	8	<1	11	18	7	2	11	118	358	19	11	5
	28/11/2012	13:00	536	446	3	<1	1	25	8	6	1	90	442	66	17	2
	18/01/2013	10:00	670	511	5	1	15	20	10	4	16	159	490	-	10	6
	19/02/2013	13:00	178	164	9	1	1	31	13	3	2	14	153	-	18	10
G04	10/10/2012	11:30	612	561	33	<1	3	25	19	2	3	51	525	12	6	17
	13/11/2012	9:30	1014	901	9	<1	85	30	11	4	85	113	807	29	19	7
	28/11/2012	9:00	1133	831	3	<1	2	32	6	6	2	302	826	46	26	<1
	18/01/2013	11:20	1876	1691	55	76	133	54	23	5	209	185	1427	-	31	18
G05	12/10/2012	11:00	496	309	7	<1	6	31	20	2	6	187	296	1	11	18
	13/11/2012	15:00	517	450	6	<1	22	16	7	2	22	67	422	19	9	5
	28/11/2012	17:00	568	468	3	<1	<1	21	8	6	<1	100	465	27	13	2
	18/01/2013	14:30	851	658	3	1	15	34	10	4	16	193	639	-	24	6
G06	11/10/2012	9:30	160	104	20	<1	3	92	84	64	3	56	81	17	8	20
	10/11/2012	6:30	239	185	6	<1	29	64	60	3	29	54	150	13	4	57
	27/11/2012	7:00	333	311	3	<1	1	70	67	34	1	22	307	41	3	33
	18/01/2013	11:00	271	210	12	1	17	69	65	42	18	61	180	-	4	23
	18/02/2013	14:30	579	242	9	1	10	147	87	75	11	337	222	-	60	12

WATERHOLE	DATE	TIME	TAN µgN/L	T-FAN µgN/L	NH3 µgN/L	N02- µgN/L	N03- µgN/L	TAP µgP/L	T-FAP µgP/L	F-RAP µgP/L	NOx µg/L	APN µgN/L	ADON µgN/L	AUN µgN/L	APP µgP/L	ADOP µgN/L
G07	11/10/2012	15:00	234	192	12	<1	7	37	35	9	7	42	173	38	2	26
	10/11/2012	9:30	459	373	12	1	6	20	16	5	7	86	354	3	4	11
	27/11/2012	13:00	356	311	3	<1	1	14	11	6	1	45	307	31	3	5
	20/01/2013	7:00	294	272	9	1	12	14	10	4	13	22	250	-	4	6
G08	14/10/2012	9:00	542	270	15	<1	<1	55	22	4	<1	272	255	10	33	18
	12/11/2012	12:30	518	347	8	<1	25	34	13	1	25	171	314	8	21	12
	30/11/2012	13:00	510	367	3	<1	2	28	10	5	2	143	362	42	18	5
	19/01/2013	14:00	875	574	47	2	111	49	13	4	113	301	414	-	36	9
	20/02/2013	12:45	332	207	17	1	54	35	11	3	55	125	135	-	24	8
G09	13/10/2012	17:00	634	488	8	<1	4	50	21	3	4	146	476	6	29	18
	12/11/2012	6:45	932	701	24	1	6	47	17	2	7	231	670	14	30	15
	30/11/2012	8:00	1443	1019	146	6	29	80	19	6	35	424	838	112	61	13
	19/01/2013	10:30	798	689	22	2	201	54	18	9	203	109	464	-	36	9
	20/02/2013	13:00	394	260	6	1	1	54	20	8	2	134	252	-	34	12
G10	13/10/2012	12:00	402	212	11	<1	<1	36	22	2	<1	190	201	40	14	20
	11/11/2012	16:30	499	334	9	<1	3	31	11	1	3	165	322	11	20	10
	29/11/2012	17:00	595	375	5	<1	1	45	10	6	1	220	369	47	35	4
	19/01/2013	8:45	1312	657	6	2	273	103	21	13	275	655	376	-	82	8
	20/02/2013	10:00	457	153	7	1	50	51	13	4	51	304	95	-	38	9

Gilbert catchment water quality laboratory analysis results: major ions

WATERHOLE	DATE	TIME	ACa mg/L	AMg mg/L	ANa mg/L	AK mg/L	ACl mg/L	ASO4 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L
G01	01/12/2012	16:30	19	28	31	8	10	1	0.948	2.304	1.349	0.205	0.282	0.021
	20/01/2013	10:00	25	30	31	6	8	-	1.248	2.469	1.349	0.153	0.226	-
G02	01/12/2012	13:00	17	8	28	5	25	1	0.848	0.658	1.218	0.128	0.705	0.021
	20/01/2013	12:00	24	11	34	5	26	-	1.198	0.905	1.479	0.128	0.733	-
G03	28/11/2012	13:00	10	20	48	6	30	2	0.499	1.646	2.088	0.153	0.846	0.042
	18/01/2013	10:00	12	15	44	4	27	-	0.599	1.234	1.914	0.102	0.762	-
	19/02/2013	13:00	17	10	20	3	10	<1	0.848	0.823	0.870	0.077	0.282	0.010
G04	28/11/2012	9:00	10	22	81	8	63	1.0	0.499	1.810	3.524	0.205	1.777	0.021
	18/01/2013	11:20	13	15	97	7	77	<1	0.649	1.234	4.220	0.179	2.172	0.001
G05	28/11/2012	17:00	11	28	59	7	43	1.0	0.549	2.304	2.567	0.179	1.213	0.021
	18/01/2013	14:30	14	22	66	5	45	-	0.699	1.810	2.871	0.128	1.269	-
G06	27/11/2012	7:00	34	54	33	5	12	1.0	1.697	4.444	1.436	0.128	0.339	0.021
	18/01/2013	11:00	40	56	34	4	11	-	1.996	4.608	1.479	0.102	0.310	-
	18/02/2013	14:30	8	9	12	2	6	<1	0.399	0.741	0.522	0.051	0.169	0.010
G07	27/11/2012	13:00	16	53	45	10	16	1.0	0.798	4.361	1.958	0.256	0.451	0.021
	20/01/2013	7:00	19	55	46	8	16	<1	0.948	4.526	2.001	0.205	0.451	0.001
G08	30/11/2012	13:00	8	6	20	4	11	2.0	0.399	0.494	0.870	0.102	0.310	0.042
	19/01/2013	14:00	3	2	6	3	4	8.0	0.150	0.165	0.261	0.077	0.113	0.167
	20/02/2013	12:45	3	2	6	2	3	6.0	0.150	0.165	0.261	0.051	0.085	0.125
G09	30/11/2012	8:00	7	5	31	9	16	1.0	0.349	0.411	1.349	0.230	0.451	0.021
	19/01/2013	10:30	4	2	5	3	4	<1	0.200	0.165	0.218	0.077	0.113	0.010
	20/02/2013	13:00	<1	1	2	2	2	<1	0.025	0.082	0.087	0.051	0.056	0.010
G10	29/11/2012	17:00	9	6	22	4	11	5	0.449	0.494	0.957	0.102	0.310	0.104
	19/01/2013	8:45	7	3	9	2	6	4	0.349	0.247	0.392	0.051	0.169	0.083
	20/02/2013	10:00	4	2	8	2	4	4	0.200	0.165	0.348	0.051	0.113	0.083

Gilbert catchment waterholes water quality profiles from field collected data. Results from each survey represent statistics generated from vertical depth profiles of pH, electrical conductivity (EC), temperature, dissolved oxygen (DO) saturation, turbidity (NTU) and secchi disk depth at three random locations across each waterhole using a calibrated hand-held Hydrolab QUANTA (multiprobe) field meter. Depth increments were standardised to 0.1 m, 0.2 m, 0.5 m, 1.0 m and at each 0.5 m increment until the bottom

WATER-HOLE	DATE	TIME	MEAN NTU	SECCHI m	MIN pH	MAX pH	MEAN pH	MIN TEMP °C	MAX TEMP °C	MEAN TEMP °C	MIN DO %sat	MAX DO %sat	MEAN DO %sat	MEAN EC µS/cm
G01	08/10/2012	13:00	-	1.20	8.60	8.75	8.67	24.12	28.06	25.83	69.80	96.80	81.80	487
	15/11/2012	6:45	14.4	1.02	8.58	8.61	8.60	25.95	26.11	26.04	93.00	97.00	94.21	502
	01/12/2012	16:30	15.0	0.89	8.69	8.91	8.76	29.54	31.55	30.71	116.00	138.10	123.95	493
	20/01/2013	10:00	-	0.30	8.25	8.60	8.38	26.56	28.02	27.13	45.60	79.80	65.35	475
	27/05/2013	10:50	25.5	1.06	8.17	8.73	8.54	18.40	19.73	19.02	88.60	105.90	97.04	469
G02	09/10/2012	8:30	-	1.20	7.51	7.60	7.57	21.11	23.80	23.33	34.50	60.00	50.28	271
	14/11/2012	14:30	21.9	0.66	7.39	7.96	7.70	25.61	29.91	27.32	27.40	80.30	56.80	315
	01/12/2012	13:00	22.1	0.78	7.59	7.89	7.76	27.52	30.76	29.04	29.10	72.50	54.72	339
	20/01/2013	12:00	-	0.40	7.46	7.57	7.52	27.62	28.47	28.08	28.30	65.20	45.38	372
	27/05/2013	13:00	89.1	0.46	7.31	7.82	7.50	18.34	20.77	19.72	47.40	80.20	59.08	189
G03	09/10/2012	16:00	-	1.35	8.63	8.85	8.80	27.66	30.34	29.10	97.10	118.70	108.69	509
	14/11/2012	7:30	5.6	-1.85	8.70	8.74	8.72	25.61	26.05	25.78	61.80	69.10	64.15	485
	28/11/2012	13:00	5.8	-1.80	7.11	8.85	8.59	28.78	29.76	29.20	84.40	93.50	89.19	475
	18/01/2013	10:00	-	0.55	8.53	9.20	8.96	27.31	28.85	28.33	42.00	101.50	74.03	343
	19/02/2013	13:00	30.4	0.70	7.05	7.61	7.27	27.69	32.36	29.24	2.90	55.50	27.14	226
	28/05/2013	8:30	8.8	1.61	7.96	8.35	8.18	19.65	20.50	20.30	76.60	88.50	81.83	316
G04	10/10/2012	11:30	-	-1.20	8.66	8.72	8.71	26.18	26.62	26.35	69.10	78.50	71.77	499
	13/11/2012	9:30	7.3	-1.10	8.87	8.91	8.89	27.31	27.75	27.56	90.30	95.10	92.21	611
	28/11/2012	9:00	10.6	-0.95	8.95	8.97	8.96	26.83	27.49	27.15	75.00	81.80	78.39	640
	18/01/2013	11:20	-	-1.30	8.45	8.53	8.50	28.45	29.86	29.16	52.90	89.60	68.81	720
	28/05/2013	10:20	7.4	-1.10	8.53	8.75	8.64	19.00	19.27	19.11	72.80	84.70	78.18	347
G05	12/10/2012	11:00	-	1.86	8.92	9.00	8.97	27.33	29.51	28.30	97.00	112.30	103.92	505
	13/11/2012	15:00	6.0	2.10	8.85	8.89	8.87	28.30	29.81	29.22	94.40	99.60	96.65	604
	28/11/2012	17:00	7.3	2.04	8.87	8.91	8.90	29.76	31.66	30.69	94.20	104.30	99.22	605

WATER-HOLE	DATE	TIME	MEAN NTU	SECCHI m	MIN pH	MAX pH	MEAN pH	MIN TEMP °C	MAX TEMP °C	MEAN TEMP °C	MIN DO %sat	MAX DO %sat	MEAN DO %sat	MEAN EC µS/cm
	18/01/2013	14:30	-	0.50	8.60	8.87	8.78	28.87	32.80	29.97	53.20	106.20	82.58	527
	28/05/2013	11:45	16.2	0.74	7.84	8.22	8.00	21.14	21.53	21.31	80.40	87.90	85.22	316
G06	11/10/2012	9:30	-	1.55	8.14	8.23	8.20	25.71	25.86	25.77	59.00	68.00	62.28	693
	10/11/2012	6:30	2.6	-1.85	8.05	8.10	8.09	26.25	26.68	26.51	53.90	73.40	68.31	709
	27/11/2012	7:00	3.6	-1.85	8.11	8.13	8.12	25.82	26.19	26.09	36.90	45.10	41.33	714
	18/01/2013	11:00	-	1.85	7.82	7.93	7.89	26.18	26.50	26.37	27.20	49.40	37.48	716
	18/02/2013	14:30	200.7	0.12	7.63	7.72	7.65	27.06	27.31	27.21	76.70	79.20	77.77	150
	27/05/2013	16:15	7.4	-1.85	8.12	8.33	8.21	21.24	22.23	21.94	110.00	126.80	119.24	719
G07	11/10/2012	15:00	-	-0.85	8.68	8.71	8.70	29.31	29.40	29.37	118.20	123.40	121.04	714
	10/11/2012	9:30	4.8	-0.85	8.59	8.63	8.61	25.98	26.02	26.00	69.00	72.30	70.20	716
	27/11/2012	13:00	3.3	-0.85	8.78	8.79	8.78	30.97	31.30	31.14	132.00	144.50	136.78	693
	20/01/2013	7:00	-	-0.85	8.51	8.53	8.51	26.25	26.30	26.28	57.00	66.20	60.32	679
	28/05/2013	6:55	5.7	-0.85	8.64	8.74	8.70	18.22	18.33	18.27	77.40	80.50	79.16	766
G08	14/10/2012	9:00	-	1.00	7.17	7.39	7.28	26.28	27.30	26.73	9.30	42.40	31.03	206
	12/11/2012	12:30	10.1	1.27	7.02	7.48	7.37	29.09	31.90	30.23	27.30	71.60	58.30	215
	30/11/2012	13:00	14.1	0.89	7.16	7.83	7.54	29.97	32.95	31.11	7.20	72.40	52.40	217
	19/01/2013	14:00	-	0.15	6.53	6.77	6.60	29.20	30.05	29.61	68.10	81.50	73.35	75
	20/02/2013	12:45	157.8	0.15	6.81	7.53	7.05	28.44	30.77	29.59	59.90	73.20	68.15	61
	29/05/2013	8:35	25.6	0.73	6.65	7.44	7.05	22.36	22.49	22.42	56.00	67.00	64.23	101
G09	13/10/2012	17:00	-	1.10	7.66	8.43	8.04	24.22	29.79	27.27	60.80	118.40	95.29	218
	12/11/2012	6:45	20.6	0.88	7.28	7.45	7.35	28.26	29.00	28.67	20.80	40.70	31.54	258
	30/11/2012	8:00	26.1	0.49	7.56	7.98	7.72	28.38	29.64	29.52	45.10	68.70	54.90	275
	19/01/2013	10:30	-	0.30	6.71	7.39	6.99	28.00	29.59	28.56	70.20	79.90	72.52	69
	20/02/2013	13:00	113.5	0.20	6.34	7.24	6.55	28.75	34.46	30.15	60.40	79.30	66.97	29
	29/05/2013	11:10	31.8	0.56	6.51	7.31	7.01	21.65	23.09	22.17	65.40	85.80	75.25	77
G10	13/10/2012	12:00	-	1.25	7.79	7.90	7.85	23.73	24.44	24.22	78.40	83.30	81.66	190
	11/11/2012	16:30	14.3	0.86	7.99	8.29	8.17	30.66	33.51	32.48	89.90	105.20	99.17	210

29/11/2012	17:00	15.7	0.86	8.52	8.66	8.58	31.25	34.00	32.86	111.20	124.90	117.01	217
19/01/2013	8:45	-	0.15	7.35	7.60	7.42	28.30	28.51	28.34	81.50	87.60	83.52	111
20/02/2013	10:00	164.5	0.13	7.15	7.44	7.31	30.28	30.42	30.34	72.00	77.80	75.40	72
29/05/2013	14:25	14.5	1.12	7.60	8.20	7.94	23.12	24.31	23.58	95.40	105.80	102.32	134

Gilbert catchment benthic sediment laboratory analysis results: Total Nitrogen (TN) and total Phosphorus (TP); Delta^{13}C (DEL ^{13}C) and Delta^{15}N (DEL ^{15}N); acid extraction 3000B analysis of chlorophyll-*a* (CHL 'a') and phaeophytin-*a* (PHAE 'a'); trichromotic method 3020B analysis of chlorophyll-*a* (TCHL 'a'), chlorophyll-*b* (TCHL 'b') and chlorophyll 'c' (TCHL 'a'). Replicates from three individual locations within the pool were taken during each sampling trip

WATERHOLE	DATE	TIME	REPLICATE	TN mg/kg	TP mg/kg	CHL 'a' mg/m^2	PHAE 'a' mg/m^2	TCHL 'a' mg/m^2	TCHL 'b' mg/m^2	TCHL 'c' mg/m^2	DEL ^{13}C ‰	DEL ^{15}N ‰
G01	08/10/2012	13:00	A	-	-	-	-	-	-	-	-	-
			B	70	177	140	88	200	5	10	-26.7	2.7
			C	420	326	63	39	89	2	4	-25.9	-0.7
G01	01/12/2012	16:30	A	330	207	290	120	380	27	11	-24.8	-1.3
			B	320	147	96	29	120	8	4	-18.5	1.5
			C	90	73	71	97	130	9	11	-14.7	1.5
G02	09/10/2012	8:30	A	50	90	23	24	38	1	2	-26.6	-0.7
			B	170	103	45	37	69	<1	2	-27.2	10.9
			C	90	153	11	120	84	<1	4	-25.1	-0.1
G02	01/12/2012	13:00	A	40	56	87	93	150	15	5	-25.2	4.0
			B	20	50	25	20	38	2	<1	-23.5	-5.0
			C	30	84	24	32	44	3	3	-23.7	-6.2
G03	09/10/2012	16:00	A	30	22	37	36	60	4	5	-25.9	0.0
			B	20	22	22	21	35	4	5	-29.2	0.0
			C	70	23	27	26	44	2	4	-26.4	0.2
G03	28/11/2012	13:00	A	80	39	110	72	160	5	11	-24.2	-0.4
			B	60	30	82	51	120	3	10	-16.2	7.9
			C	70	135	61	43	90	2	6	-24.8	3.6
G04	10/10/2012	11:30	A	60	42	86	79	140	3	11	-21.0	-2.5
			B	90	67	94	54	130	1	9	-22.0	0.0
			C	70	62	75	70	120	3	10	-22.0	-4.8
G04	28/11/2012	9:00	A	80	103	95	55	130	4	10	-18.8	2.1
			B	140	40	100	50	130	4	8	-16.9	1.2
			C	410	96	110	66	150	4	10	-17.9	0.9
G05	12/10/2012	11:00	A	100	34	33	32	54	6	4	-27.3	0.2

			B	40	34	17	22	31	3	2	-25.9	2.6
			C	110	45	71	75	120	9	5	-26	2.2
G05	28/11/2012	17:00	A	40	95	48	19	61	2	4	-25.6	-1.6
			B	50	43	31	17	42	2	3	-24.8	1.9
			C	70	90	37	31	56	5	7	-25.3	1.6

WATERHOLE	DATE	TIME	REPLICATE	TN mg/kg	TP mg/kg	CHL 'a' mg/m²	PHAE 'a' mg/m²	TCHL 'a' mg/m²	TCHL 'b' mg/m²	TCHL 'c' mg/m²	DEL ^{13}C ‰	DEL ^{15}N ‰
G06	11/10/2012	9:30	A	60	14	120	110	190	4	6	-28.9	2.2
			B	160	46	70	61	110	2	3	-29.9	3.8
			C	80	39	26	20	39	2	2	-29.8	4.2
G06	27/11/2012	7:00	A	90	48	100	99	170	6	9	-25.6	3.1
			B	80	49	63	48	94	1	5	-15.9	12.8
			C	150	91	97	64	140	2	7	-25.0	3.1
G07	11/10/2012	15:00	A	90	139	99	39	130	5	4	-29.0	0.5
			B	100	41	220	62	270	6	15	-29.6	0.7
			C	940	134	120	75	170	7	4	-28.3	4.0
G07	27/11/2012	13:00	A	220	154	120	71	170	24	2	-20.4	-0.6
			B	120	70	54	52	87	2	4	-22.2	3.3
			C	200	98	86	54	120	7	5	-18.6	3.5
G08	14/10/2012	9:00	A	40	31	2	24	18	<1	<1	-27.2	4.4
			B	300	126	35	99	96	11	7	-26.1	4.0
			C	220	50	9	120	80	2	3	-27.8	4.0
G08	30/11/2012	13:00	A	70	48	100	78	150	3	11	-26.5	12.4
			B	30	118	35	39	60	7	7	-26.1	5.0
			C	40	26	18	30	37	2	3	-28.6	1.5
G09	13/10/2012	17:00	A	230	37	34	100	94	9	5	-27.9	5.2

			B	180	74	17	76	64	4	3	-28.3	3.7
			C	40	21	24	130	100	12	11	-27.8	4.7
G09	30/11/2012	8:00	A	800	218	100	560	440	36	3	-26.1	6.0
			B	220	92	67	200	190	22	15	-27.6	4.0
			C	160	70	79	260	230	26	16	-28.5	5.0
G10	13/10/2012	12:00	A	140	111	78	120	150	30	12	-26.1	4.2
			B	120	98	30	48	60	10	6	-26.0	3.4
			C	50	16	28	30	46	7	4	-28.4	10.7
G10	29/11/2012	17:00	A	60	45	58	63	97	13	5	-26.4	-9.7
			B	150	61	84	120	160	30	14	-26.0	-0.4
			C	70	52	5	17	14	3	2	-27.0	-0.5

Appendix B Aquatic invertebrate summary statistics and raw data

Taxa counts and index values for aquatic invertebrate communities in waterholes with edge habitat

CATCHMENT	WATERHOLE	SURVEY	TOTAL ABUNDANCE	TAXONOMIC RICHNESS	SIGNAL	SHANNON DIVERSITY (H')	EVENNESS (J')
Flinders	F1	29/10/12	408	29	3.28	2.71	0.80
		7/12/12	330	24	3.1	2.33	0.73
	F5	27/10/12	402	24	3.56	2.67	0.84
		9/12/12	330	23	3.33	2.29	0.73
	F9	26/10/12	137	22	3.50	2.69	0.87
		10/12/12	621	27	3.41	2.13	0.65
Gilbert	G01	8/10/12	306	29	3.43	2.62	0.78
		1/12/12	250	23	3.71	2.41	0.77
	G02	9/10/12	269	25	3.25	2.71	0.84
		1/12/12	211	31	3.44	2.53	0.74
	G03	9/10/12	269	23	3.47	2.57	0.82
		28/11/12	328	23	3.68	2.31	0.74
	G04	10/10/12	239	31	3.74	2.95	0.86
		28/11/12	417	29	3.30	2.87	0.85
	G05	10/10/12	148	26	3.81	2.70	0.83
		28/11/12	361	20	3.87	2.11	0.70
	G06	11/10/12	326	34	4.00	2.55	0.72
		27/11/12	520	32	3.42	2.33	0.67
	G07	11/10/12	176	24	3.95	2.63	0.83
		27/11/12	253	31	3.56	2.93	0.85

CATCHMENT	WATERHOLE	SURVEY	TOTAL ABUNDANCE	TAXONOMIC RICHNESS	SIGNAL	SHANNON DIVERSITY (H')	EVENNESS (J')
	G08	14/10/12	890	34	3.32	1.82	0.52
		30/11/12	586	29	3.13	2.35	0.70
	G09	13/10/12	941	28	3.57	1.83	0.55
		30/11/12	1162	33	3.56	2.42	0.69
	G10	13/10/12	288	25	3.48	2.71	0.84
		29/11/12	426	30	3.72	2.84	0.84

Taxa counts and index values for aquatic invertebrate communities in waterholes with pool bottom habitat

CATCHMENT	WATERHOLE	SURVEY	TOTAL ABUNDANCE	TAXONOMIC RICHNESS	SIGNAL	SHANNON DIVERSITY (H')	EVENNESS (J')
Flinders	F1	29/10/12	368	17	3.50	2.17	0.77
		7/12/12	122	12	3.63	1.81	0.73
	F2	28/10/12	2528	20	3.38	1.55	0.52
	F3	28/10/12	689	16	3.45	1.88	0.68
		8/12/12	101	18	2.92	2.35	0.81
	F4	28/10/12	310	10	3.63	0.97	0.42
		8/12/12	565	9	2.80	1.17	0.53
	F5	27/10/12	287	15	3.90	2.33	0.86
		9/12/12	122	13	3.63	2.10	0.82
	F7	25/10/12	335	14	4.10	1.95	0.74
		11/12/12	350	16	3.62	1.78	0.64
	F8	25/10/12	240	12	3.71	1.61	0.65
			49	8	3.60	1.78	0.86
	F9	26/10/12	172	12	3.89	1.99	0.80
		10/12/12	133	12	3.00	2.07	0.83
Gilbert	G01	1/12/12	256	12	3.63	2.10	0.85
	G02	9/10/12	202	15	3.70	2.17	0.80
		1/12/12	171	13	4.00	1.67	0.65
	G03	9/10/12	374	15	3.45	2.08	0.77
		28/11/12	389	17	3.50	1.81	0.64
	G04	10/10/12	234	19	4.00	2.03	0.69
		28/11/12	346	16	3.25	2.22	0.80
	G05	10/10/12	142	14	4.27	2.02	0.77
		28/11/12	364	12	3.75	1.83	0.73

CATCHMENT	WATERHOLE	SURVEY	TOTAL ABUNDANCE	TAXONOMIC RICHNESS	SIGNAL	SHANNON DIVERSITY (H')	EVENNESS (J')
	G06	11/12/12	352	21	3.87	1.96	0.64
		27/11/12	337	25	3.86	2.24	0.70
	G07	11/10/12	231	23	3.94	2.50	0.80
		27/11/12	290	20	3.60	1.98	0.66
	G08	30/11/12	317	21	3.47	2.37	0.78
	G09	30/11/12	811	18	3.23	1.84	0.64
	G10	13/10/12	160	10	3.86	1.93	0.84
		29/11/12	483	10	3.50	1.63	0.71

Taxa counts and index values for aquatic invertebrate communities in waterholes with macrophyte habitat

CATCHMENT	WATERHOLE	SURVEY	TOTAL ABUNDANCE	TAXONOMIC RICHNESS	SIGNAL	SHANNON DIVERSITY (H')	EVENNESS (J')
Flinders	F3	28/10/12	1079	26	2.90	1.73	0.53
		8/12/12	318	16	3.25	2.10	0.76
	F8	25/10/12	1743	26	2.95	1.65	0.51
		11/12/12	2200	24	2.94	1.55	0.49
	F10	27/10/12	973	24	3.16	2.25	0.71

Edge habitat aquatic invertebrates (continued over page)

WATERHOLE	F01		F05		F09		G01		G02		G03		G04		G05		G06		G07		G08		G09		G10	
DATE	29/10/2012	07/12/2012	09/12/2012	27/10/2012	26/10/2012	10/12/2012	08/10/2012	01/12/2012	09/10/2012	01/12/2012	09/10/2012	28/11/2012	10/10/2012	28/11/2012	10/10/2012	28/11/2012	11/10/2012	27/11/2012	11/10/2012	27/11/2012	14/10/2012	30/11/2012	13/10/2012	30/11/2012	13/10/2012	29/11/2012
FAMILY																										
Acarina	3	0	130	10	20	85	9	8	40	2	33	32	4	20	18	95	24	12	5	15	16	13	2	21	17	33
Aeshnidae	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ancylidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atyidae	0	0	2	0	0	1	4	17	4	11	0	1	3	0	8	1	2	14	0	5	8	16	26	89	2	1
Baetidae	62	4	0	13	8	48	66	42	33	4	20	107	3	2	20	32	95	27	35	10	44	21	95	62	38	14
Belostomatidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0
Caenidae	4	3	8	0	18	6	3	7	27	2	18	10	6	50	0	10	42	20	9	22	1	2	29	26	14	6
Ceratopogonidae	2	1	4	2	4	1	2	0	0	3	0	0	2	2	1	4	0	6	0	0	1	0	0	1	3	5
Chironominae	41	10	1	30	14	39	17	5	16	22	14	36	19	19	9	31	7	36	3	14	43	17	6	66	21	55
Cladocera	35	110	3	52	0	270	36	15	12	0	65	35	0	6	2	6	3	23	0	5	70	56	141	66	5	12
Coenagrionidae	9	32	1	4	0	0	46	47	2	1	5	4	11	7	2	2	31	17	23	20	7	11	6	8	45	16
Copepoda	12	14	14	17	9	47	31	22	6	2	2	17	2	15	6	16	5	19	1	5	521	190	478	115	15	30
Corallanidae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corbiculidae	2	0	4	0	0	0	0	0	0	1	10	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Corixidae	8	0	26	12	12	0	2	51	4	0	9	3	13	44	32	110	32	229	16	6	0	0	5	418	1	23
Culicidae	1	3	0	0	0	0	2	0	0	0	0	1	0	5	0	0	1	7	0	2	0	0	0	0	0	0
Dugesiidae	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	4	2	8	0	0	1
Dytiscidae	14	5	15	19	4	14	8	5	13	64	3	0	12	23	5	5	4	2	19	37	24	49	31	55	7	21
Ecnomidae	3	1	0	1	3	1	0	1	1	1	8	1	2	4	4	0	1	2	0	0	0	0	6	3	1	3
Elmidae	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Gerridae	2	1	0	0	0	0	2	1	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0
Gomphidae	0	0	12	3	1	0	0	1	11	3	8	5	30	50	3	11	4	0	11	14	11	4	7	1	4	8
Gyrinidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hebridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
Hemicorduliidae	0	0	0	2	0	0	0	1	0	1	0	2	0	0	0	0	1	1	0	1	1	0	2	6	0	0
HUL complex	0	6	0	4	0	0	7	7	2	2	2	0	0	1	0	0	1	7	8	5	2	4	1	1	1	0

Hydraenidae	29	2	8	55	8	11	2	1	2	16	0	0	23	15	0	0	0	0	0	1	10	0	6	19	4	7
Hydridae	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	16	0	0
Hydrochidae	29	15	10	34	7	6	15	2	11	31	0	0	14	3	1	0	0	4	0	0	12	14	4	36	12	16
Hydrometridae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

WATERHOLE	F01		F05		F09		G01		G02		G03		G04		G05		G06		G07		G08		G09		G10	
DATE	**29/10/2012**	**07/12/2012**	**09/12/2012**	**27/10/2012**	**26/10/2012**	**10/12/2012**	**08/10/2012**	**01/12/2012**	**09/10/2012**	**01/12/2012**	**09/10/2012**	**28/11/2012**	**10/10/2012**	**28/11/2012**	**10/10/2012**	**28/11/2012**	**11/10/2012**	**27/11/2012**	**11/10/2012**	**27/11/2012**	**14/10/2012**	**30/11/2012**	**13/10/2012**	**30/11/2012**	**13/10/2012**	**29/11/2012**
Hydrophilidae	12	3	2	5	1	5	3	0	3	7	0	0	3	3	0	0	1	0	0	1	4	2	1	14	2	3
Hydroptilidae	0	0	0	0	0	1	0	0	0	0	2	0	0	0	1	0	1	0	0	0	0	0	0	0	2	0
Hyriidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Isostictidae	0	0	0	0	1	13	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Leptoceridae	3	0	17	18	13	5	2	0	29	10	20	7	2	1	3	3	13	0	6	1	30	19	10	1	39	5
Leptophlebiidae	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	15	3	2	1	0	0	0	0	0	0
Libellulidae	0	1	0	3	1	0	0	0	0	0	1	1	19	9	0	0	6	2	8	0	0	0	0	1	0	1
Limnichidae	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lymnaeidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Macromiidae	1	0	0	0	0	0	0	7	0	1	0	7	0	0	1	2	1	1	1	4	0	0	5	1	0	1
Mesoveliidae	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Naucoridae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	10	0	0	2	0	0	0	0	0
Nepidae	4	7	0	0	1	4	5	0	0	3	0	0	6	0	0	0	1	0	0	2	3	6	1	1	5	6
Notonectidae	9	4	0	0	0	3	0	4	2	1	3	29	4	21	5	2	1	7	1	6	7	1	4	1	3	0
Ochteridae	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta	1	0	1	3	1	2	1	2	5	1	1	0	3	5	2	2	0	2	1	3	1	1	0	14	0	4
Orthocladiinae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Ostracoda	0	10	7	21	4	6	1	1	0	0	24	12	26	24	1	1	1	5	1	14	9	19	2	24	0	33
Palaemonidae	6	6	17	3	0	0	20	1	13	2	2	2	11	31	2	0	7	0	6	5	1	8	1	0	5	3
Parastacidae	0	0	0	0	0	0	0	0	1	0	0	0	1	2	0	0	0	0	2	0	0	0	0	0	0	0
Planorbidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	1	16	0	0
Pleidae	79	52	10	18	4	5	2	0	2	8	1	1	3	3	1	0	3	35	2	10	34	108	51	61	27	81
Polycentropodidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0
Protoneuridae	0	0	0	0	0	0	2	0	0	0	0	0	0	0	3	0	3	6	13	31	1	0	0	0	0	0
Psephenidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Pyralidae	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Scirtidae	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0	4	0	0	0	0	1	1	3	4	6	5
Sisyridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Staphylinidae	11	3	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
Stratiomyidae	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Tabanidae	0	0	0	0	1	0	0	0	0	1	0	0	1	3	1	0	0	0	1	0	3	0	0	1	0	0
Tanypodinae	13	5	2	5	2	12	6	2	28	4	16	12	10	38	10	19	8	14	1	9	12	3	9	12	9	15

Thiaridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	2	0	0	0	0	0	0	0	0
Tipulidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Veliidae	11	32	35	68	0	15	9	0	0	3	2	2	0	10	5	5	0	0	0	0	1	1	0	1	0	9
Viviparidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	5	0	1	0	0

Flinders catchment waterhole bottom habitat aquatic invertebrates (continued over page)

WATERHOLE	F01		F02	F03		F04		F05		F07		F08		F09	
DATE	29/10/2012	07/12/2012	28/10/2012	28/10/2012	08/12/2012	8/12/2012	28/10/2012	27/10/2012	09/12/2012	25/10/2012	11/12/2012	25/10/2012	11/12/2012	26/10/2012	10/12/2012
FAMILY															
Acarina	47	7	53	9	0	1	1	15	36	17	67	18	0	32	7
Aeshnidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ancylidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atyidae	0	0	0	0	0	0	0	0	0	0	1	3	4	0	0
Baetidae	10	2	89	66	1	0	0	62	0	1	0	0	0	2	0
Belostomatidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caenidae	63	13	35	18	9	0	0	22	11	104	114	3	3	15	13
Ceratopogonidae	20	1	0	2	0	1	0	4	4	40	12	2	0	12	4
Chironominae	28	5	3	3	2	0	1	14	15	8	15	16	2	28	0
Cladocera	2	7	709	91	4	20	0	59	3	93	0	66	10	0	24
Coenagrionidae	0	0	0	6	19	0	0	0	1	0	0	1	0	0	0
Copepoda	14	5	55	100	2	19	0	18	6	19	96	8	12	13	2
Corallanidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corbiculidae	5	0	0	0	0	0	0	0	7	4	1	0	0	0	0
Corixidae	21	0	1284	2	1	380	180	21	12	7	1	0	0	7	1
Culicidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dugesiidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dytiscidae	84	53	72	118	16	48	14	5	0	0	1	0	0	0	15

Ecnomidae	2	0	2	0	0	0	0	0	0	0	0	0	0	3	0
Elmidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gerridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gomphidae	0	1	7	0	0	0	1	4	0	3	1	0	0	2	0
Gyrinidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hebridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemicorduliidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HUL complex	0	3	0	0	4	0	0	6	0	0	0	0	0	0	0
Hydraenidae	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Hydridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydrochidae	2	0	0	0	0	0	0	0	0	0	1	0	0	1	11
Hydrometridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

WATERHOLE	F01		F02	F03		F04		F05		F07		F08		F09	
DATE	**29/10/2012**	**07/12/2012**	**28/10/2012**	**28/10/2012**	**08/12/2012**	**8/12/2012**	**28/10/2012**	**27/10/2012**	**09/12/2012**	**25/10/2012**	**11/12/2012**	**25/10/2012**	**11/12/2012**	**26/10/2012**	**10/12/2012**
Hydrophilidae	1	0	41	0	2	4	0	0	0	0	0	0	0	0	3
Hydroptilidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hyriidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isostictidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptoceridae	2	0	4	1	1	0	1	8	1	17	9	2	0	0	0
Leptophlebiidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Libellulidae	0	0	3	0	5	0	0	4	0	0	0	0	0	0	0
Limnichidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lymnaeidae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Macromiidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mesoveliidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naucoridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Nepidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Notonectidae	0	0	16	0	2	0	0	0	0	0	0	0	0	0	0
Ochteridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta	0	0	0	1	1	0	0	0	3	0	0	1	0	4	0
Orthocladiinae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ostracoda	0	0	4	241	2	46	1	34	1	8	18	105	3	0	38
Palaemonidae	0	0	40	4	0	0	2	0	0	1	2	0	14	0	0
Parastacidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Planorbidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pleidae	1	2	28	4	23	0	0	0	0	0	1	0	0	0	1
Polycentropodidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protoneuridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Psephenidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyralidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scirtidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sisyridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staphylinidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stratiomyidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tabanidae	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tanypodinae	65	23	56	23	6	46	108	11	22	13	10	15	1	53	14
Thiaridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tipulidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Veliidae	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0
Viviparidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Gilbert catchment waterhole bottom habitat aquatic invertebrates (continued over page)

WATERHOLE	G01	G02		G03		G04		G05		G06		G07		G08	G09	G10	
DATE	01/12/2012	09/10/2012	01/12/2012	09/10/2012	28/11/2012	10/10/2012	28/11/2012	10/10/2012	28/11/2012	11/10/2012	27/11/2012	11/10/2012	27/11/2012	30/11/2012	30/11/2012	13/10/2012	29/11/2012
FAMILY																	
Acarina	36	70	62	29	39	6	71	21	109	38	13	5	5	72	121	35	21
Aeshnidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ancylidae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Atyidae	1	0	0	0	1	0	0	0	0	0	0	0	0	1	3	0	0
Baetidae	15	3	3	13	16	3	2	3	3	55	34	32	54	24	6	0	0
Belostomatidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caenidae	61	12	61	16	153	40	46	5	25	147	99	52	118	0	21	18	1
Ceratopogonidae	11	7	4	10	25	1	15	3	19	1	8	9	9	5	30	35	27
Chironominae	38	20	13	67	33	67	50	32	35	5	8	36	16	25	42	34	31
Cladocera	2	8	0	8	3	0	0	0	3	4	0	1	2	37	35	0	159
Coenagrionidae	0	0	0	0	0	2	0	0	0	5	2	1	2	0	0	0	0
Copepoda	12	15	5	12	1	1	12	3	4	5	3	0	19	27	102	14	10
Corallanidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corbiculidae	0	7	1	3	4	3	2	0	1	0	0	0	0	0	0	0	0
Corixidae	31	9	0	56	4	1	3	29	68	44	86	5	23	10	344	2	3
Culicidae	0	0	0	0	0	0	5	0	0	2	0	0	2	0	0	0	0
Dugesiidae	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Dytiscidae	0	1	0	0	0	1	0	0	0	1	0	6	0	20	4	0	0
Ecnomidae	3	3	0	24	5	15	3	4	5	0	0	3	3	0	0	5	1
Elmidae	0	0	0	0	0	0	0	1	0	0	0	2	1	0	0	0	0
Gerridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gomphidae	0	7	2	0	2	16	5	5	0	8	9	11	2	3	0	0	0
Gyrinidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hebridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemicorduliidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HUL complex	0	1	0	0	0	1	0	0	0	3	0	4	5	2	0	0	0

Hydraenidae	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0
Hydridae	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Hydrochidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Hydrometridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

WATERHOLE	G01	G02		G03		G04		G05		G06		G07		G08	G09	G10	
DATE	**01/12/2012**	**09/10/2012**	**01/12/2012**	**09/10/2012**	**28/11/2012**	**10/10/2012**	**28/11/2012**	**10/10/2012**	**28/11/2012**	**11/10/2012**	**27/11/2012**	**11/10/2012**	**27/11/2012**	**30/11/2012**	**30/11/2012**	**13/10/2012**	**29/11/2012**
Hydrophilidae	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0
Hydroptilidae	0	0	0	0	0	0	0	0	0	2	2	0	1	0	0	0	0
Hyriidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isostictidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptoceridae	0	0	3	0	0	0	0	1	0	7	0	5	0	4	1	1	0
Leptophlebiidae	0	0	0	0	0	1	0	0	0	2	2	7	0	0	0	0	0
Libellulidae	0	0	0	0	0	11	0	0	0	0	3	4	1	0	0	0	0
Limnichidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lymnaeidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macromiidae	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Mesoveliidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naucoridae	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Nepidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Notonectidae	0	0	0	0	4	0	10	0	0	0	1	1	0	0	0	0	0
Ochteridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta	8	8	2	11	1	3	19	1	3	1	2	7	0	2	6	0	0
Orthocladiinae	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Ostracoda	0	0	0	0	1	3	31	0	0	2	8	2	2	37	1	4	156

Palaemonidae	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0
Parastacidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Planorbidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0
Pleidae	0	0	0	0	0	0	2	0	0	0	2	0	0	1	2	0	0
Polycentropodidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protoneuridae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Psephenidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyralidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scirtidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sisyridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staphylinidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stratiomyidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tabanidae	0	0	0	0	0	0	0	0	0	0	1	4	1	0	0	0	0
Tanypodinae	38	31	12	121	95	58	70	32	89	15	13	29	23	40	88	12	74
Thiaridae	0	0	0	0	0	0	0	0	0	4	20	0	0	0	0	0	0
Tipulidae	0	0	0	0	0	1	0	0	0	0	1	4	0	0	0	0	0
Veliidae	0	0	2	2	2	0	0	2	0	0	2	0	0	0	0	0	0
Viviparidae	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0

Aquatic macrophyte habitat aquatic invertebrates (continued over page)

WATERHOLE	F03		F08		F10
DATE	28/10/2012	08/12/2012	25/10/2012	11/12/2012	27/10/2012
FAMILY					
Acarina	4	0	9	14	3
Aeshnidae	0	0	0	0	3
Ancylidae	0	0	0	0	0
Atyidae	0	0	53	335	0
Baetidae	161	7	4	2	42
Belostomatidae	0	0	6	7	0
Caenidae	0	17	7	25	1
Ceratopogonidae	1	0	4	0	0
Chironominae	2	1	20	33	56
Cladocera	66	29	435	992	128
Coenagrionidae	26	92	32	20	131
Copepoda	20	12	445	135	283
Corallanidae	0	0	0	0	0
Corbiculidae	0	0	0	0	0
Corixidae	2	0	1	0	12
Culicidae	40	3	7	0	4
Dugesiidae	0	0	0	0	0
Dytiscidae	21	32	1	7	35
Ecnomidae	0	0	0	1	0
Elmidae	0	0	0	0	0
Gerridae	1	0	0	0	0
Gomphidae	0	0	0	0	0
Gyrinidae	0	0	0	0	3
Hebridae	0	0	0	0	0
Hemicorduliidae	0	0	0	0	0
HUL complex	6	16	15	21	17
Hydraenidae	6	0	0	2	0
Hydridae	0	0	0	0	0
Hydrochidae	0	0	0	2	0
Hydrometridae	1	0	0	0	0
Hydrophilidae	7	0	2	10	0
Hydroptilidae	0	0	0	0	0
Hyriidae	0	0	0	0	0
Isostictidae	0	0	0	0	0
Leptoceridae	11	0	4	0	1
Leptophlebiidae	0	0	0	0	0
Libellulidae	11	0	3	5	49
Limnichidae	0	0	0	0	0
Lymnaeidae	1	0	6	1	0
Macromiidae	0	3	0	0	0
Mesoveliidae	1	0	9	4	1

WATERHOLE	F03		F08		F10
DATE	28/10/2012	08/12/2012	25/10/2012	11/12/2012	27/10/2012
FAMILY					
Naucoridae	0	0	0	0	0
Nepidae	0	0	0	2	0
Notonectidae	5	2	0	0	22
Ochteridae	0	0	0	0	0
Oligochaeta	0	0	1	1	0
Orthocladiinae	0	0	0	0	0
Ostracoda	585	13	645	570	120
Palaemonidae	0	8	6	5	1
Parastacidae	0	0	0	0	0
Planorbidae	0	0	0	0	0
Pleidae	79	78	15	3	52
Polycentropodidae	0	0	0	0	0
Protoneuridae	0	0	0	0	0
Psephenidae	0	0	0	0	0
Pyralidae	0	0	0	0	2
Scirtidae	0	0	0	0	0
Sisyridae	0	0	0	0	0
Staphylinidae	0	0	0	0	0
Stratiomyidae	0	0	0	0	0
Tabanidae	2	0	0	0	1
Tanypodinae	4	4	9	3	5
Thiaridae	0	0	0	0	0
Tipulidae	0	0	0	0	0
Veliidae	13	1	1	0	0
Viviparidae	3	0	3	0	1

Appendix C Fish data

Fish recorded in the Flinders and Gilbert catchments

FAMILY NAME	SPECIES NAME	COMMON NAME
Ambassidae	*Ambassis* sp.	Glassfish
Apogonidae	*Glossamia aprion*	Mouth almighty
Ariidae	*Neoarius graeffei*	Lesser salmon catfish
	Neoarius leptaspis	Salmon catfish
	Neoarius midgleyi	Shovel-nosed catfish
Atherinidae	*Craterocephalus stercusmuscarum*	Fly-specked hardyhead
Belonidae	*Strongylura krefftii*	Longtom
Clupeidae	*Nematalosa erebi*	Bony bream
Eleotridae	*Mogurnda mogurnda*	Northern trout gudgeon
	Oxyeleotris lineolatus	Sleepy cod
	Oxyeleotris selheimi	Giant gudgeon
Engraulidae	*Thryssa scratchleyi*	Freshwater anchovy
Gobiidae	*Glossogobius aureus*	Golden goby
	Glossogobius giuris	Flathead goby
Centropomidae	*Lates calcarifer*	Barramundi
Megalopidae	*Megalops cyprinoides*	Tarpon
Melanotaenidae	*Melanotaenia splendida inornata*	Chequered rainbowfish
Plotosidae	*Anodontiglanis dahli*	Toothless catfish
	Neosilurus ater	Black catfish
	Neosilurus hyrtlii	Hyrtl's tandan
Soleidae	*Brachirus selheimi*	Freshwater sole
Terapontidae	*Amniataba percoides*	Barred grunter
	Hephaestus fuliginosus	Sooty grunter
	Leiopotherapon unicolor	Spangled perch

	Scortum ogilbyi	Gulf grunter
Toxotidae	*Toxotes chatareus*	Seven-spot archerfish

Fish recorded in the Flinders Catchment. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited traps (0.2 x 0.2 x 0.4 m). [1]Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	E-fishing	Traps	Gill net	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole F01	**575 s**	**4x2 hrs**	**2 hrs**		**184 s**		**2 hrs**		
Ambassis sp.	1								**1**
N. erebi	10		8		10		9		**37**
O. lineolatus	1	2			3				**6**
G. aureus	1				1				**2**
M. splendida inornata	4								**4**
N. hyrtlii	1								**1**
A. percoides					2				**2**
L. unicolor	3				5				**8**
Waterhole F02	**184 s**	**4x2 hrs**							
N. erebi	10								**10**
G. aureus	6	4							**10**
M. splendida inornata	3								**3**
N. hyrtlii		1							**1**
A. percoides	1								**1**
Waterhole F03	**865 s**	**4x2 hrs**			**874 s**				
Ambassis sp.	7	1			3				**11**
N. erebi	2				7				**9**
O. lineolatus	16				4				**20**
M. splendida inornata	5				73				**78**
N. hyrtlii	1								**1**
A. percoides	9								**9**
L. unicolor	4				3				**7**
Waterhole F04	**552 s**	**4x o/n**	**2 hrs**						
Ambassis sp.	4		22						**26**
N. erebi	47								**47**

O. lineolatus		3							**3**
G. aureus	2	3							**5**
M. splendida inornata		8							**8**
L. unicolor	2								**2**

Fish recorded in the Flinders Catchment. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited traps (0.2 x 0.2 x 0.4 m). [1]Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	E-fishing	Traps	Gill net	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole F05	**405 s**	**4x2 hrs**	**2 hrs**		**633 s**	**4x2 hrs**	**2 hrs**		
Ambassis sp.	1								**1**
N. graeffei			2						**2**
N. erebi			2		1		4		**7**
O. lineolatus	7				4				**11**
G. aureus	6				3				**9**
M. splendida inornata					3				**3**
A. dahli							1		**1**
A. percoides	13				5				**18**
H. fuliginosus						1			**1**
L. unicolor	6				1				**7**
T. chatareus				P			1		**1**
Waterhole F07	**294 s**	**4x2 hrs**	**2 hrs**		**364 s**	**4x o/n**	**2.5 hrs**		
N. graeffei			9						**9**
N. erebi	2		15		2		11		**30**
O. lineolatus	3		2						**5**
G. aureus	13				9				**22**
L. calcarifer			6				2		**8**
M. splendida inornata					3				**3**
N. ater			1						**1**
A. percoides	4								**4**

L. unicolor				P	1				**1**
T. chatareus							2		**2**
Waterhole F08	**264 s**	**4x2 hrs**	**2 hrs**		**370 s**	**4x2.5 hrs**			
Ambassis sp.	11		1		1				**13**
G. aprion								P	**P**
N. graeffei			22						**22**
N. erebi	26		1						**27**
O. lineolatus	10				8				**18**
G. aureus	4								**4**
M. splendida inornata	7								**7**
A. percoides								P	**P**
L. unicolor	4			P	1				**5**

Fish recorded in the Flinders Catchment. 1. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited traps (0.2 x 0.2 x 0.4 m). 1Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	Seine net	Traps	Gill net	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole F09	**50 m**	**4x2 hrs**	**2 hrs**		**683 s**	**4x o/n**	**2 hrs**		
G. aprion					1				**1**
N. graeffei			1				1		**2**
N. erebi	17		9		4		6		**36**
O. lineolatus			2			4			**6**
T. scratchleyi							3		**3**
G. aureus					11				**11**
M. splendida inornata	3				1				**4**
M. cyprinoides			1						**1**
A. dahli							7		**7**
A. percoides					5				**5**
S. ogilbyi			2		1		3		**6**
L. unicolor				P	4				**4**
T. chatareus							3		**3**

Fish recorded in the Gilbert Catchment. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited traps (0.2 x 0.2 x 0.4 m). 1Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	E-fishing	Traps	Gill net	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole G01	**316 s**	**4x2 hrs**	**3 hrs**		**361 s**	**4x2 hrs**	**2 hrs**		
N. erebi			6		1		4		**11**
M. mogurnda	6				5				**11**
M. splendida inornata	80	5			160	220			**465**
A. dahli			4						**4**
N. hyrtlii	1				2				**3**
A. percoides					2				**2**
H. fuliginosus	4				4				**8**
L. unicolor	17				24				**41**
Waterhole G02	**394 s**	**4x o/n**			**207 s**	**4x2 hrs**			
C. stercusmuscarum								P	**P**
N. erebi	45								**45**
O. lineolatus	5								**5**
M. splendida inornata	85				70				**155**
A. percoides	7				2				**9**
H. fuliginosus	6								**6**
L. unicolor	16				7				**23**
T. chatareus				P				P	**P**
Waterhole G03	**579 s**	**4x2 hrs**			**394 s**	**4x2 hrs**	**2 hrs**		
Ambassis sp.	25								**25**
C. stercusmuscarum	25								**25**
S. krefftii	2							P	**2**
M. mogurnda					2				**2**
O. lineolatus	5				6				**11**
O. selheimi	4								**4**
M. splendida inornata	80				47				**127**

A. percoides	15	2	10	1			**28**
H. fuliginosus	1					P	**1**
L. unicolor	1		2				**3**
S. ogilbyi						P	**P**
T. chatareus	2				1		**3**

Fish recorded in the Gilbert Catchment. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited crab traps (0.2 x 0.2 x 0.4 m). [1]Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	E-fishing	Traps	Angling	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole G04	**510 s**	**4x o/n**			**497 s**	**4x o/n**	**2 hrs**		
Ambassis sp.	100								**100**
N. graeffei							1		**1**
C. stercusmuscarum	100								**100**
S. krefftii	1								**1**
G. aureus					2				**2**
M. splendida inornata	200								**200**
A. percoides	100	2			59	1			**162**
L. unicolor	15				1				**16**
T. chatareus	1								**1**
Waterhole G05	**240 s**	**4x2 hrs**			**440 s**				
Ambassis. sp.	25								**25**
G. aprion					4				**4**
C. stercusmuscarum	25				10				**35**
N. erebi				P					**P**
M. mogurnda					1				**1**
O. lineolatus	7				13				**20**
G. aureus					1				**1**
M. splendida inornata	62				35				**97**
A. percoides	8				60				**68**
H. fuliginosus				P	1				**1**
L. unicolor	1				3				**4**
T. chatareus				P				P	**P**
Waterhole G06	**411 s**	**4x o/n**	**40 min**						
C. stercusmuscarum	110								**110**
N. erebi				P					**P**

M. mogurnda	10			**10**
M. splendida inornata	2			**2**
A. percoides			P	**P**
H. fuliginosus	2	5		**7**
L. unicolor	1	4		**5**

Fish recorded in the Gilbert Catchment. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited traps (0.2 x 0.2 x 0.4 m). [1]Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	E-fishing	Traps	Gill net	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole G07	976 s	4x2 hrs			362 s	4x o/n			
Ambassis sp.	125								125
G. aprion	1				2				3
C. stercusmuscarum	125				20	1			146
M. mogurnda	2								2
M. splendida inornata	1				11				12
A. percoides	5								5
H. fuliginosus	7				3				10
L. unicolor	17				5				22
Waterhole G08	**396 s**	**4x2 hrs**			**351 s**				
Ambassis sp.	120								**120**
G. aprion					3				**3**
C. stercusmuscarum	120				40				**160**
S. krefftii					2				**2**
N. erebi				P					**P**
O. lineolatus	9				18				**27**
G. aureus					1				**1**
L. calcarifer	1								**1**
M. splendida inornata	200				270				**470**
N. ater	1								**1**
A. percoides	1				6				**7**
L. unicolor	5				2				**7**
T. chatareus	6				40				**46**
Waterhole G09	**583 s**	**4x o/n**	**2 hrs**		**524 s**	**4x o/n**	**20 min**		
Ambassis sp.					16				**16**
G. aprion	8		1		3				**12**
N. graeffei							5		**5**

N. erebi			3				1		**4**
O. lineolatus	24				46				**70**
O. selheimi					13				**13**
G. aureus					2				**2**
M. cyprinoides							2		**2**
M. splendida inornata	100				120				**220**
N. ater			1				1		**2**
A. percoides	3				1		1		**5**
L. unicolor	3				16				**19**
T. chatareus	2		1				1		**4**

Fish recorded in the Gilbert catchment. E-fishing = backpack electrofishing assisted by visual observation. Gill net: 30 x 2 m, mesh size 7.5 cm. Seine net: 30 x 2 m, mesh size 2.5 cm. Traps = baited traps (0.2 x 0.2 x 0.4 m). [1]Visual observations are given as presence (P) where species were not captured using other methods

SPECIES NAME	SURVEY 1				SURVEY 2				
	E-fishing	Traps	Gill net	Visual[1]	E-fishing	Traps	Gill net	Visual[1]	TOTAL
Waterhole G10	**356 s**				**309 s**	**4x2 hrs**			
Ambassis sp.	30								**30**
C. stercusmuscarum	30				100				**130**
N. erebi	10								**10**
M. splendida inornata	100				500				**600**
B. selheimi					1				**1**
A. percoides	41				100				**141**
H. fuliginosus					1				**1**
L. unicolor	40				40				**80**
T. chatareus				P					**P**

Appendix D Dataset used in multivariate biotic comparisons (BIOENV analysis)

ENVIRONMENTAL VARIABLE (UNIT MEASUREMENT)	CODE
Surface area (m^2)	SA
Wetted volume (m^3)	WW
Riparian score (see methods)	RS
Woody debris (% coverage)	WD
Detritus (% coverage)	Det
No riparian species	NoRS
Mean turbidity (hydrolab 20min data) (NTU)	Mean NTU
Max. secchi depth: depth ratio	Max Zsec:Z
Max. euphotic depth: depth ratio	Max Zeu:Z
Min. dissolved oxygen (hydrolab 20min data) (%)	Min DO
Mean electrical conductivity (hydrolab 20 min data) (uS/cm)	Mean EC
Min. surface temperature (continuous temperature logger; 20 mins) (^{o}C)	MinSurfTemp
Mean surface water temperature (continuous temperature logger; 20 mins) (^{o}C)	MeanSurfTemp
Max. surface water temperature (continuous temperature logger; 20mins) (^{o}C)	MaxSurfTemp
% time difference > 1.0^{o}C btw surface and bottom water temperature over prior period before field survey (%)	%Diff>1.0
% time difference > 1.5^{o}C btw surface and bottom water temperature over prior period before field survey (%)	%Diff>1.5
TSS (mg/L)	TSS
Aqueous ammonia (mg/L)	AA
Aqueous particulate phosphorus	APP
Total filterable aqueous phosphorus (mg/L)	TFAP
Aqueous particulate nitrogen (mg/L)	APN
Aqueous dissolved organic nitrogen (mg/L)	ADON
Aqueous urea (mg/L)	AU
Total chlorophyll-*a*	TCa
Aqueous total organic carbon (mg/L)	ATOC
Aqueous dissolved inorganic nitrogen (mg/L)	ADIN

Appendix E Flinders River catchment waterhole habitat descriptions

WATERHOLE F01

FEATURE	DESCRIPTION
Waterhole	F01
Catchment	Flinders River
Watercourse	Fairlight Creek
Waterhole location	-20.655402°, 143.895401°. Located at the junction of Flinders River and Fairlight Creek.
Waterhole elevation	~ 270 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 18-Sept-12
	Survey 2: 29-Oct-12
	Survey 5: 7-Dec-12
	Survey 6: 19-Dec-12
	Survey 7: 17-Jan-13
	Survey 9: 1-Jun-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~2600 m^2
	Waterhole volume: ~2700 m^3
	Wetted perimeter: ~ 530 m
	Maximum depth: 2 m
	Average depth: 0.9 m
	Waterhole length: 250 m
Instream habitats	This waterhole has a predominantly silty bottom habitat, with some sandy sections in the upstream area. No aquatic macrophytes were present in the waterhole. Some larger logs and branches provide habitat along waterhole edges. Epilithic and planktonic algae were most dense during the September 2012 survey, densities declined during the survey period.
Riparian zone	The riparian zone has a relatively high density of rubber vine (*Cryptostegia grandiflora*), which is smothering many native riparian trees. Riparian tree cover is sparse, offering only ~5 % shade across the waterhole surface. Grass cover on steeper bank sections is dense.
Waterhole depth changes	Water depth declined steadily by over a meter between September and December 2012. During January 2013 depth increased by ~2 meters then declined rapidly to May 2013.
Other notes	Cattle access damage is evident where cattle can access the more gently sloping riparian areas. There is evidence of pig damage in the riparian zone and shallow instream habitats.

a)

b)

Figure 1a) GoogleEarth 2005 aerial view of F01. b) Left to right: 1) Upstream from Flinders River junction, note sand berm across the confluence with the Flinders River. 2) Downstream from Flinders River junction. 3) Upstream from right bank, fixed camera point. 4) Upstream from right bank, fixed camera point

Figure 2 Bathymetry map of waterhole F01. Depth and waterhole perimeter data generated from data collected Oct 2012

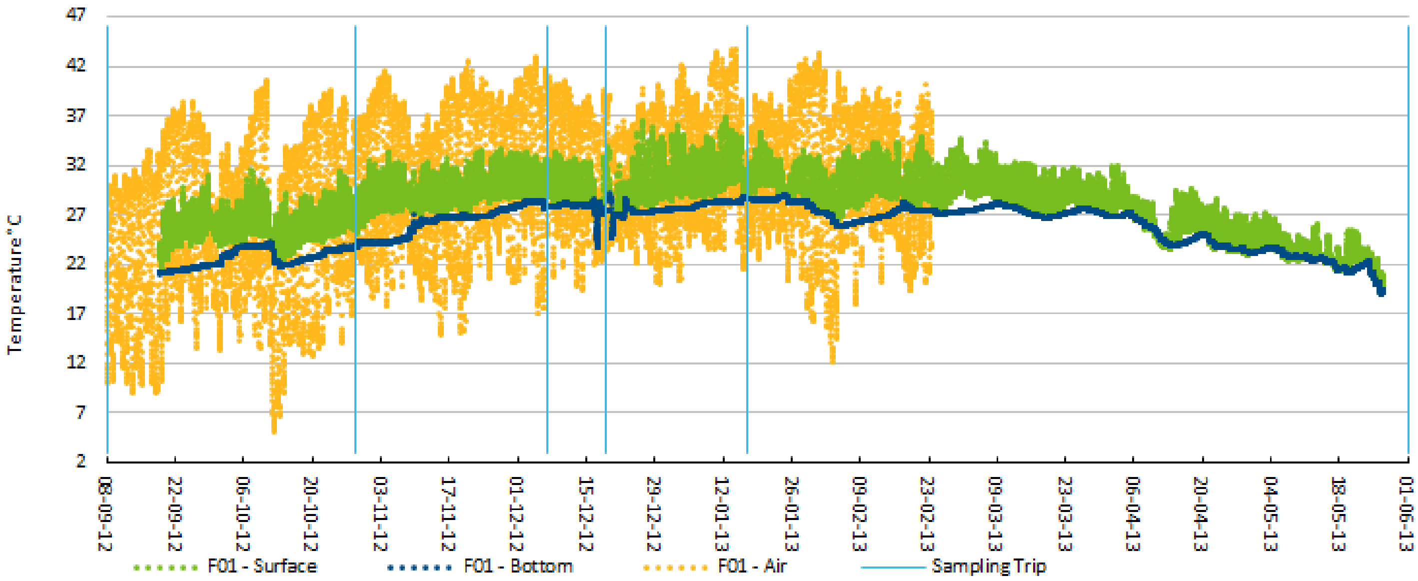
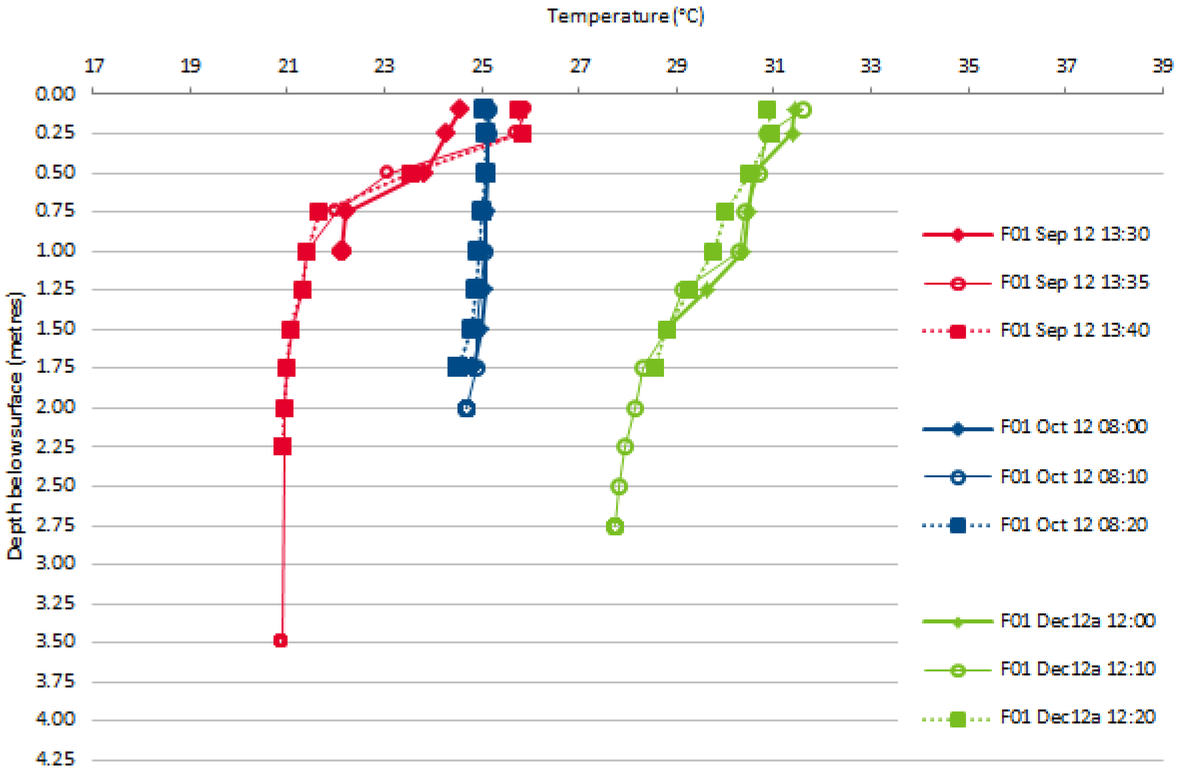


Figure 3 Long term temperature logger data for waterhole F01. Air temperature logger malfunction in Februar 2013

Table 1 Continuous water and air temperature logger summary statistics for each survey at waterhole F01.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Sep 12	18-09-12 21:20	29-09-12 21:20	11	6.7	25.9	39.5	22.0	25.8	29.4	21.7	22.6	23.6	-0.1	3.2	7.2	96.9	93.8	88.2
Oct 12	13-10-12 00:15	25-10-12 00:15	12	17.1	31.8	42.9	28.6	30.6	33.6	27.4	27.9	28.5	0.2	2.6	6.3	99.1	89.8	72.7
Dec12a	27-11-12 00:15	06-12-12 00:15	9	24.1	29.1	34.8	24.7	26.4	28.6	24.7	26.0	28.5	0.0	0.3	0.8	41.1	0.0	0.0
Dec12b	20-12-12 00:15	21-12-12 00:15	1	23.6	33.9	43.7	28.9	32.0	36.8	28.2	28.3	28.4	0.7	3.8	8.6	100.0	95.6	84.8
Jan 13	09-01-13 00:15	15-01-13 00:15	6	-	-	-	20.9	22.8	25.2	20.9	21.7	22.3	-0.2	1.1	3.7	76.1	48.1	24.9
May 13	21-05-13 00:15	25-05-13 00:15	4	6.7	25.9	39.5	22.0	25.8	29.4	21.7	22.6	23.6	-0.1	3.2	7.2	96.9	93.8	88.2



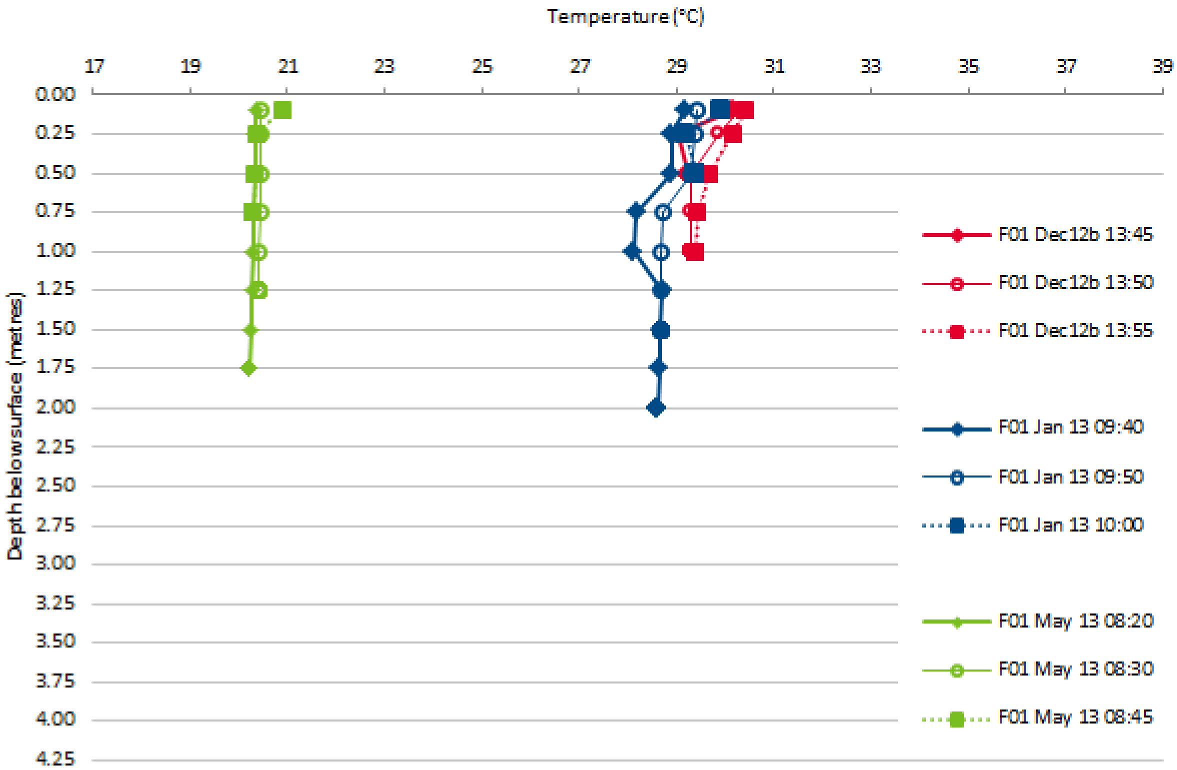
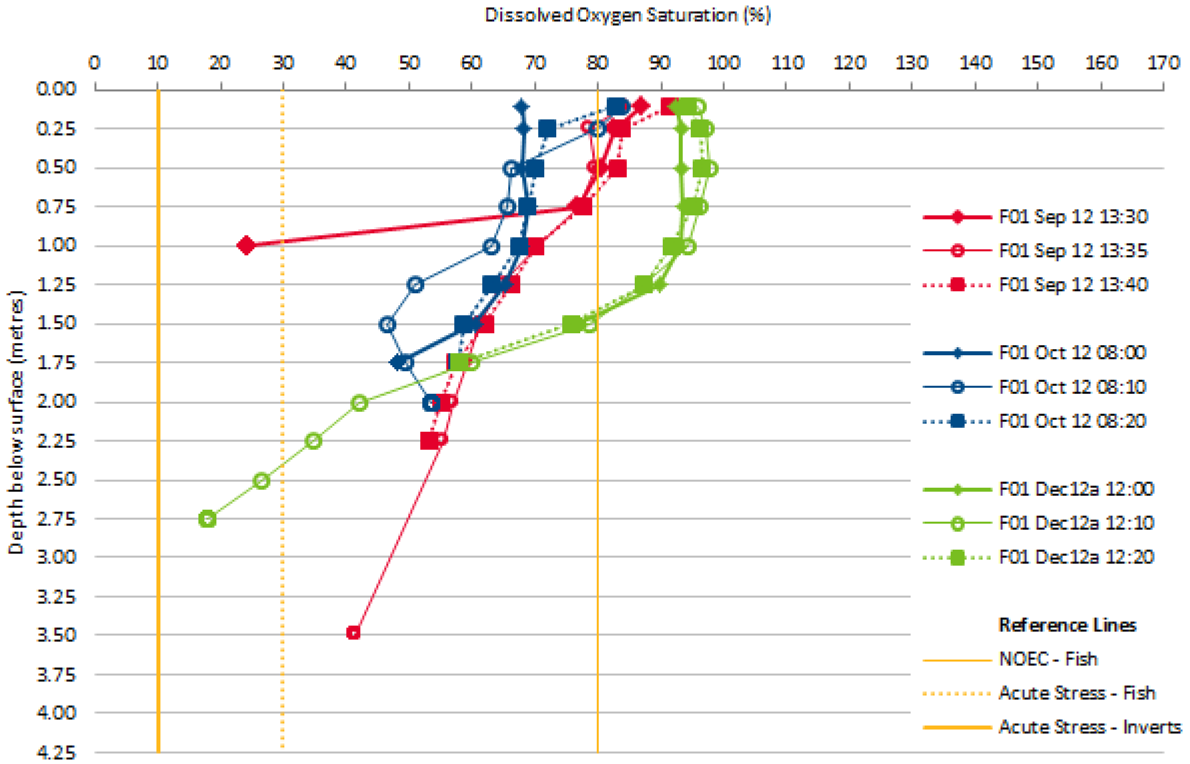


Figure 4 Temperature vertical water column profiles across the waterhole F01. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



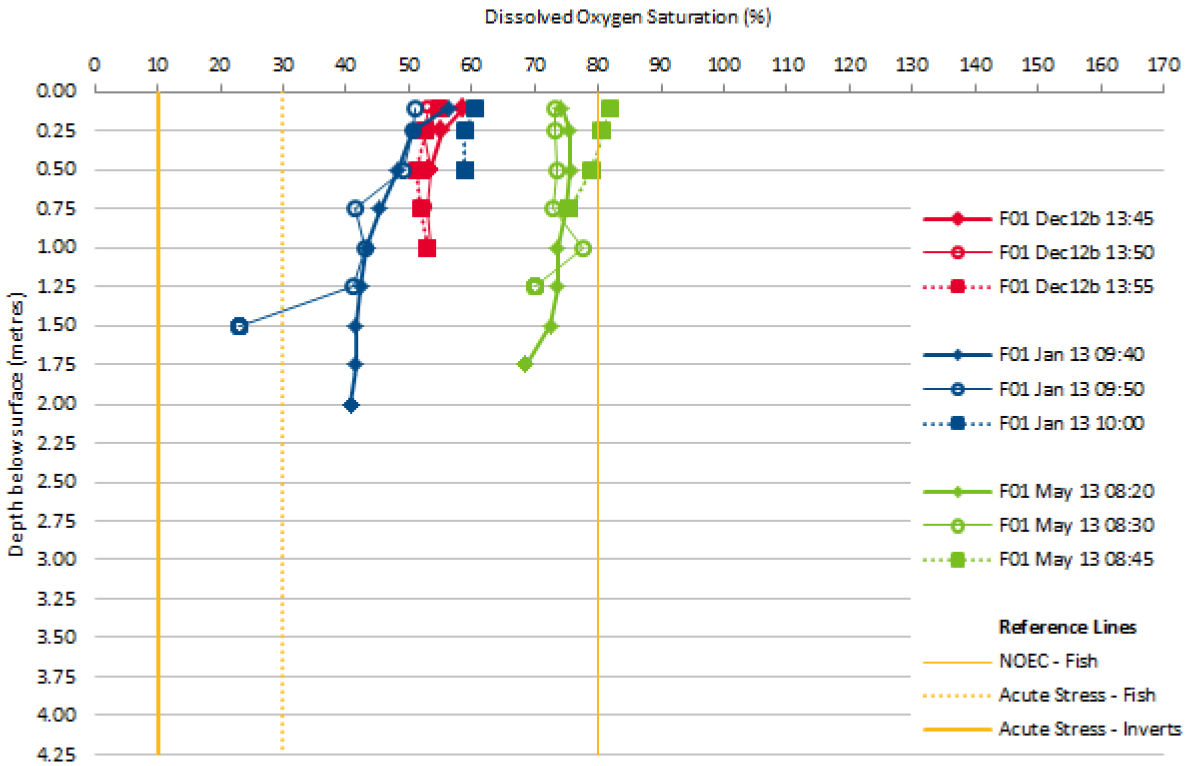
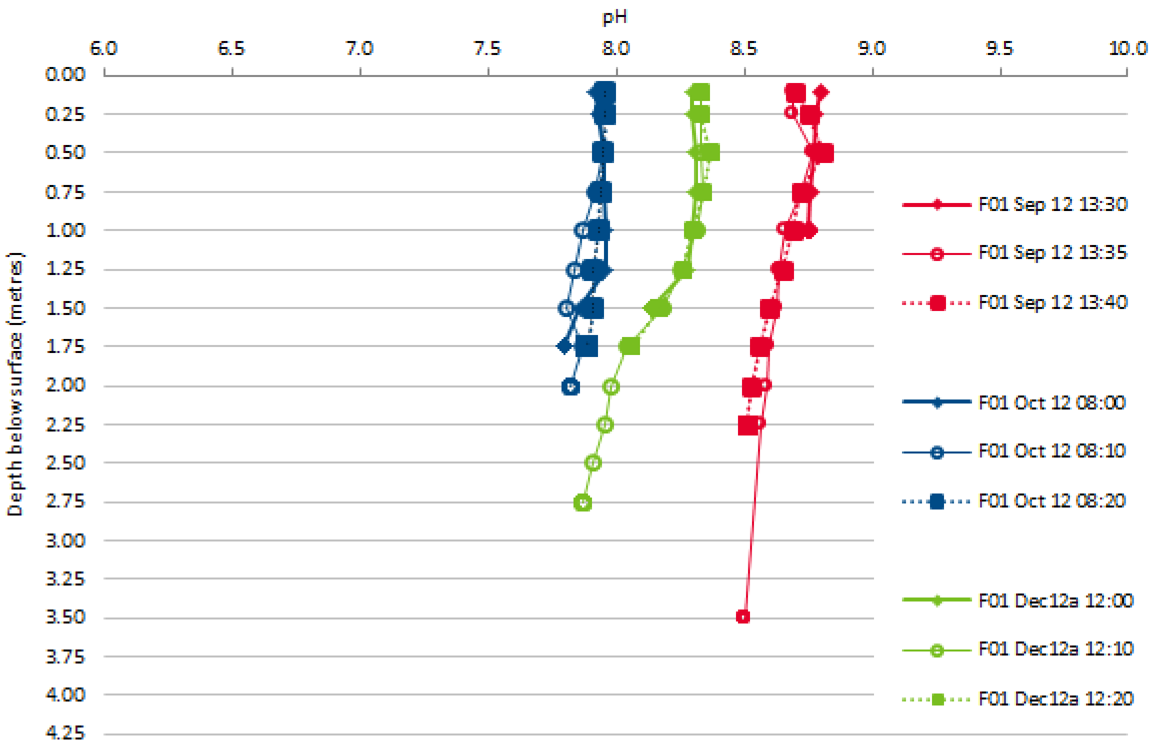


Figure 5 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F01. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



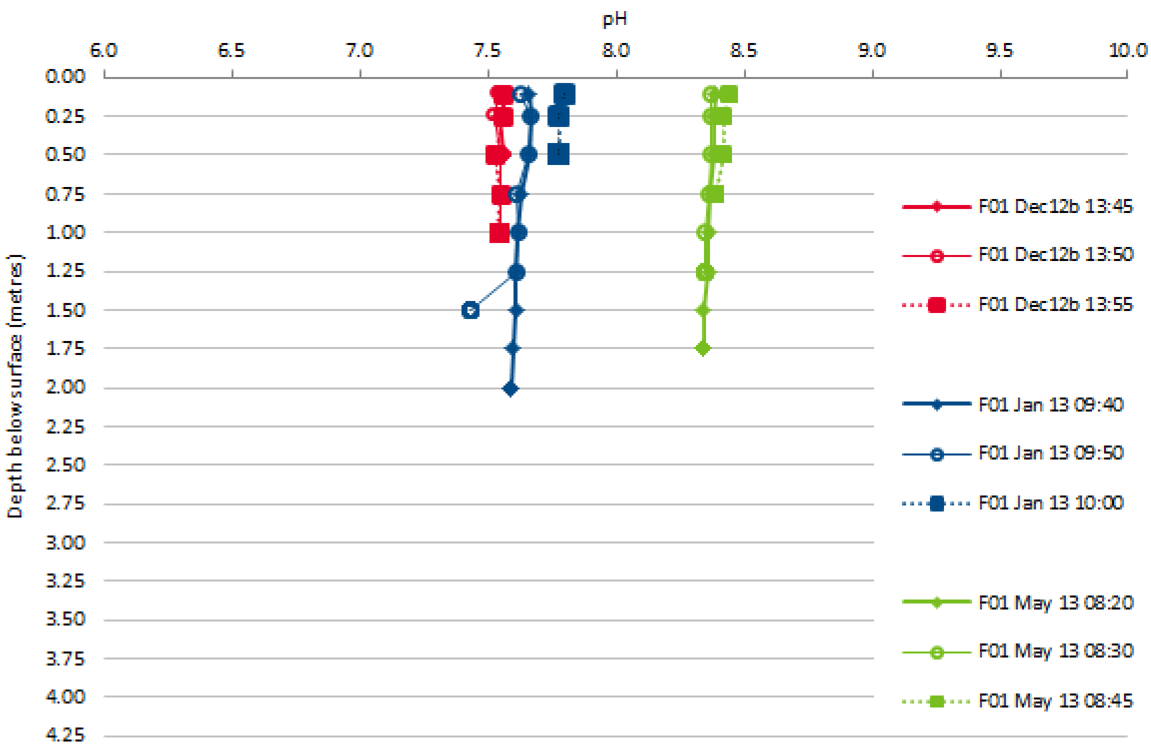
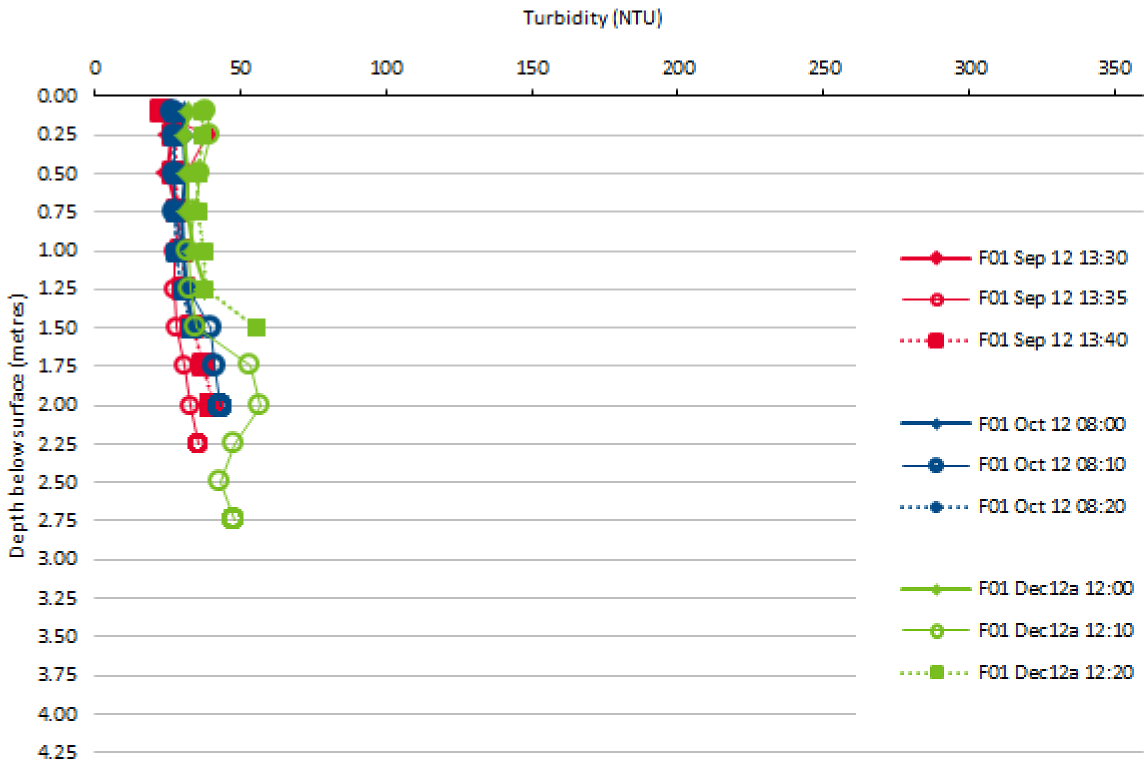


Figure 6 pH vertical water column profiles at waterhole F01. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



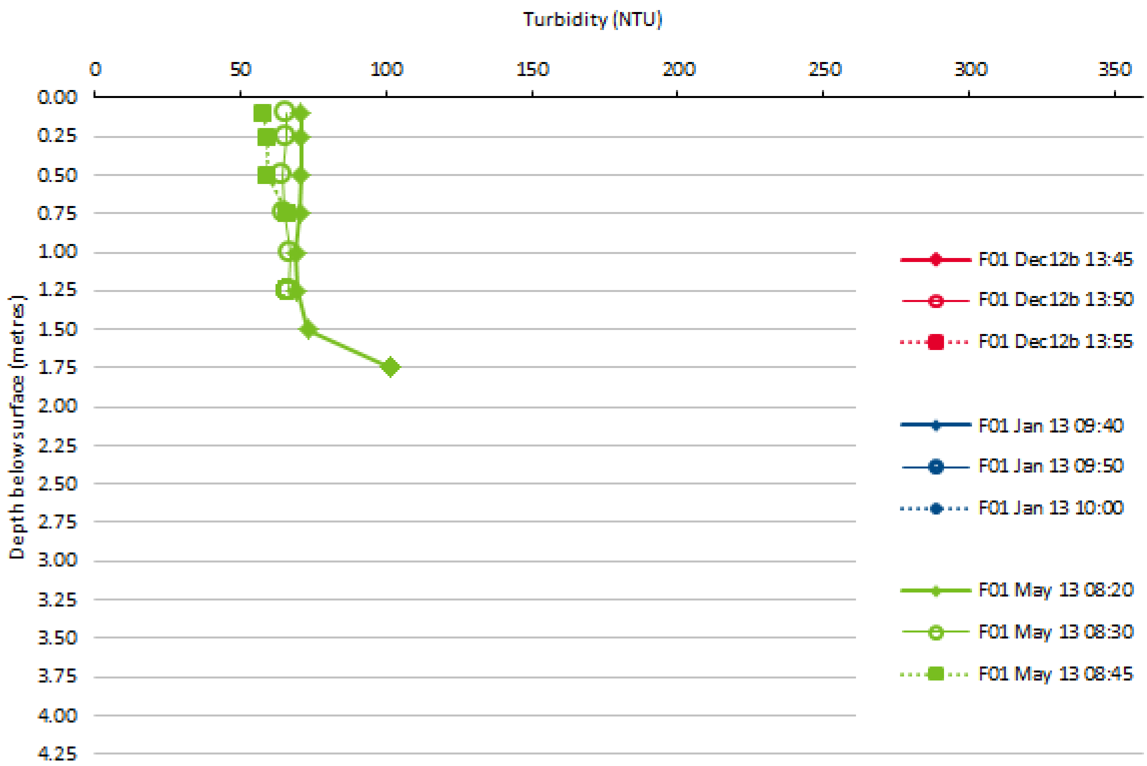
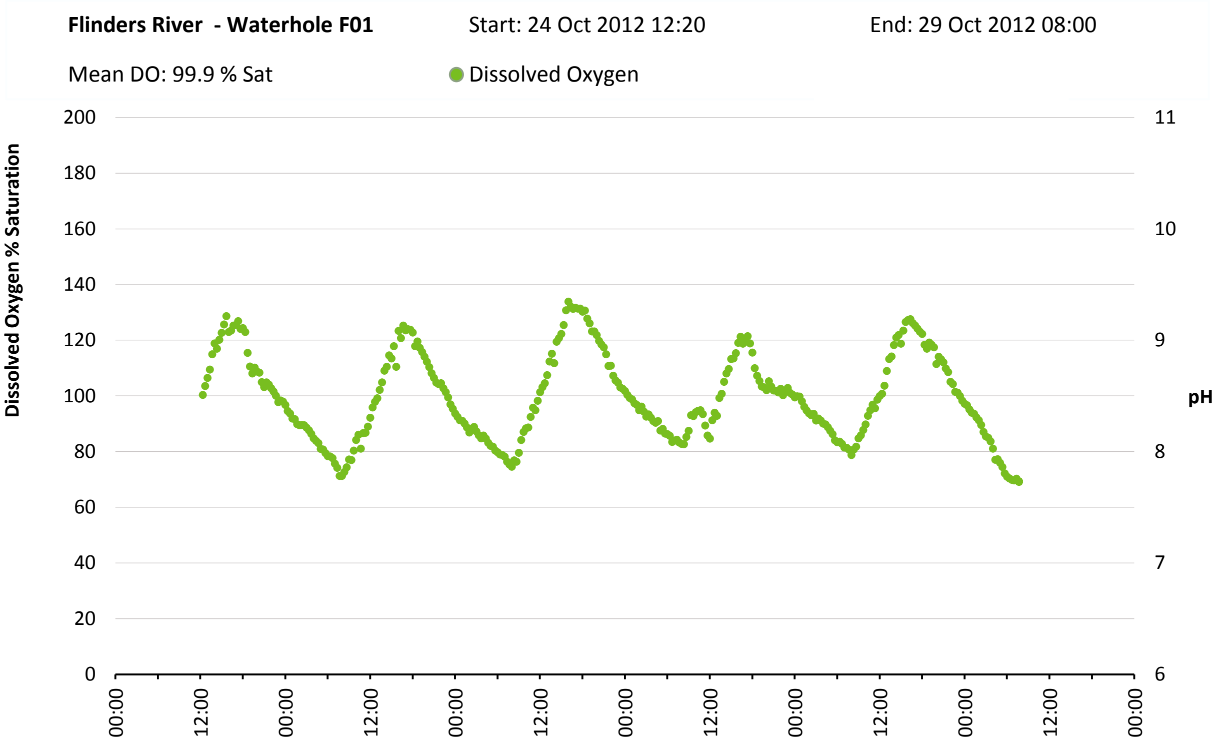


Figure 7 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F01. No turbidity data was collected in Jan or May 2013. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



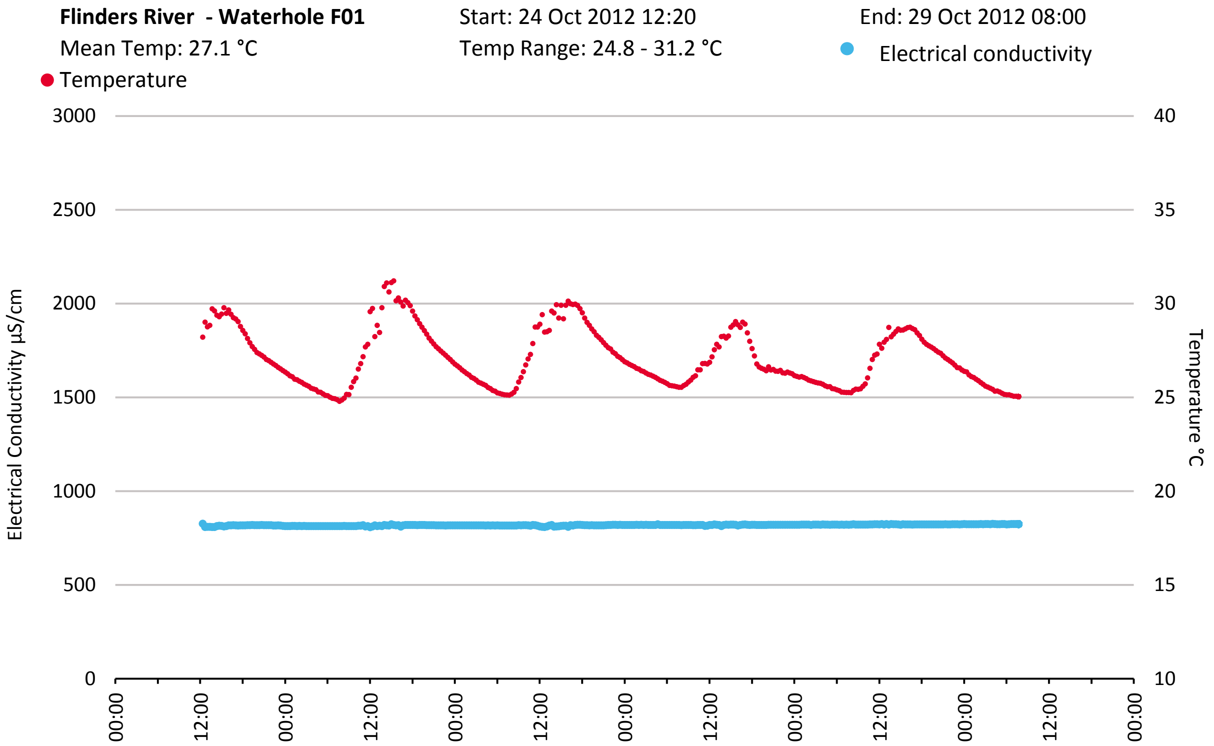


Figure 8 Diel physico chemical data for waterhole F01, Oct 2012

WATERHOLE F02

FEATURE	DESCRIPTION
Waterhole	F02
Catchment	Flinders River
Waterhole location	-20.794137°, 143.444195°
Waterhole elevation	~ 228 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 7-Sept-12
	Survey 2: 28-Oct-12
	Survey 6: 19-Dec-12
	Survey 7: 14-Jan-13
	Survey 8: 23-Feb-13
	Survey 9: 31-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~17,100 m^2
	Waterhole volume: ~8900 m^3
	Wetted perimeter: ~ 940 m
	Maximum depth: 1.5 m
	Average depth: 0.5 m
	Waterhole length: 50 m
Instream habitats	This waterhole has 90% sandy bottom habitat, with a small amount of silt and rock at the downstream end against the causeway. No aquatic macrophytes were present at the waterhole. Very few larger logs and branches are available. Detritus was present at waterhole edges and on the waterhole bottom. Planktonic algae were dense during September 2012, and declined over the survey period.
Riparian zone	The riparian zone was in good condition at this waterhole. The riparian zone is relatively wide, and hosts *Eucalyptus* and *Melaleuca* species. Due to the width of the river in this reach, riparian shade offered over the waterhole surface is low. Groundcover was fairly dense.
Waterhole depth changes	Water depth declined rapidly by one metre between September and October 2012, with maximum waterhole depth measured at 0.6 m during October. By mid December the depth had risen by 3 m, at which point it declined steadily to February 2013 when the waterhole became completely dry.
Other notes	Minimal damage from cattle access damage is evident at this waterhole. The road causeway has assisted bunding of water at the downstream end of the waterhole.

a)

b)

Figure 9 a) GoogleEarth 2004 aerial view of F02. b) Left to right: 1) Upstream from causeway. 2) Downstream towards causeway. 3) Downstream towards causeway. 4) Upstream from causeway

Figure 10 Bathymetry map of waterhole F02. Depth and waterhole perimeter data generated from data collected Oct 2012

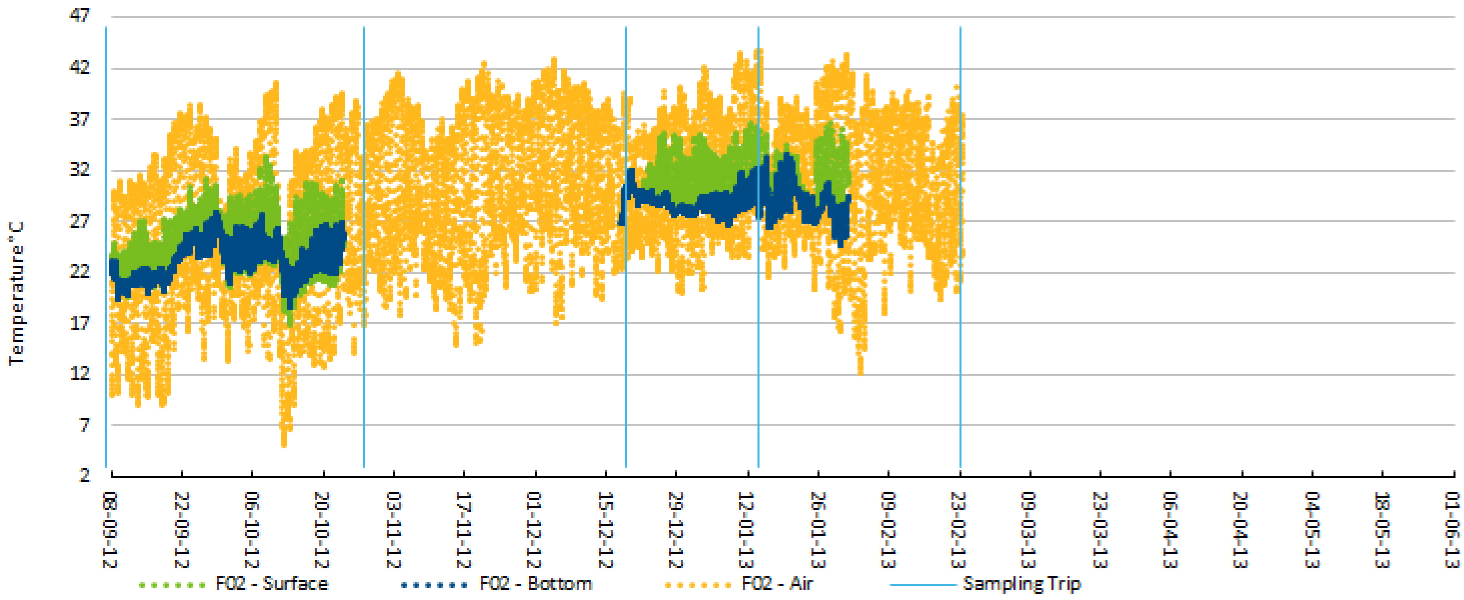


Figure 11 Long term temperature logger data for waterhole F02. Water temperature data during November and December 2012 removed due to shallowness and loggers recorded similar temperature to ambient air temperature. Waterhole received some inflow mid December 2012, however, dried again late Janueary 2013

Table 2 Continuous water and air temperature logger summary statistics for each survey at waterhole F02.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Sep 12	08-09-12 00:15	10-09-12 00:15	2	10.0	20.6	30.9	19.5	22.2	24.8	19.5	21.6	23.2	-0.1	0.7	2.7	49.7	31.7	16.6
Oct 12	12-10-12 20:15	24-10-12 20:15	12	6.7	25.7	39.5	16.9	24.3	30.9	18.7	23.3	26.9	-2.0	1.0	8.1	43.7	36.8	32.8
Dec12b	18-12-12 22:15	20-12-12 22:15	2	23.4	29.6	39.1	29.5	30.5	32.0	29.5	30.4	32.0	-0.1	0.1	0.7	1.4	0.0	0.0
Jan 13	12-01-13 00:15	14-01-13 00:15	2	23.6	34.9	43.6	28.7	31.9	36.7	28.5	30.2	32.2	-0.1	1.7	7.2	49.0	40.7	36.6

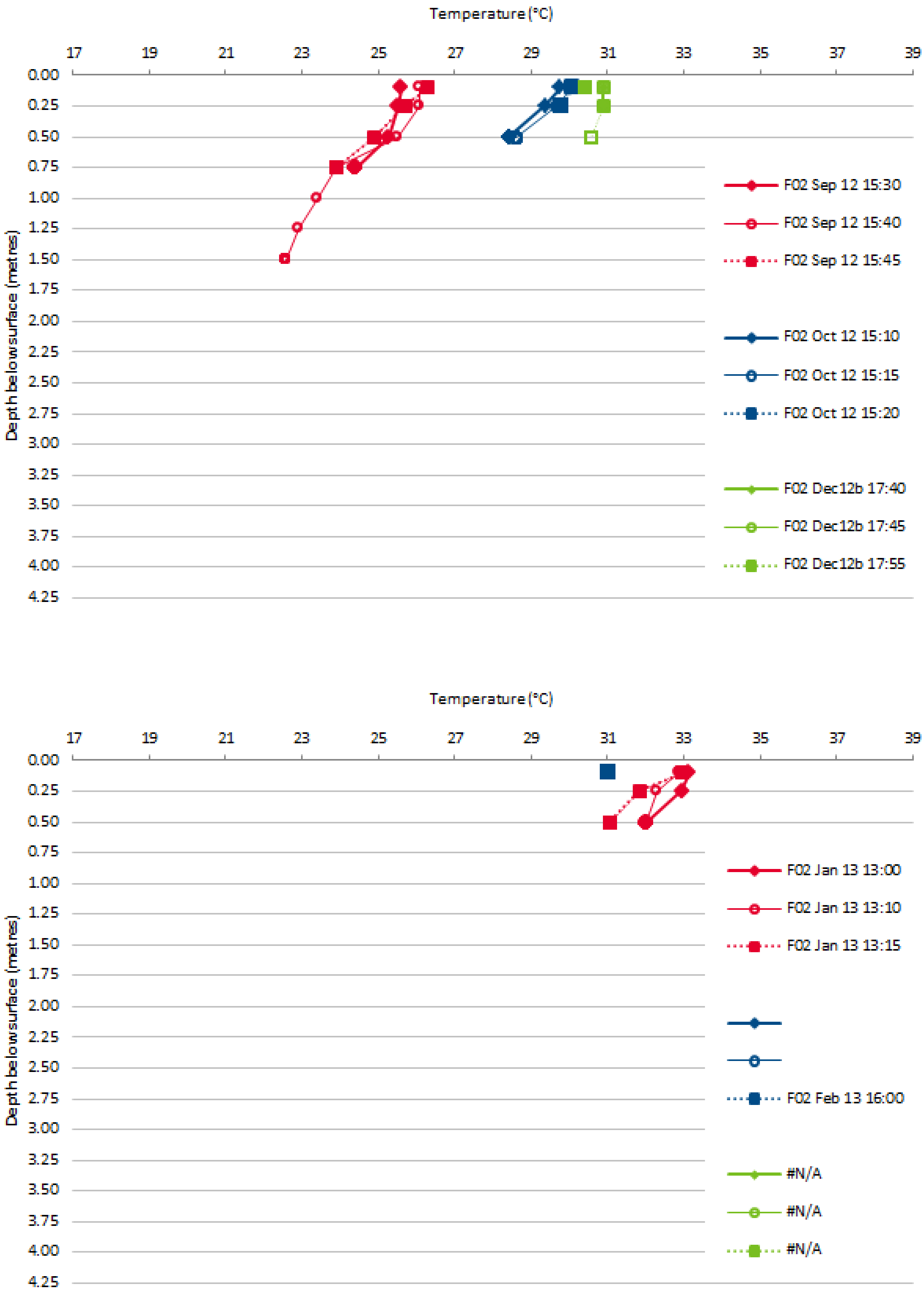
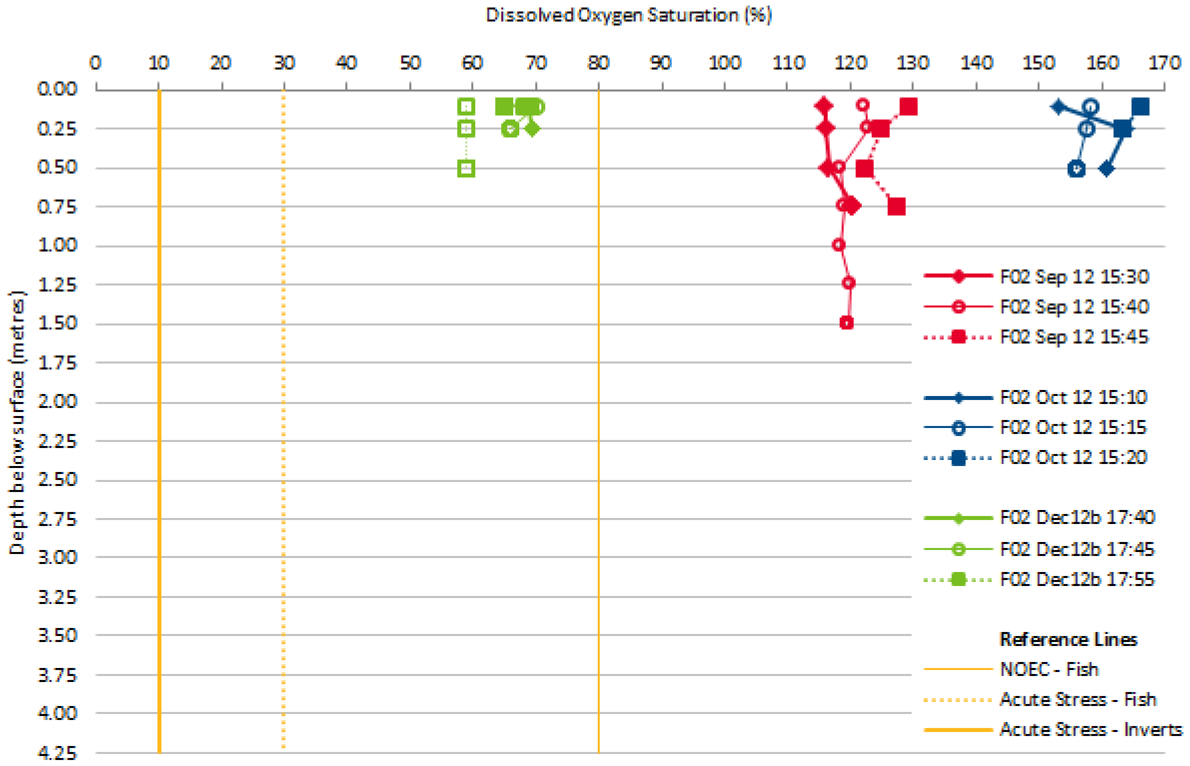


Figure 12 Temperature vertical water column profiles at waterhole F02. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



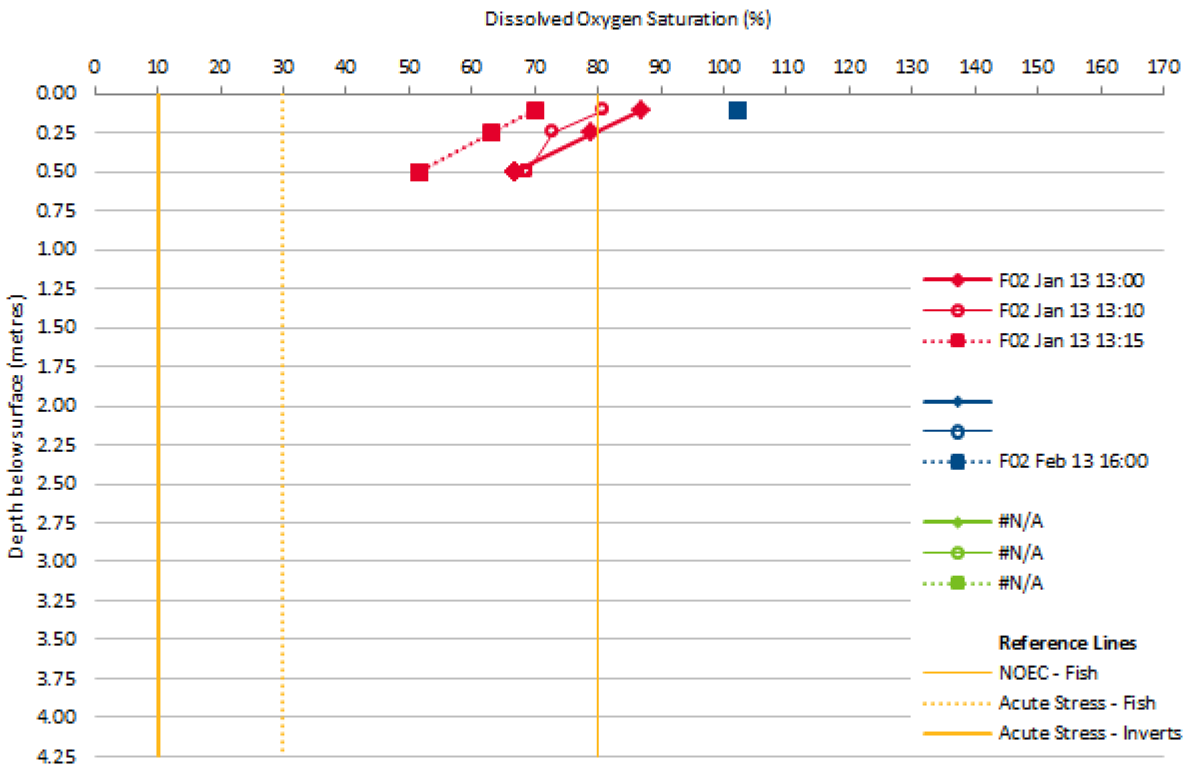
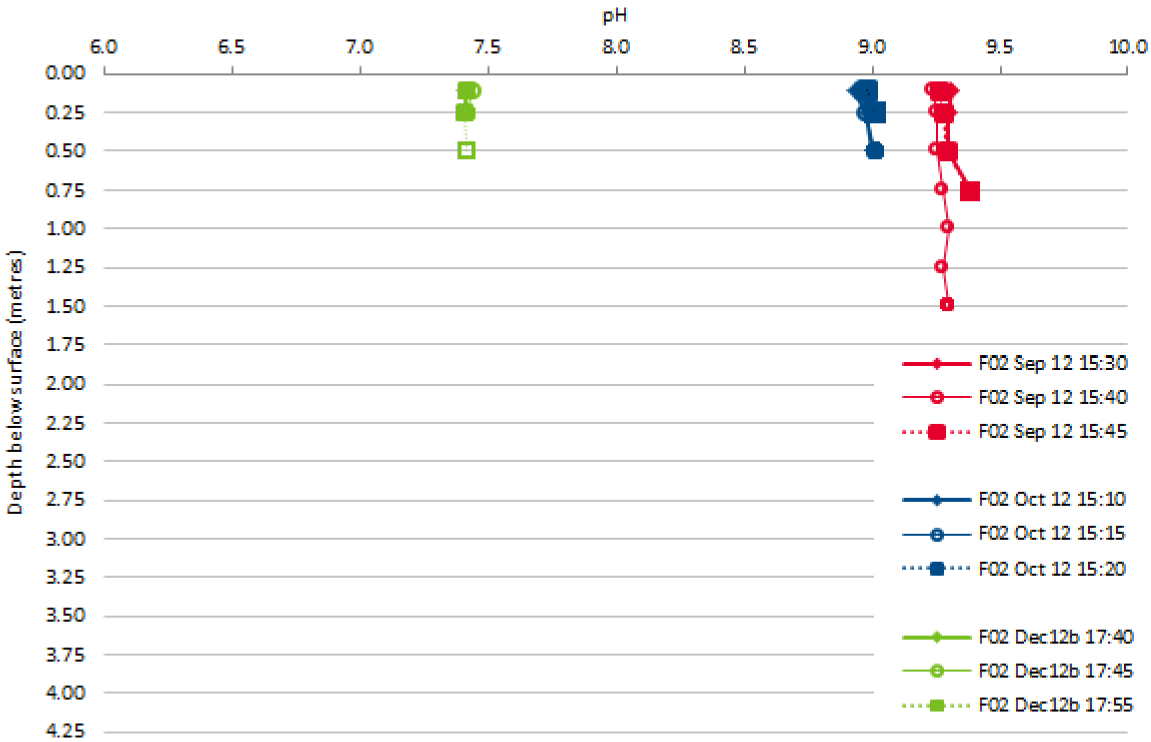


Figure 13 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F02. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



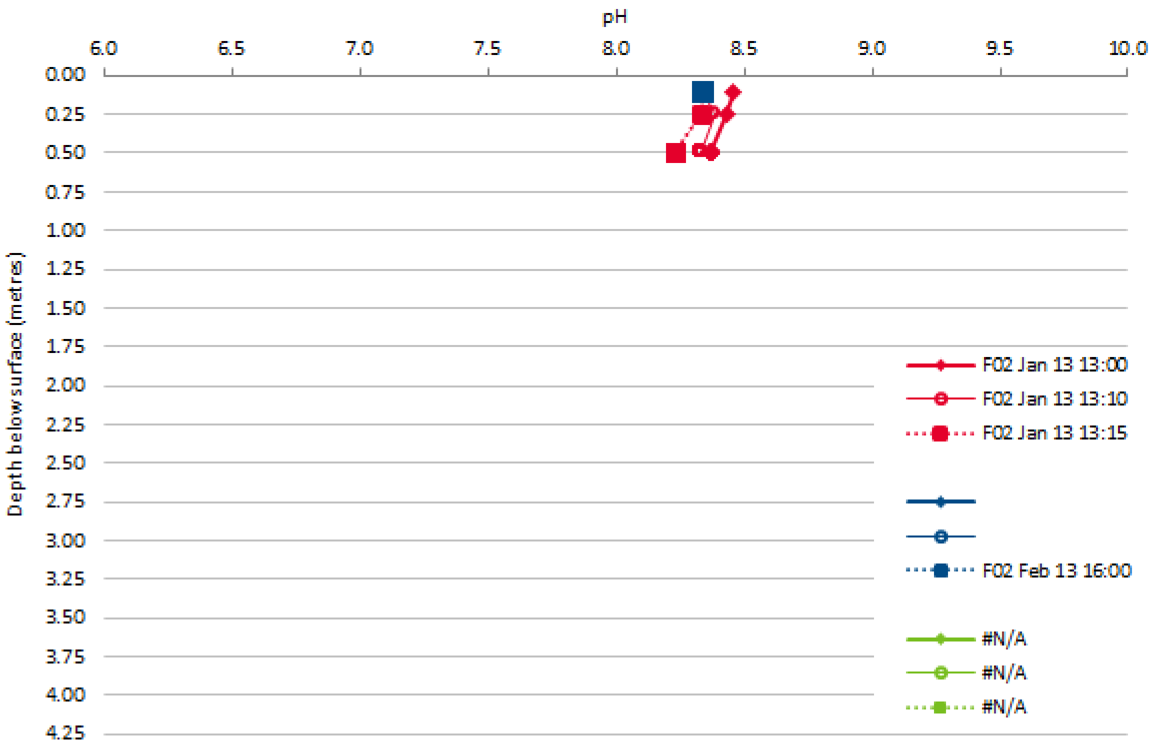


Figure 14 pH vertical water column profiles at waterhole F02. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

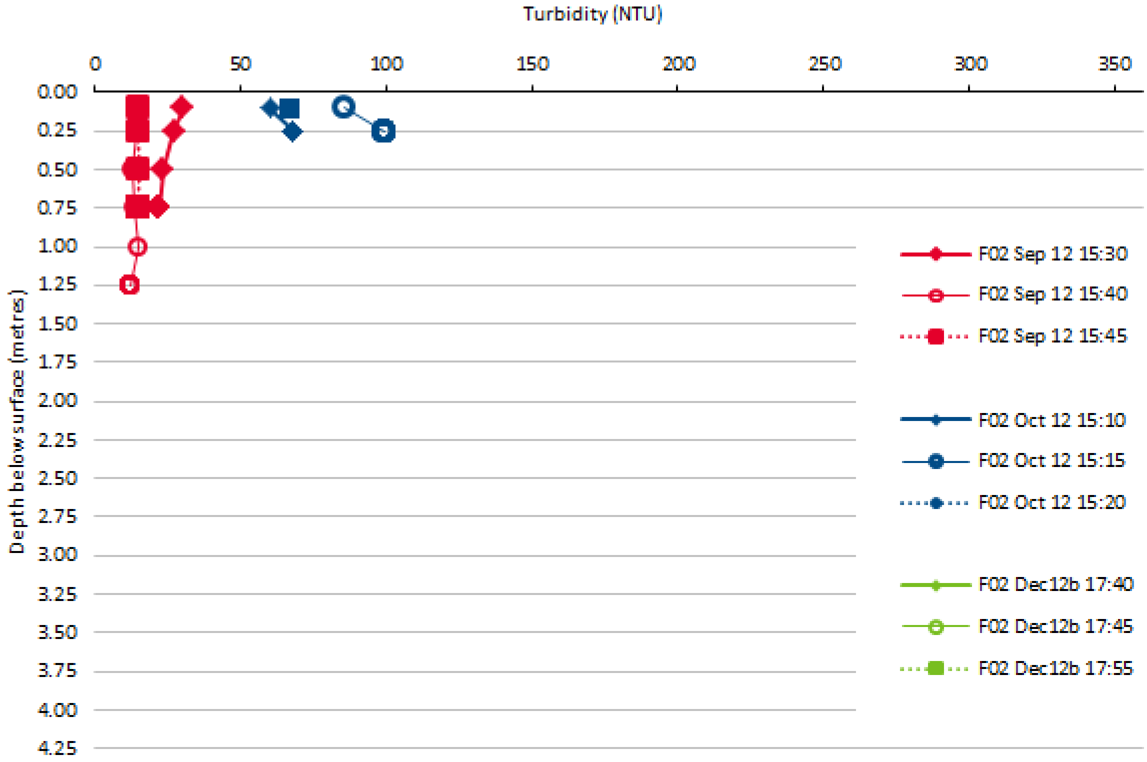


Figure 15 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F02. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

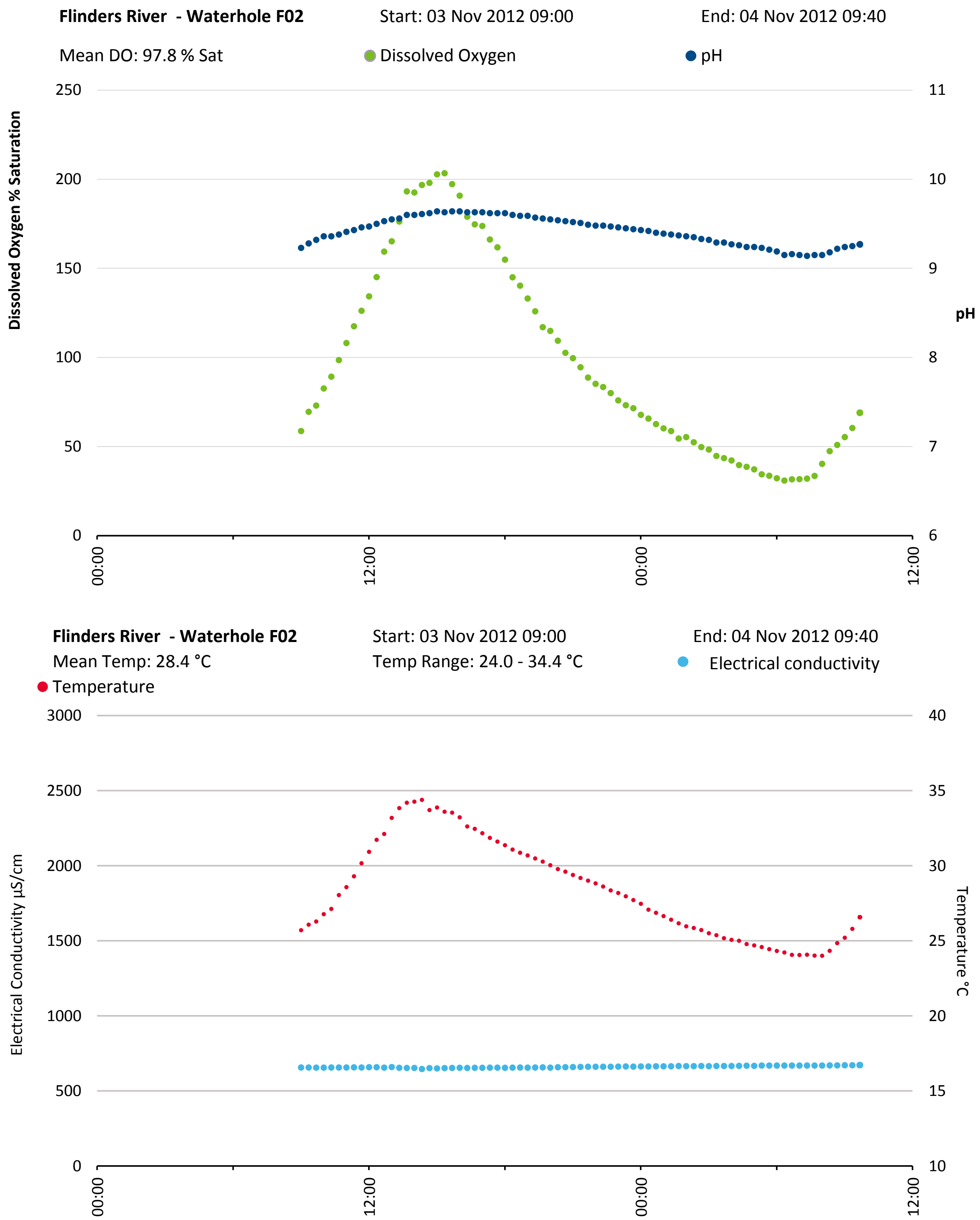


Figure 16 Diel physico chemical data for waterhole F02, Nov 2012

WATERHOLE F03

FEATURE	DESCRIPTION
Waterhole	F03
Catchment	Flinders River
Watercourse	Off channel waterway
Waterhole location	-20.808247°, 143.438439°
Waterhole elevation	~ 225 m (GoogleEarth elevation data, ± 30 m accuracy)
Dates surveyed	Survey 1: 7-Sept-12
	Survey 2: 28-Oct-12
	Survey 5: 8-Dec-12
	Survey 7: 14-Jan-13
	Survey 9: 31-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~200 m^2
	Waterhole volume: ~700 m^3
	Wetted perimeter: ~ 350 m
	Maximum depth: 1 m
	Average depth: 0.4 m
	Waterhole length: 160 m
Instream habitats	This waterhole has a fine silty bottom habitat. Instream there was a high biomass of *Myriophyllum* sp. The density of *Myriophyllum* increased until most of the waterhole became dry by late December 2012. *Potamogeton crispus* and *Chara* spp. were also present in low densities. Dense epilithic and planktonic algal biomass was also common. Low levels of woody debris are present along waterhole margins.
Riparian zone	Groundcover is relatively dense at this waterhole, with tall grasses present along both sides of the waterhole. Riparian tree species are low in density, and dominanted by *Acacia* species. The riparian zone is very narrow at this waterhole.
Waterhole depth changes	Water depth declined steady across the assessment period. The waterhole became dry by late January 2013.
Other notes	Some pig damage was evident instream and along waterhole margins. No cattle damage was identified. This waterhole is bunded by the road on the downstream end.

a)

b)

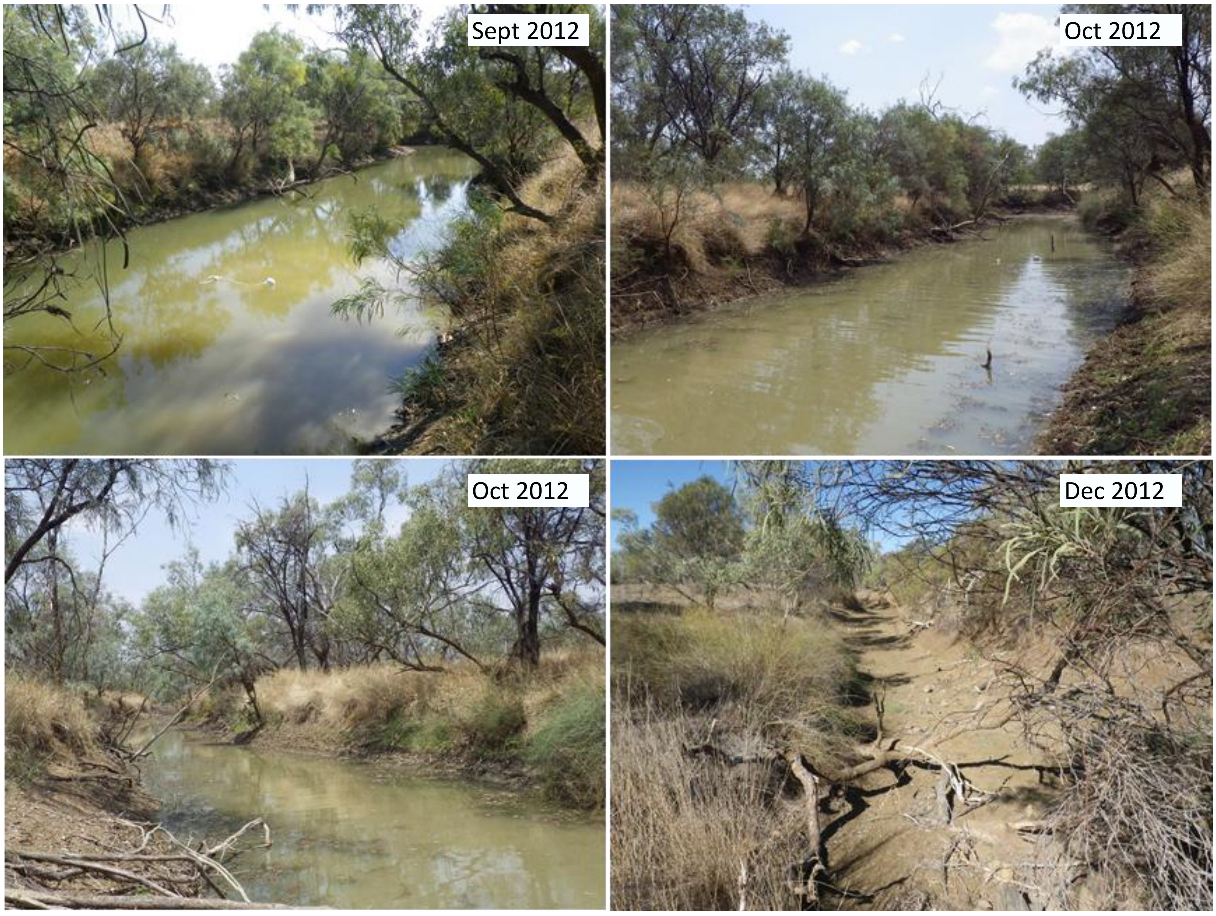


Figure 17 a) GoogleEarth 2004 aerial view of F03. b) Left to right: 1) Upstream from left bank; 2)Downstream from right bank; 3) Downstream from mid stream location; and 4) Upstream from right bank

Figure 18 Bathymetry map of waterhole F03. Depth and waterhole perimeter data generated from data collected Oct 2012

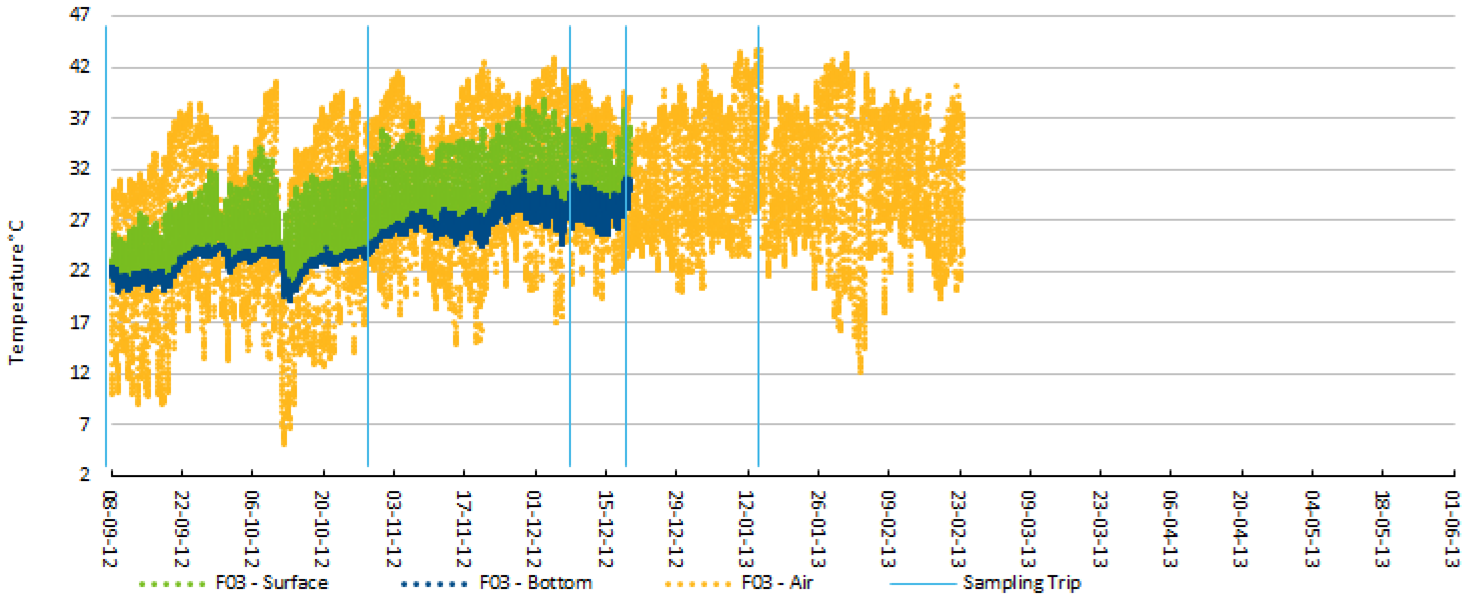
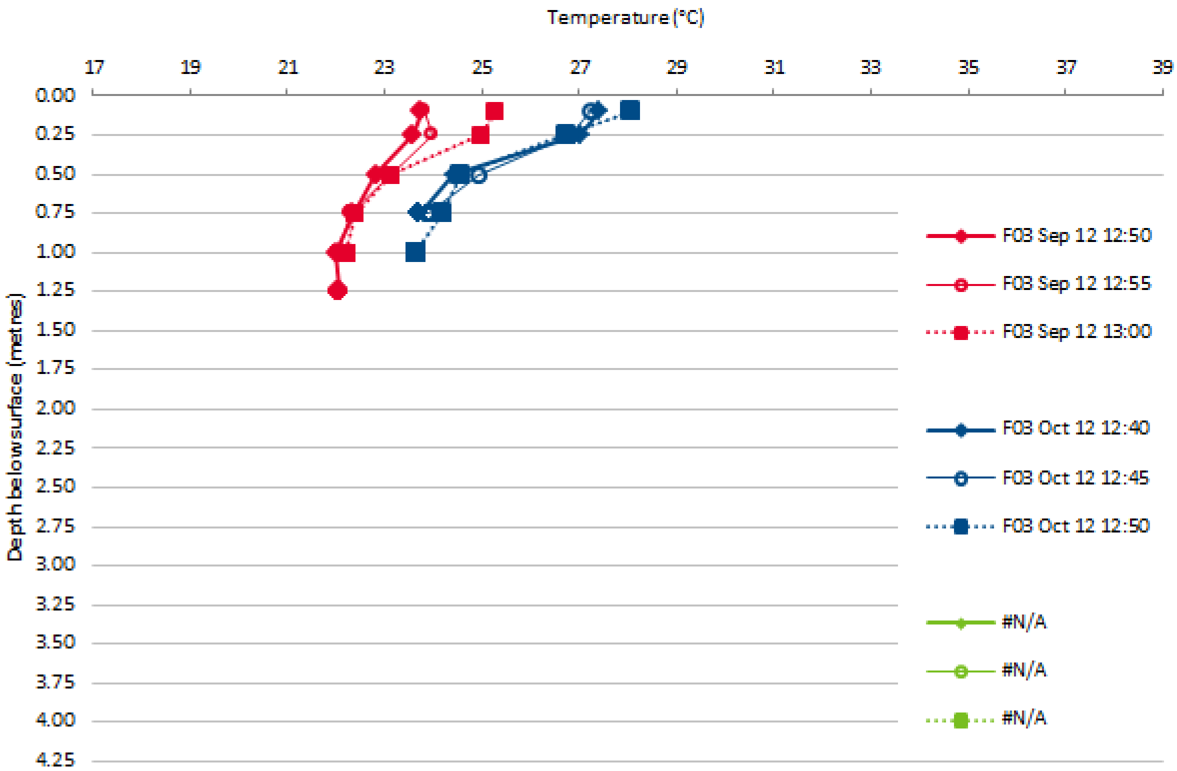


Figure 19 Long term temperature logger data for waterhole F03. Waterhole dried December 2012 and remained dry

Table 3 Continuous water and air temperature logger summary statistics for each survey at waterhole F03.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE			WATER SURFACE TEMPERATURE			WATER BOTTOM TEMPERATURE			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5.		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Sep 12	08-09-12 00:15	20-09-12 00:15	12	9.1	21.3	35.4	20.3	23.1	28.7	20.0	21.3	22.3	-0.1	1.8	7.2	70.6	57.6	49.1
Oct 12	14-10-12 00:15	24-10-12 00:15	10	9.1	26.2	39.5	20.2	26.0	32.0	20.1	22.6	24.3	0.0	3.3	9.4	82.9	73.5	68.2
Dec12a	08-12-12 00:15	14-12-12 00:15	6	19.8	31.7	40.6	25.9	30.2	36.3	25.8	28.3	31.3	-0.2	1.9	7.9	51.2	43.5	39.4



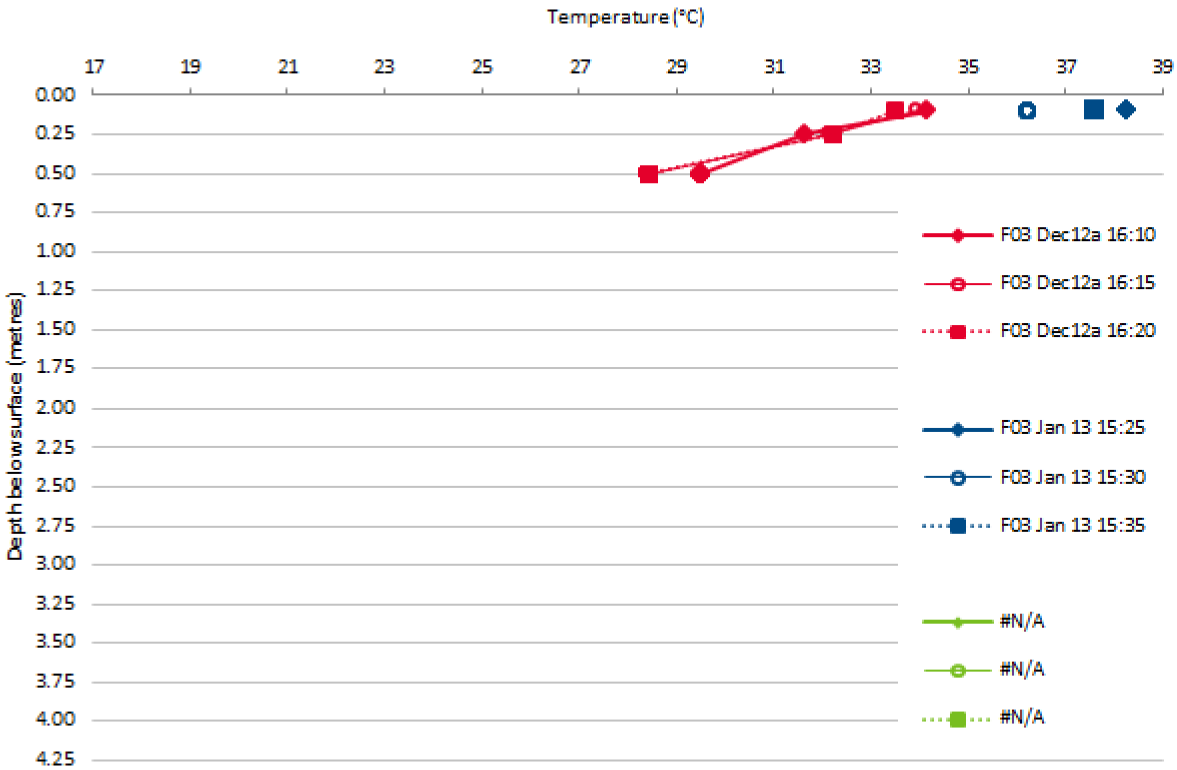
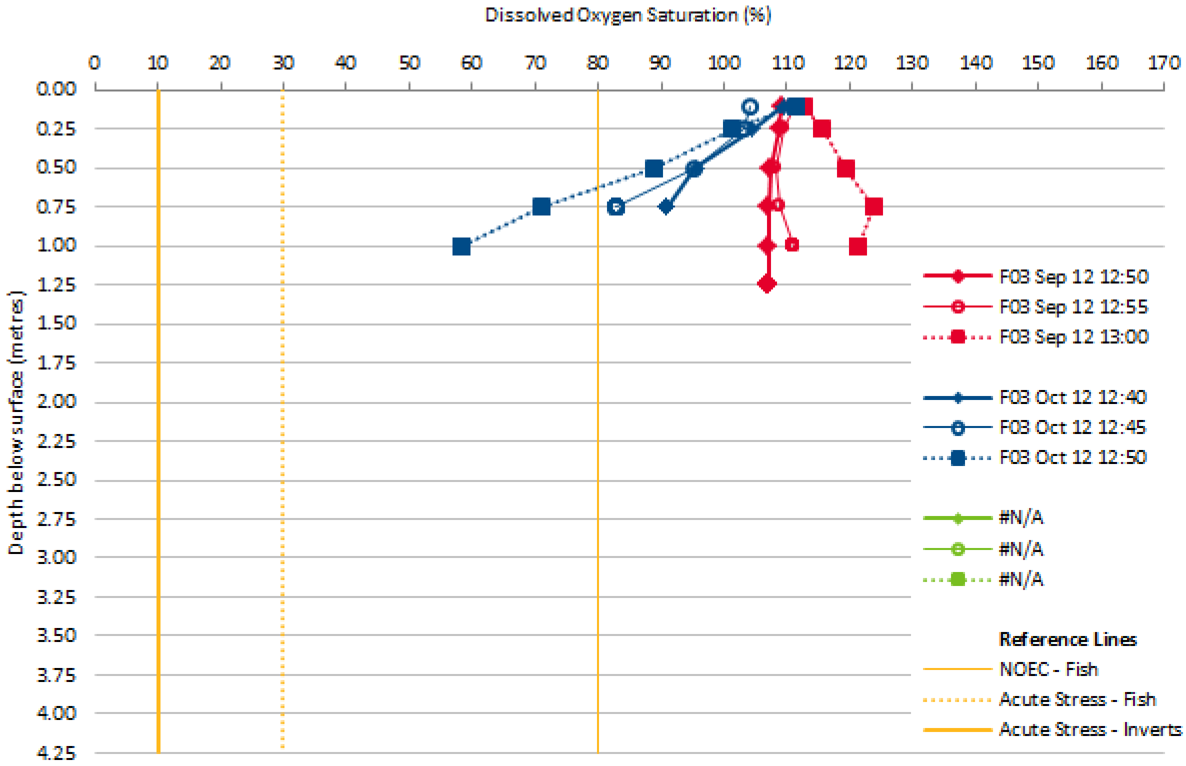


Figure 20 Temperature vertical water column profiles at waterhole F03. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



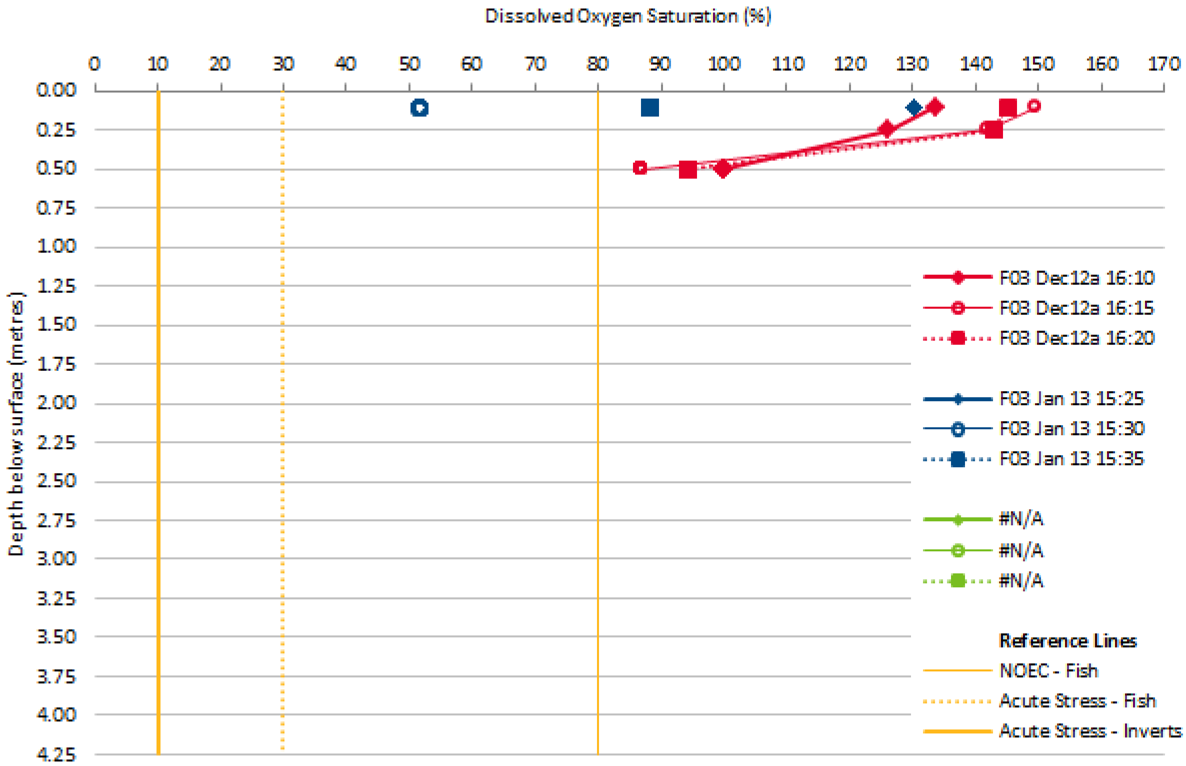
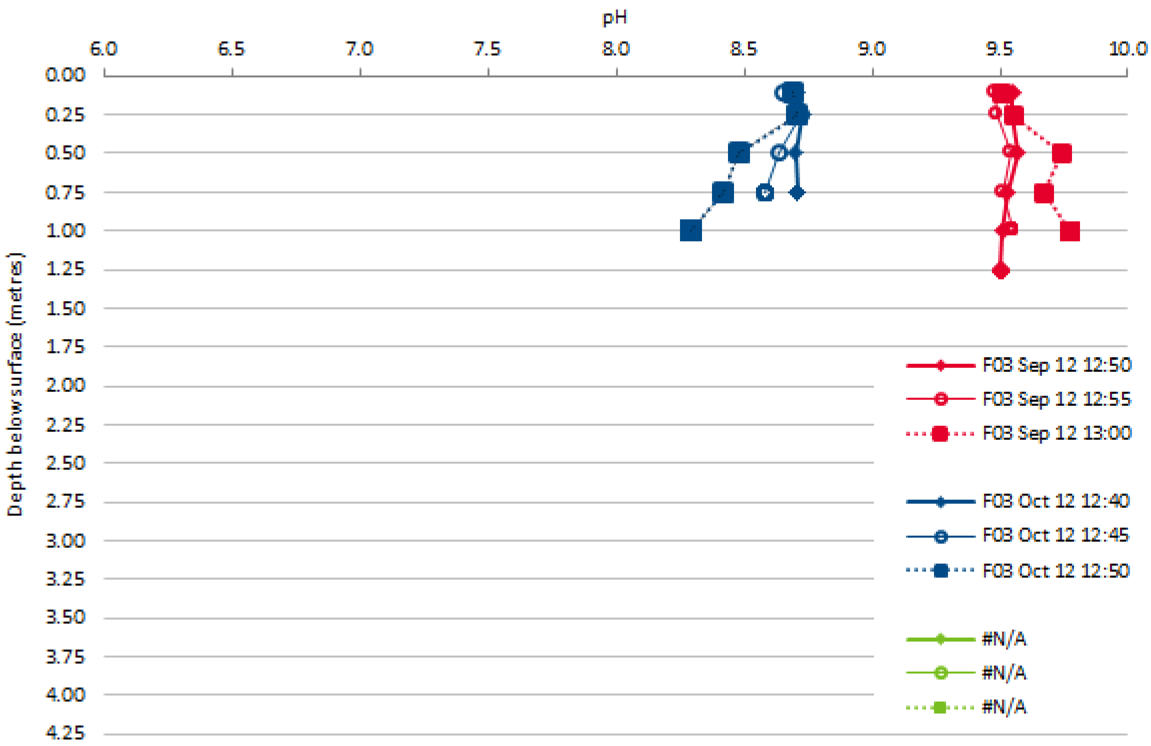


Figure 21 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F03. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



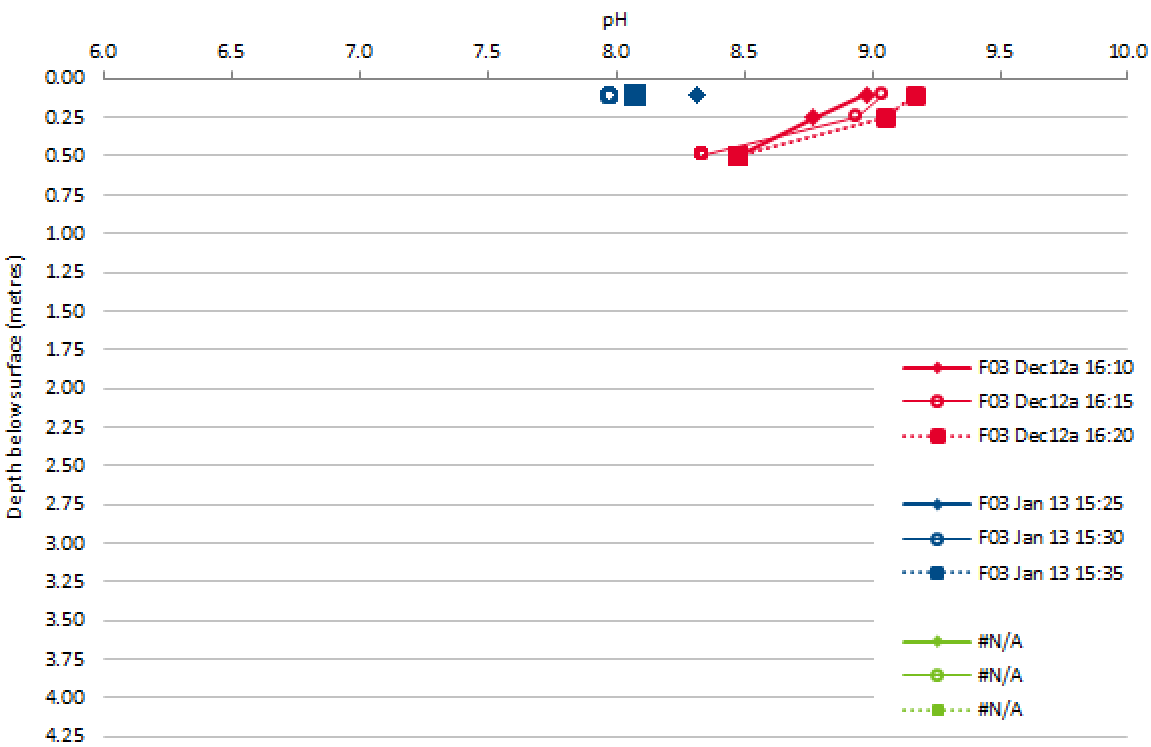


Figure 22 pH vertical water column profiles at waterhole F03. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

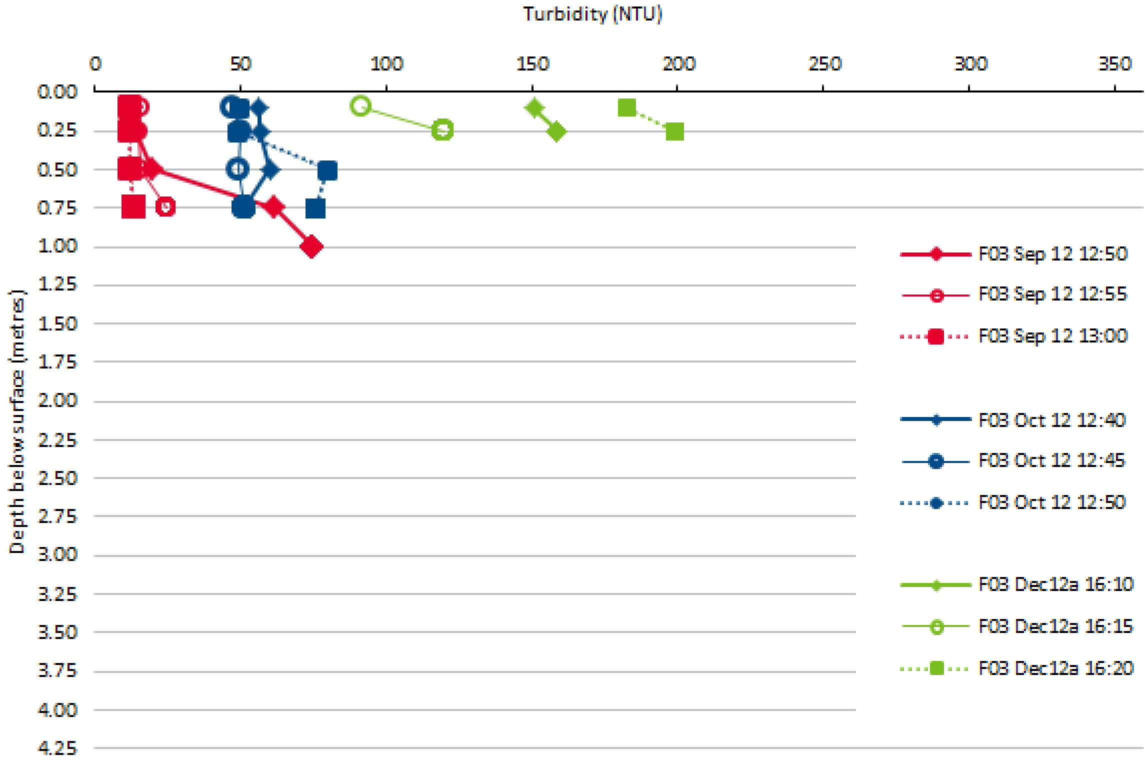
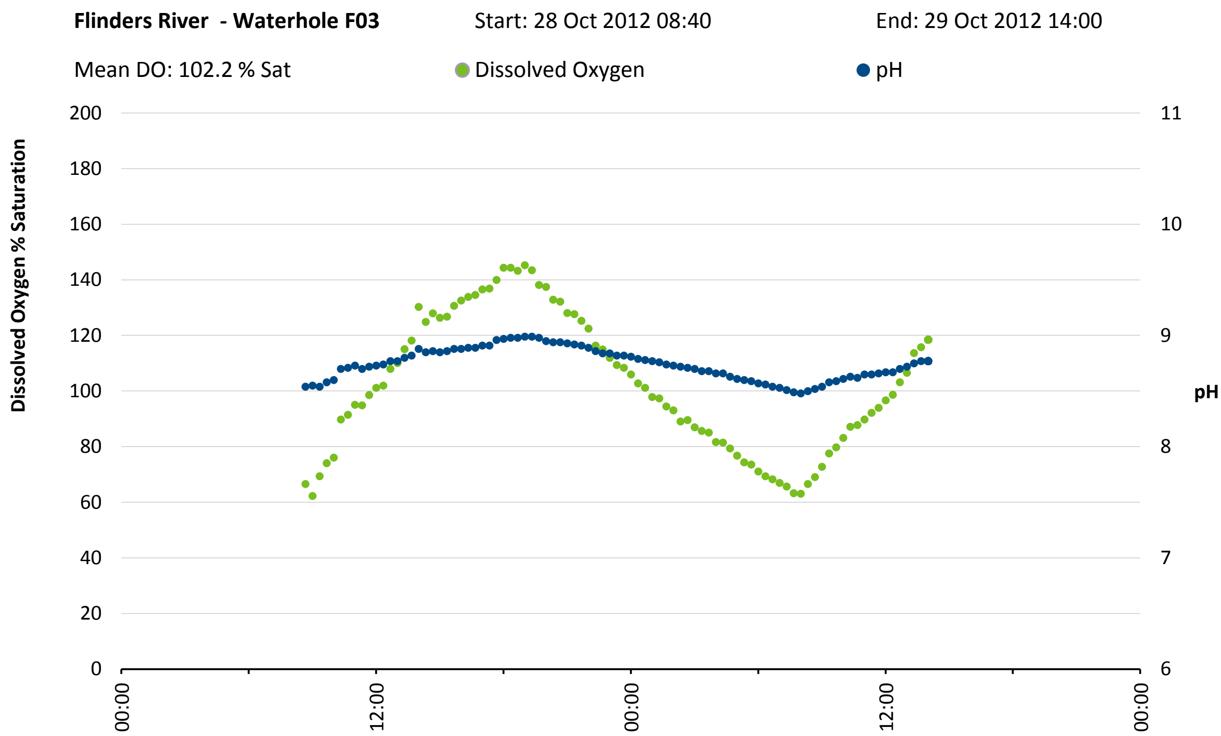


Figure 23 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F03. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



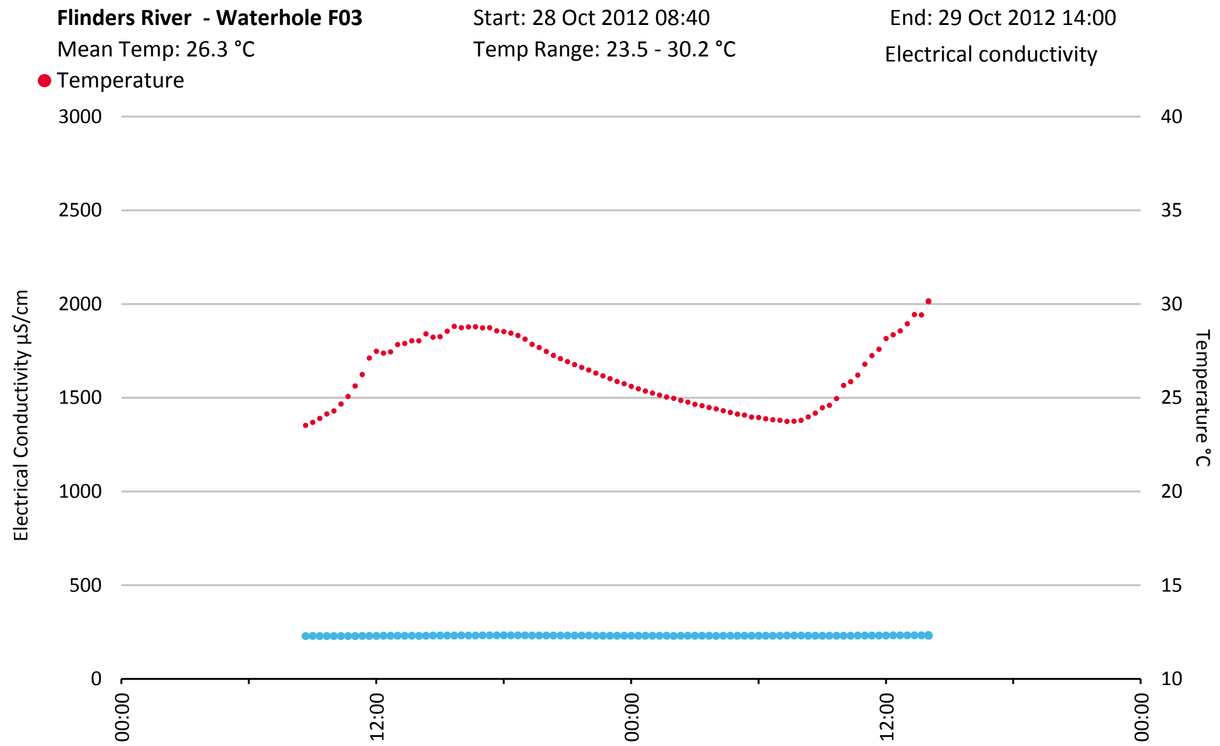


Figure 24 Diel physico chemical data for waterhole F03, Oct 2012

WATERHOLE F04

FEATURE	DESCRIPTION
Waterhole	F04
Catchment	Flinders River
Watercourse	Off channel waterway
Waterhole location	-20.798578°, 143.437209°
Waterhole elevation	~ 225 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 18-Sept-12
	Survey 2: 28-Oct-12
	Survey 5: 8-Dec-12
	Survey 6: 19-Dec-12
	Survey 9: 31-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~13,400 m^2
	Waterhole volume: ~3200 m^3
	Wetted perimeter: ~ 1180 m
	Maximum depth: 0.75 m
	Average depth: 0.2 m
	Waterhole length: 570 m
Instream habitats	This waterhole has a fine silty bottom habitat. No aquatic plants were identified. Algal biomass was low. The water was highly turbid. Large woody debris was present in very low densities.
Riparian zone	Groundcover is present in very low densities at this waterhole. Tree species inclue both *Acacia* and *Eucalyptus* species in low densities.
Waterhole depth changes	Water depth declined rapidly between September and December 2012. The waterhole became completely dry by mid December.
Other notes	Cattle damage is extensive along all poor margins, and within the stream channel itself.

a)

b)

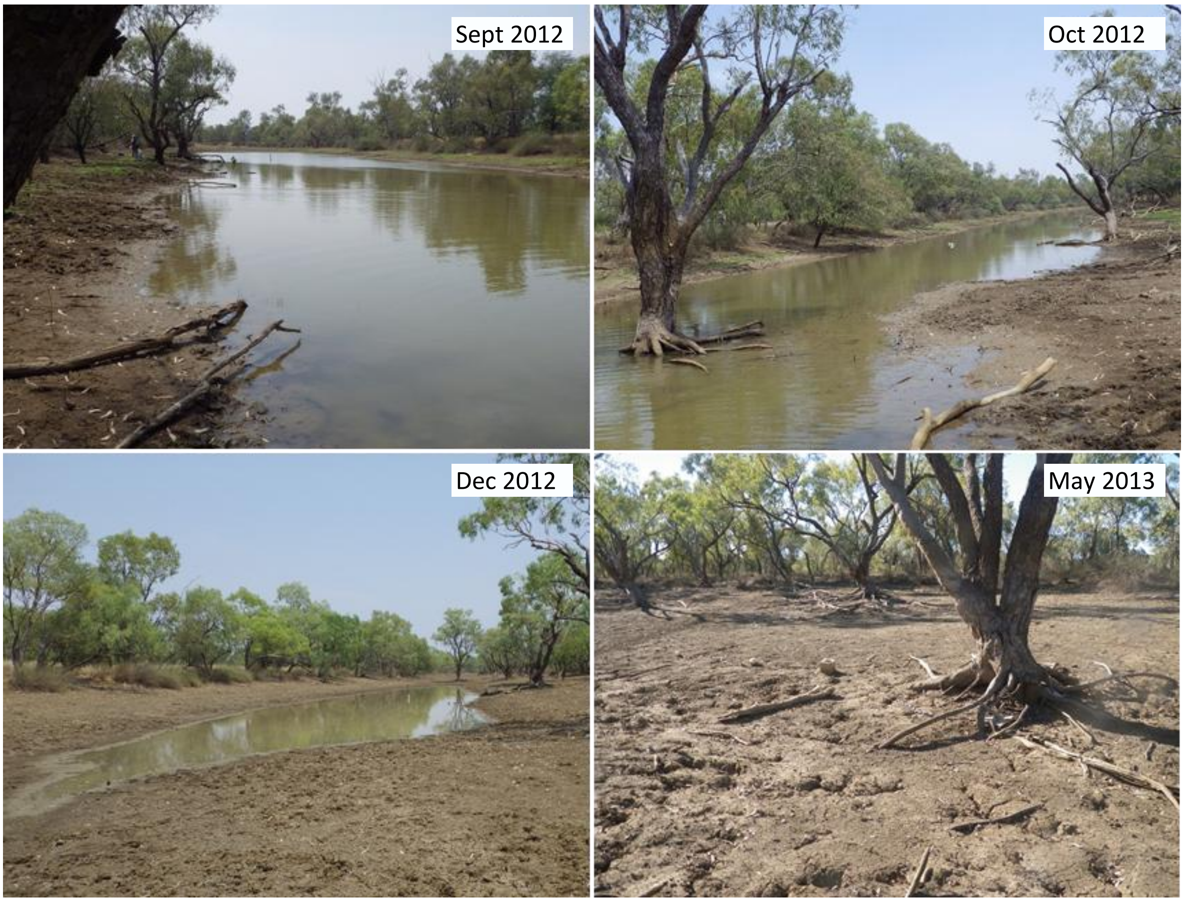


Figure 25 a) GoogleEarth 2004 aerial view of F04. b) Left to right: 1) Upstream from right bank. 2). Downstream from right bank. 3) Right bank. 4) Downstream from right bank

Figure 26 Bathymetry map of waterhole F04. Depth and waterhole perimeter data generated from data collected Oct 2012

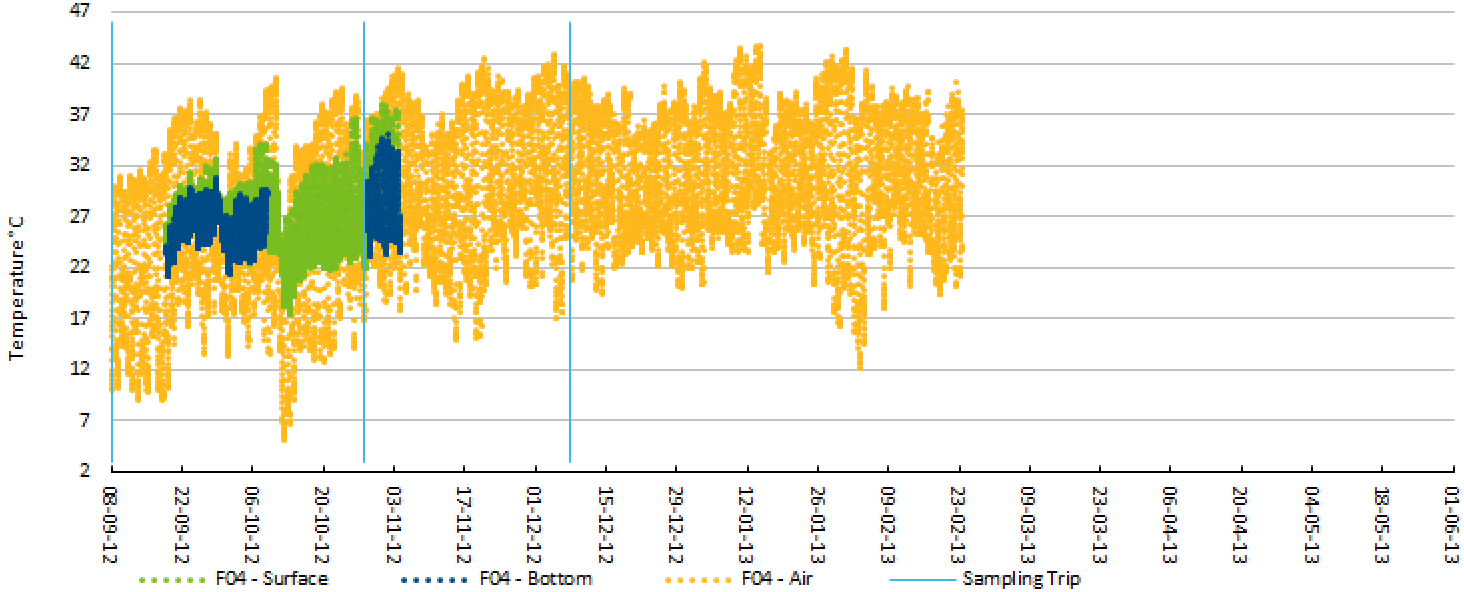
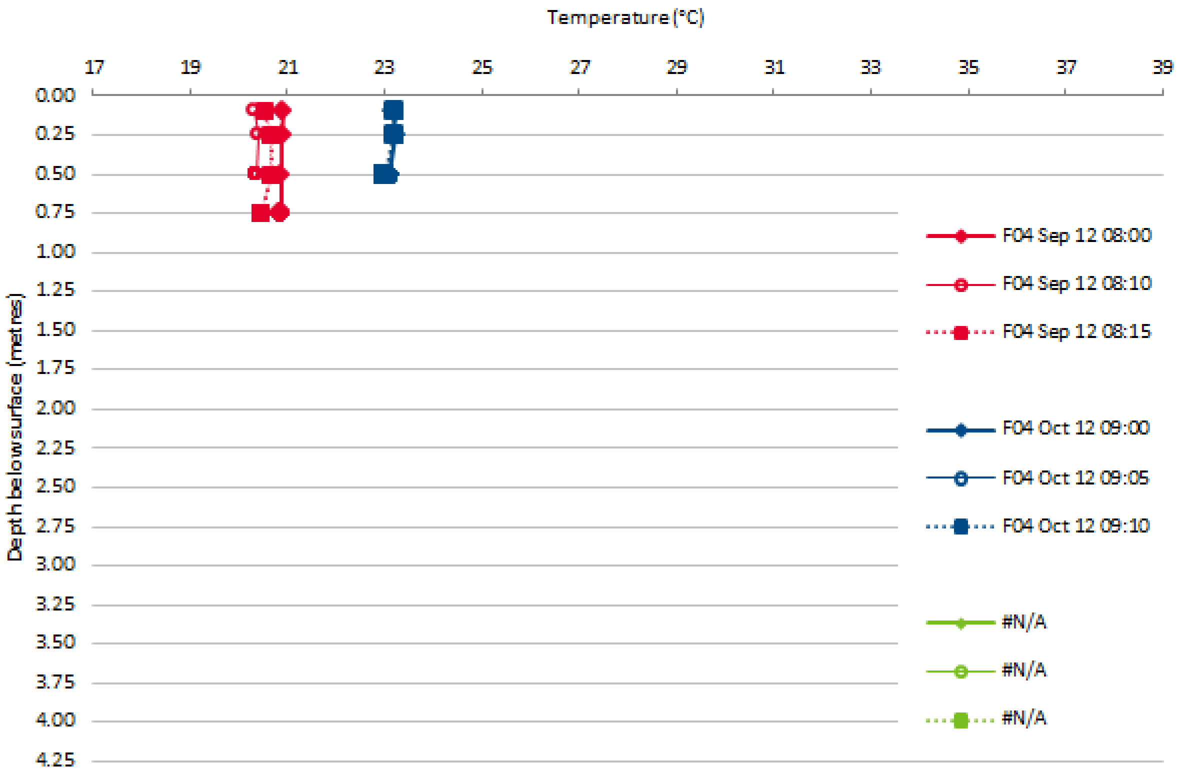


Figure 27 Long term temperature logger data for waterhole F04. Bottom water logger error during October 2012, while waterhole dried November 2012 and remained dry

Table 4 Continuous water and air temperature logger summary statistics for each survey at waterhole F04.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5°C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Sep 12	20-09-12 00:15	24-09-12 00:15	4	14.4	27.4	38.4	22.6	26.9	31.4	22.5	26.3	29.9	-0.1	0.6	2.6	32.5	22.8	15.9
Oct 12	29-10-12 00:15	03-11-12 00:15	5	18.6	29.7	40.8	23.4	29.9	37.9	23.1	28.7	35.0	-0.1	1.2	6.4	41.8	34.9	29.9



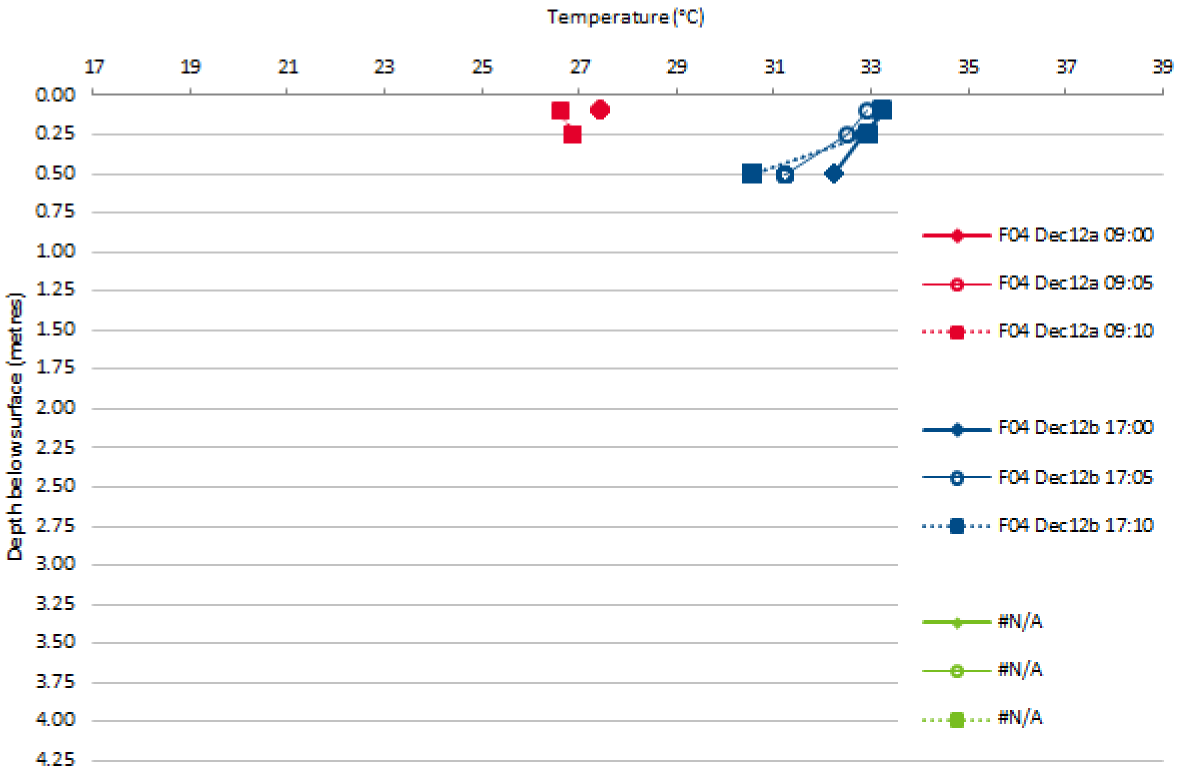


Figure 28 Temperature vertical water column profiles at waterhole F04. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

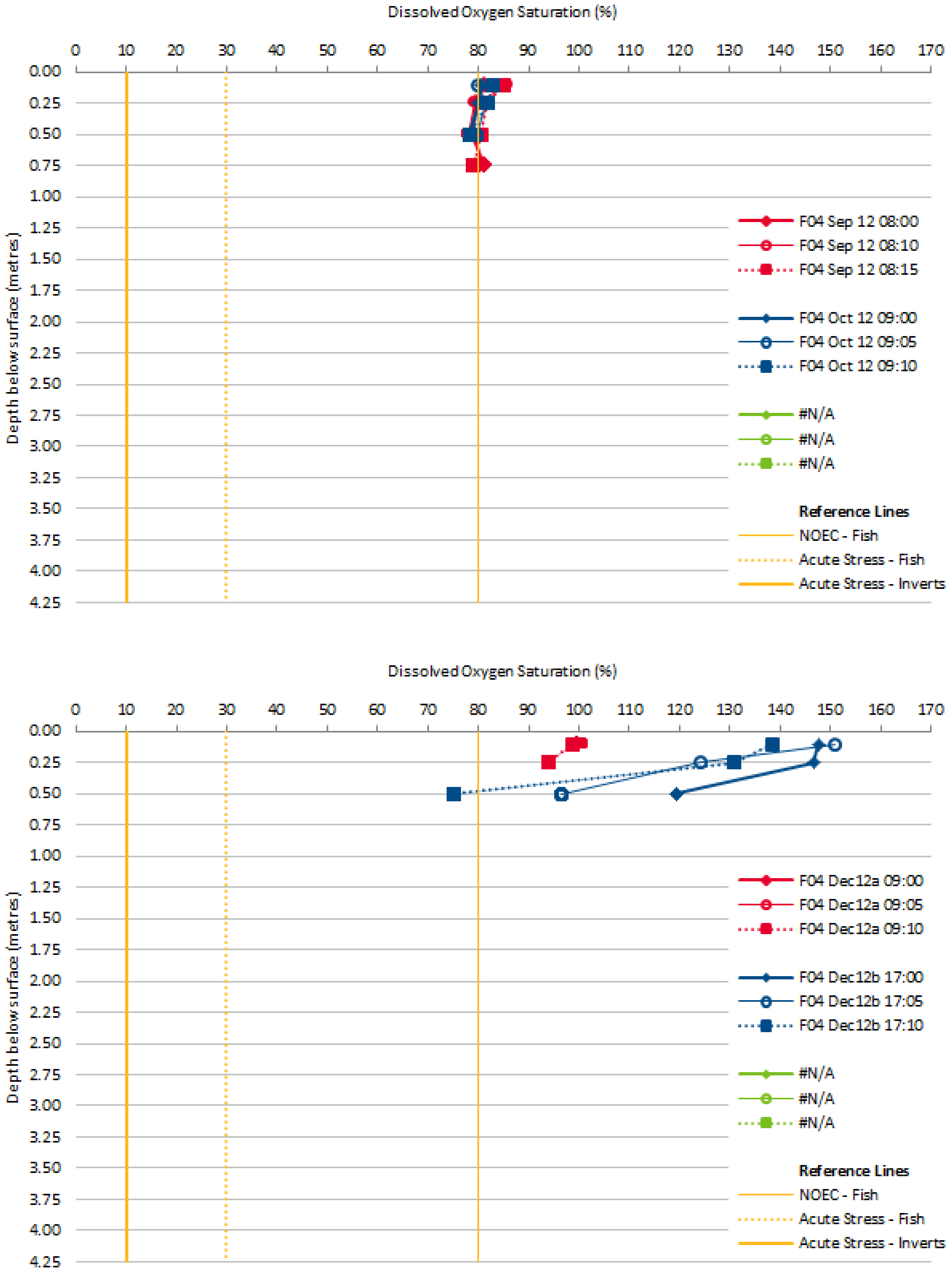
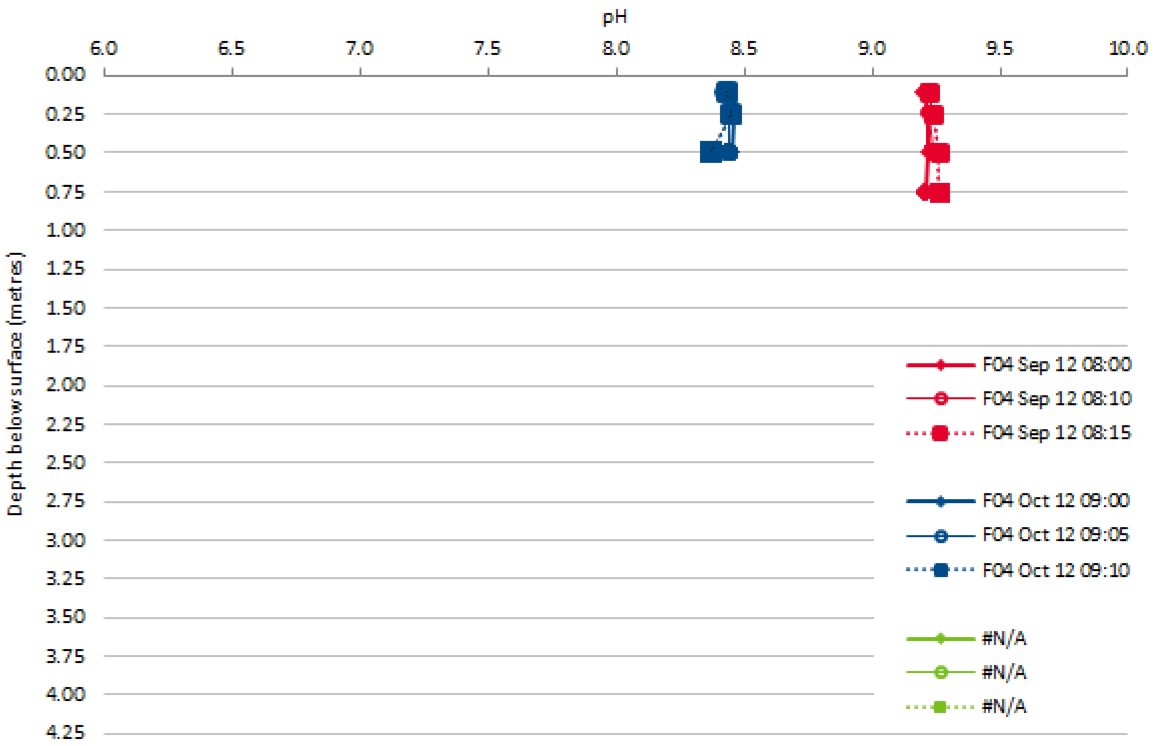


Figure 29 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F04. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



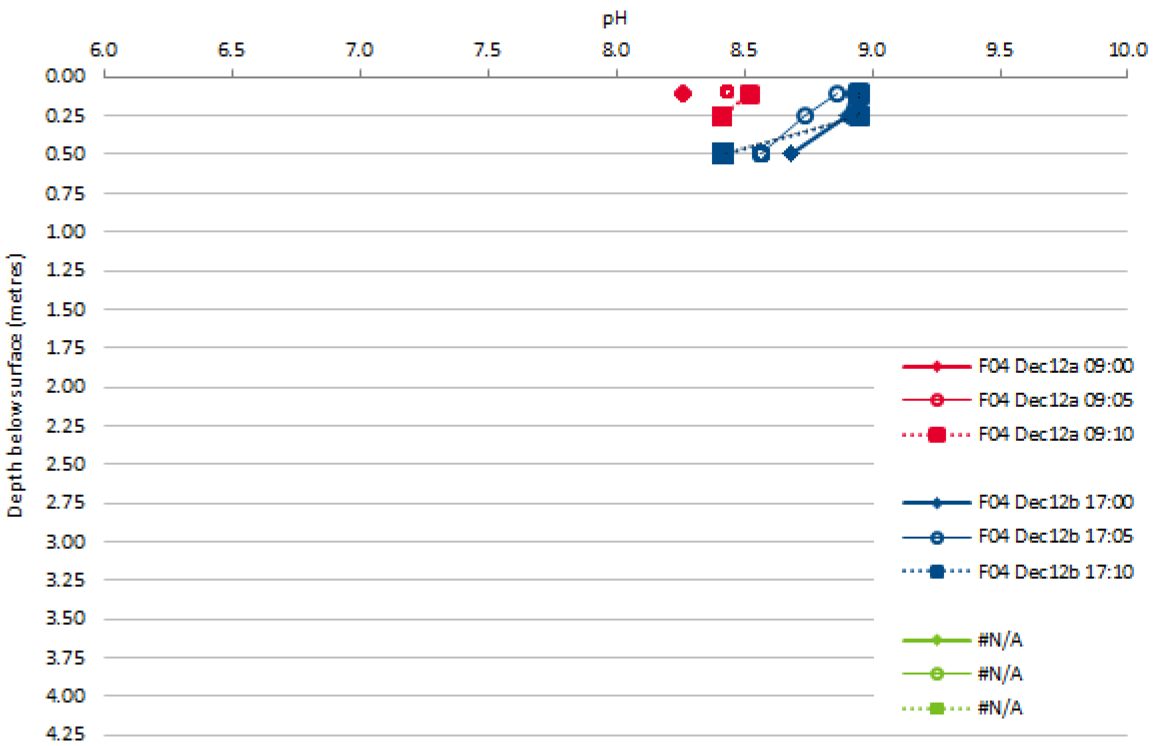
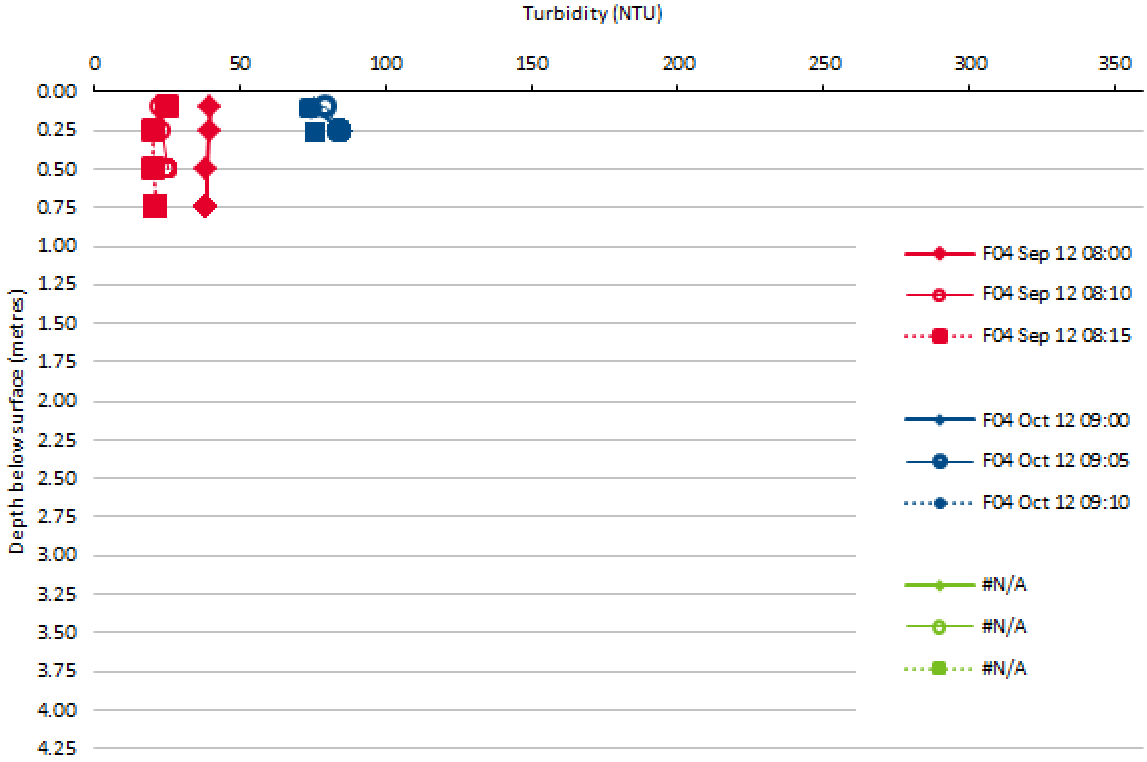


Figure 30 pH vertical water column profiles at waterhole F04. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



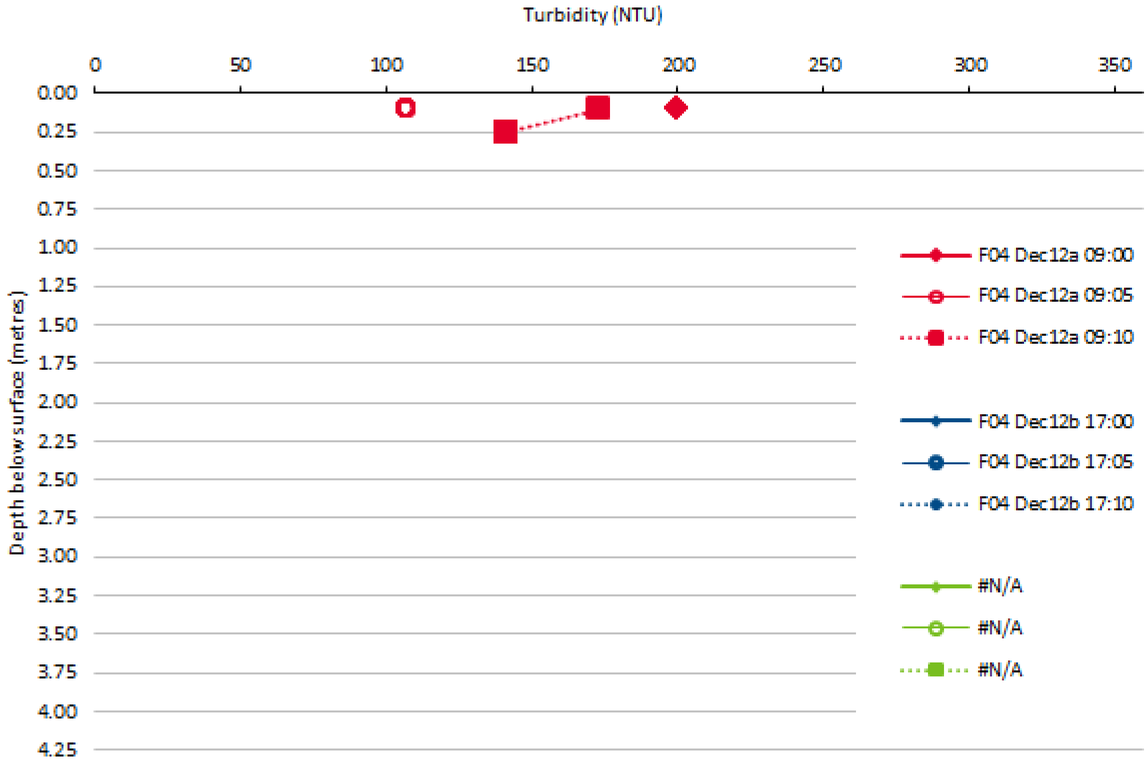
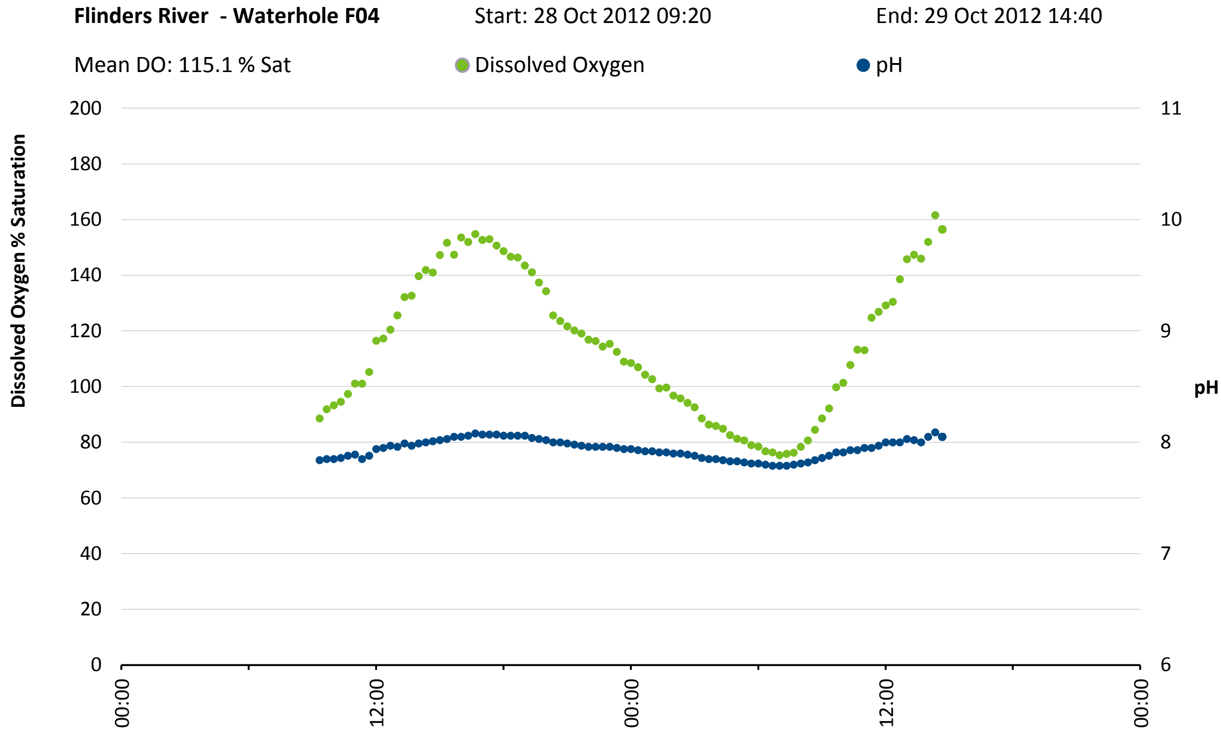


Figure 31 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F04. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



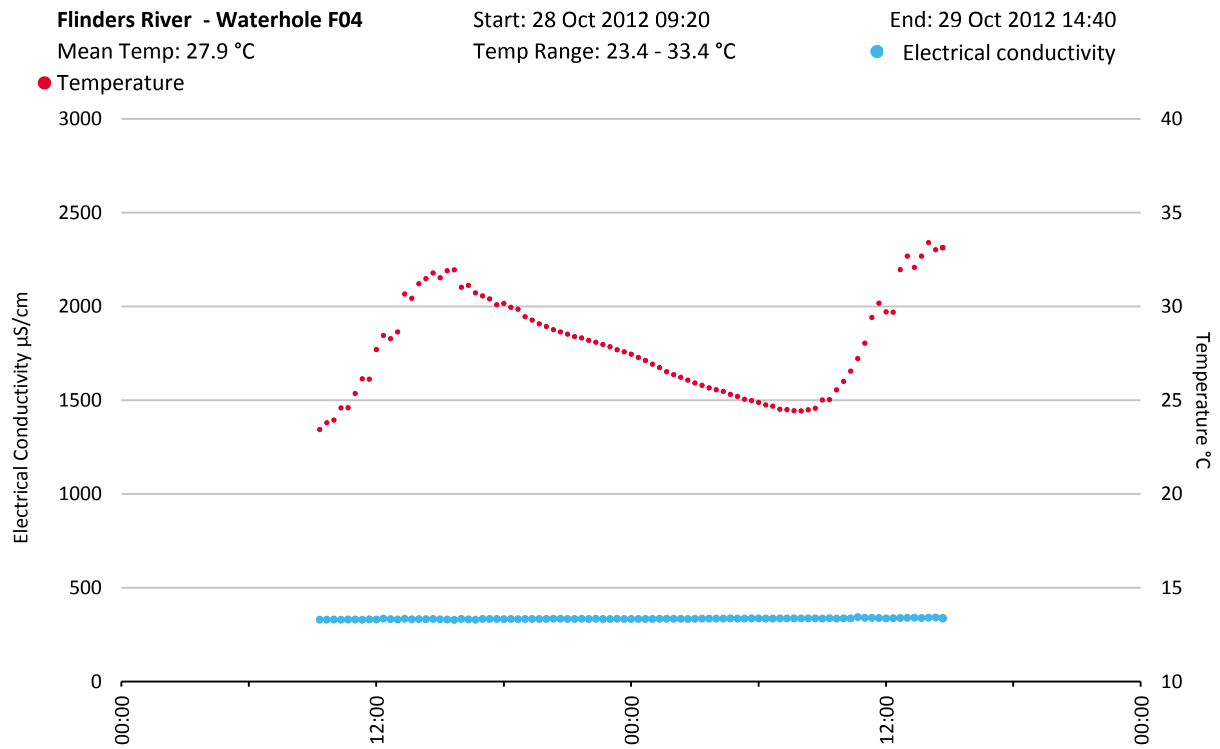
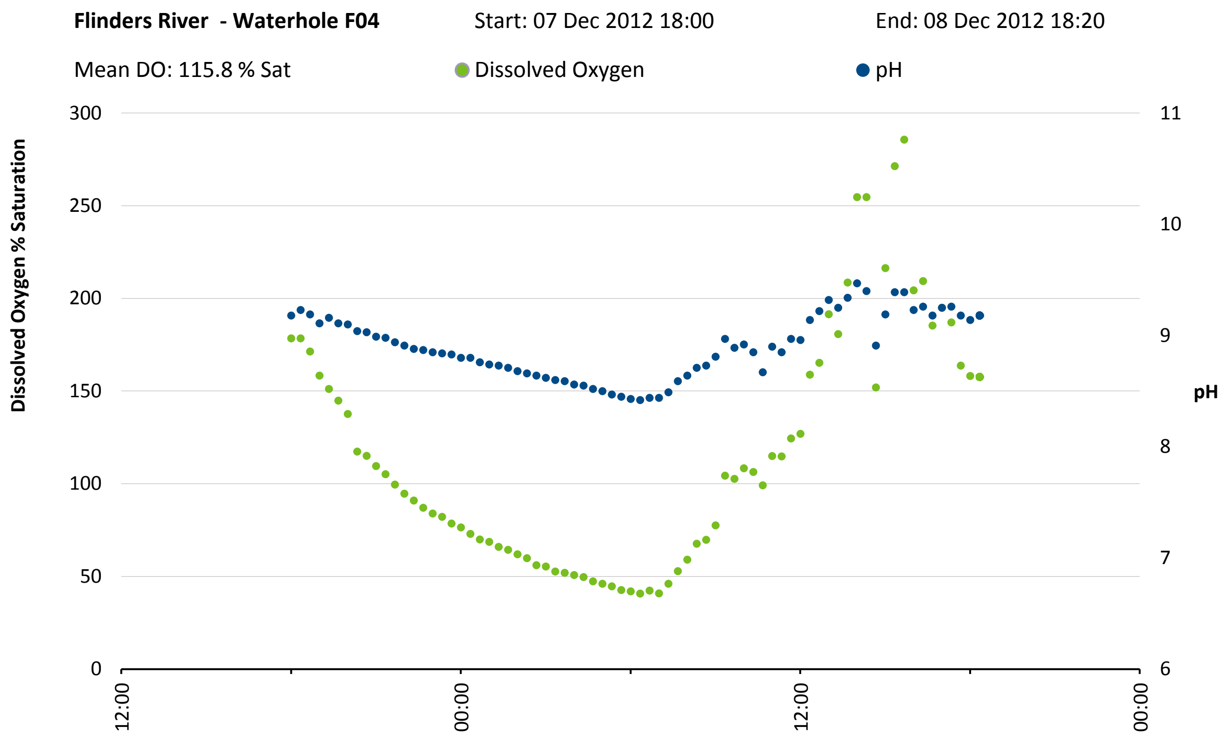


Figure 32 Diel physico chemical data for waterhole F04, Oct 2012



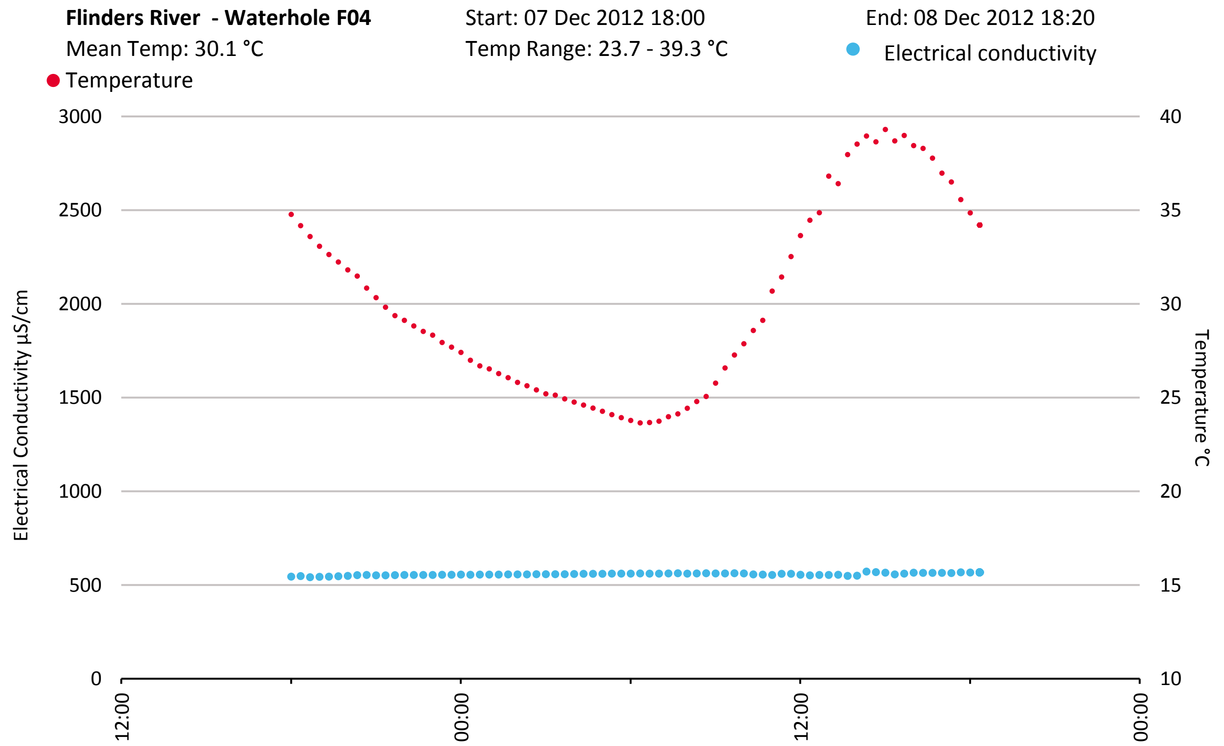


Figure 33 Diel physico chemical data for waterhole F04, Dec 2012

WATERHOLE F05

FEATURE	DESCRIPTION
Waterhole	F05
Catchment	Flinders River
Waterhole location	-20.798578°, 143.437209°
Waterhole elevation	~ 180 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 8-Sept-12
	Survey 2: 27-Oct-12
	Survey 5: 9-Dec-12
	Survey 6: 20-Dec-12
	Survey 8: 23-Feb-13
	Survey 9: 31-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~15,500 m^2
	Waterhole volume: ~16,500 m^3
	Wetted perimeter: ~ 750 m
	Maximum depth: 1.87 m
	Average depth: 1.1 m
	Waterhole length: 360 m
Instream habitats	This is a sandy waterhole with a silty substrate along the waterhole margins. A thin layer of silt lies on top of the predominantly sandy substrate. Waterhole banks are steep. A very small amount of woody debris or detritus was available as habitat. Scattered aquatic macrophytes, including *Myriophyllum* sp. and *Chara* spp. were present. The biomass of *Chara* increased towards mid-2013. Planktonic algae were relatively dense. Epilithic algae were present in lesser densities.
Riparian zone	Couch grasses provide good groundcover. Some thistles are scattered along the riparian zone. River red gums (*Eucalyptus camaldulensis*) are the dominant riparian tree species, and many large individuals line the mid to high bank. The waterhole margins are very steep, allowing few trees to become established. Bank slumping is common along the waterhole margins.
Waterhole depth changes	Water depth declined steadily to December 2012. Maximum depth increased by 3 m during January 2013 then reduced steadily again to May 2013.
Other notes	Some evidence of pig access was obvious at this waterhole.

a)

b)

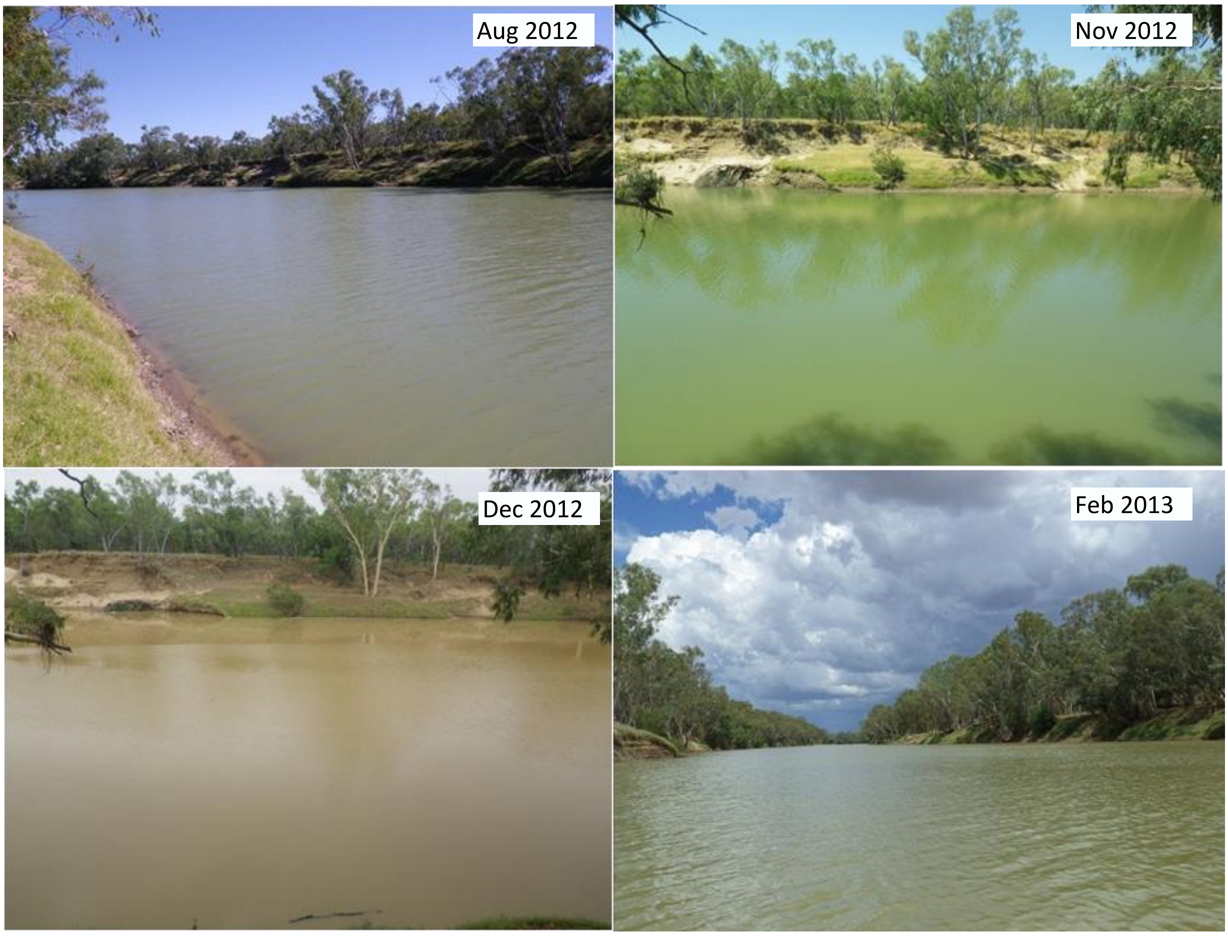


Figure 34 a) GoogleEarth 2005 aerial view of F05. b) Left to right: 1) Downstream from left bank. 2) Towards right bank from fixed camera point, Nov 5th 2012. 3) Towards right bank from fixed camera point, Dec 20th 2012. 4) Looking downstream from centre of waterhole

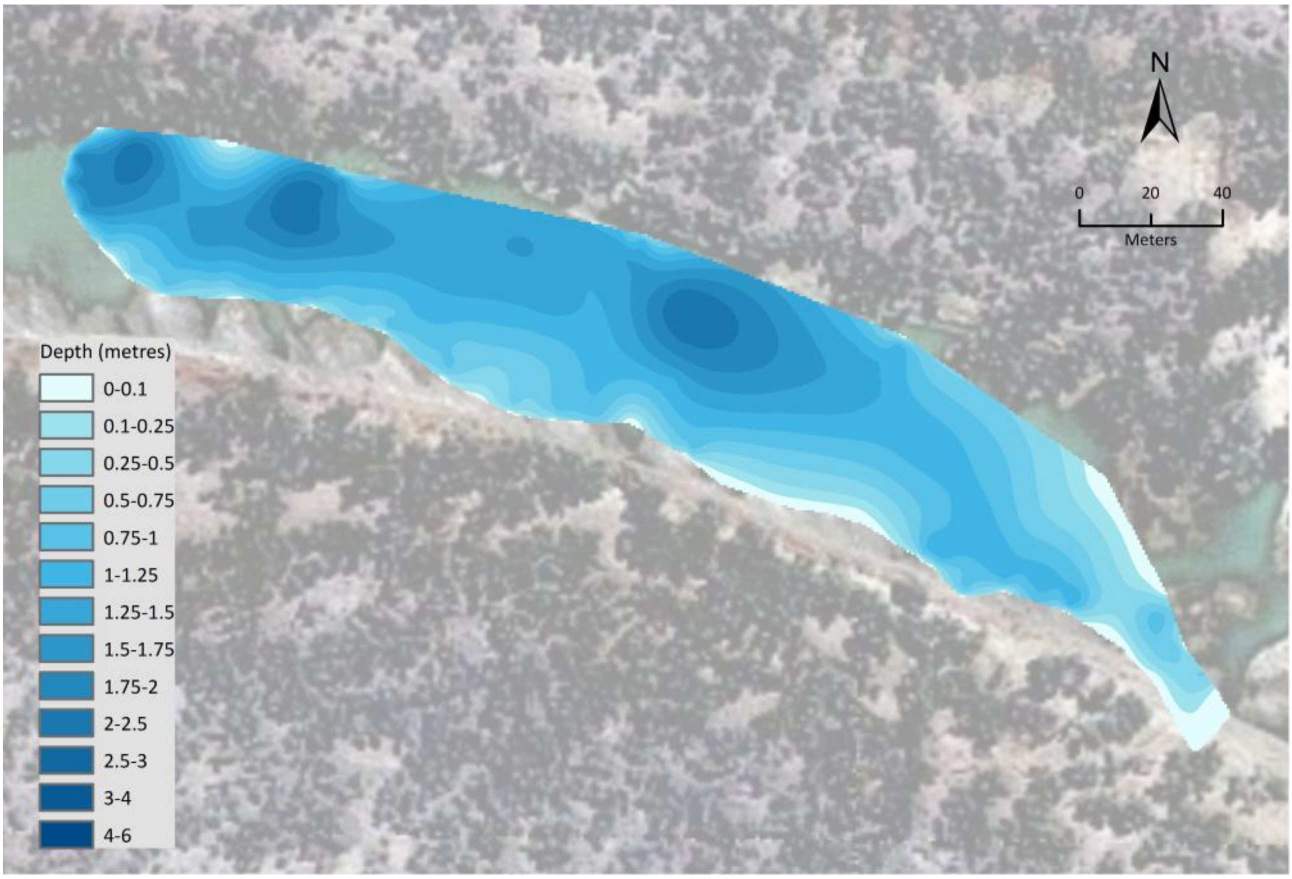


Figure 35 Bathymetry map of waterhole F05. Depth and waterhole perimeter data generated from data collected Oct 2012

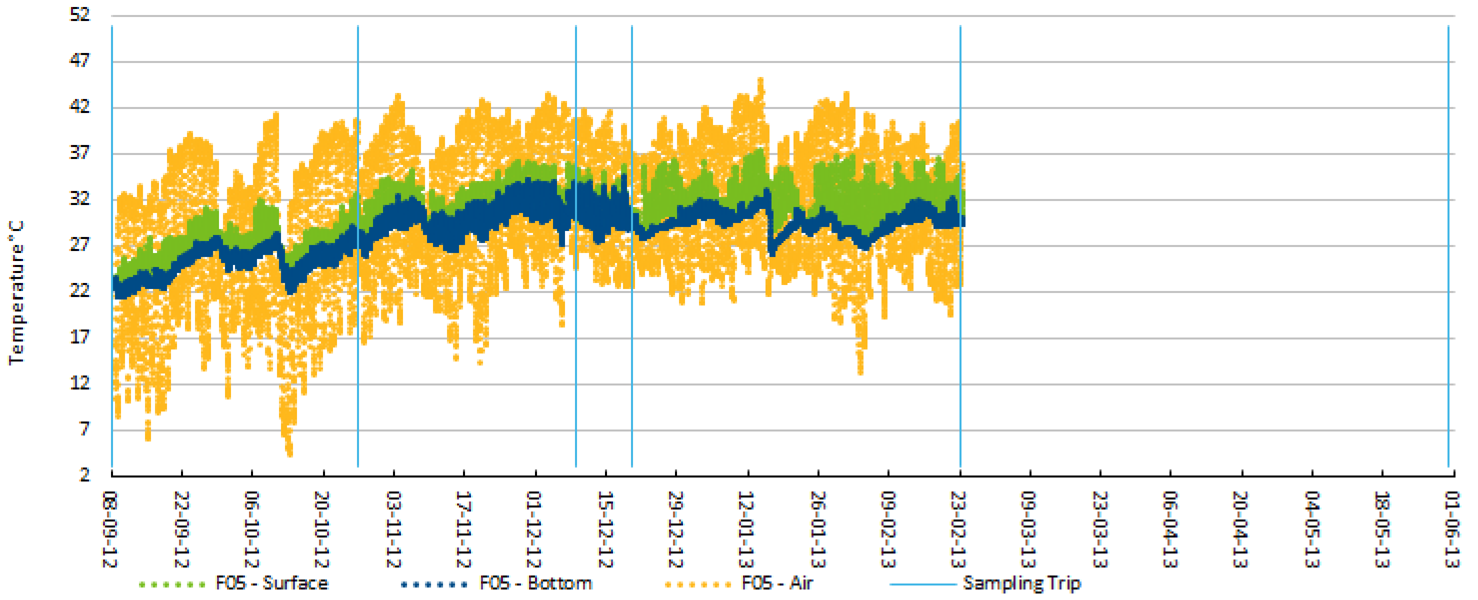
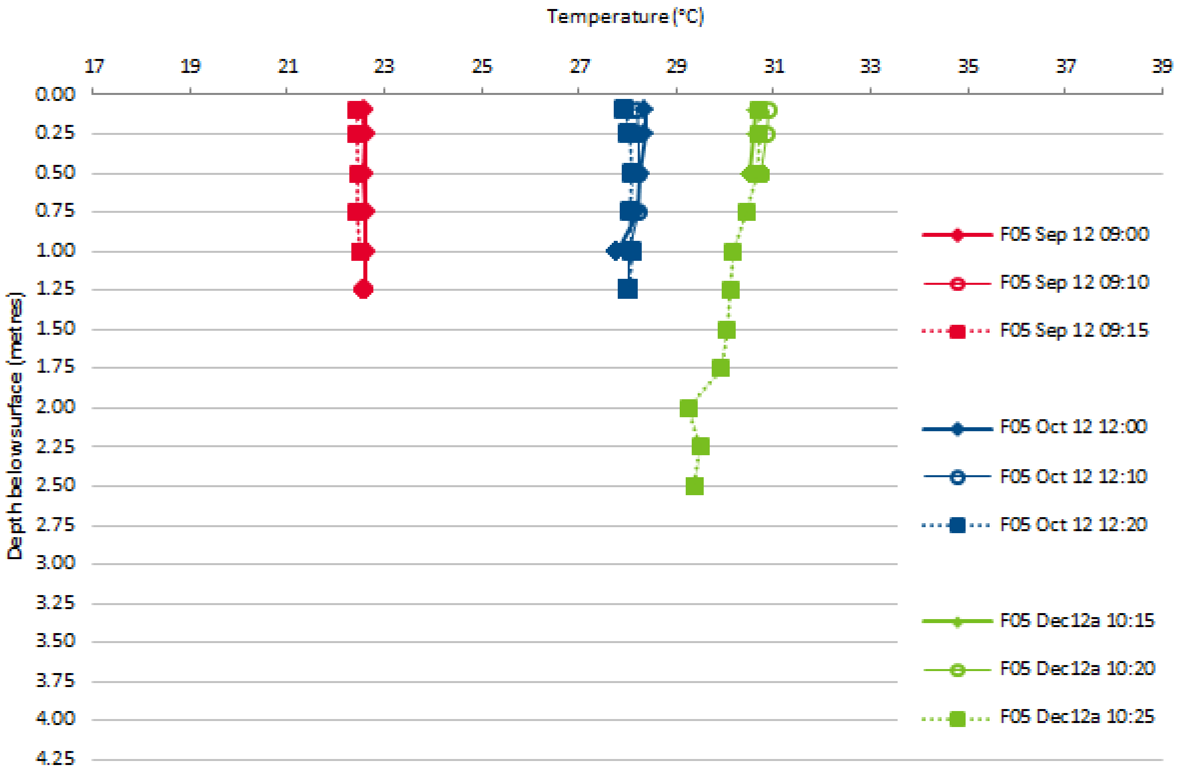


Figure 36 Long term temperature logger data for waterhole F05

Table 5 Continuous water and air temperature logger summary statistics for each survey at waterhole F05.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5°C[2]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Sep 12	10-09-12 00:15	20-09-12 00:15	10	6.1	22.5	37.4	21.8	24.2	27.9	21.7	23.1	24.4	-0.1	1.1	4.6	60.1	46.6	34.0
Oct 12	26-10-12 00:15	05-11-12 00:15	10	16.5	30.4	43.2	26.1	30.0	34.4	26.0	29.0	32.5	-0.1	1.1	4.3	58.0	43.6	31.8
Dec12a	06-12-12 00:15	09-12-12 00:15	3	18.4	33.0	42.5	27.4	31.4	36.0	27.3	30.7	34.0	-0.2	0.6	3.4	41.9	26.7	18.9
Dec12b	19-12-12 00:15	20-12-12 00:15	1	22.8	29.2	38.3	28.9	30.1	31.1	28.8	30.0	31.1	0.0	0.1	1.2	2.7	2.7	0.0
Feb 13	06-02-13 00:15	18-02-13 00:15	12	19.4	30.6	40.4	28.4	31.5	36.1	27.8	29.9	32.0	-0.1	1.6	6.5	71.8	55.5	43.9



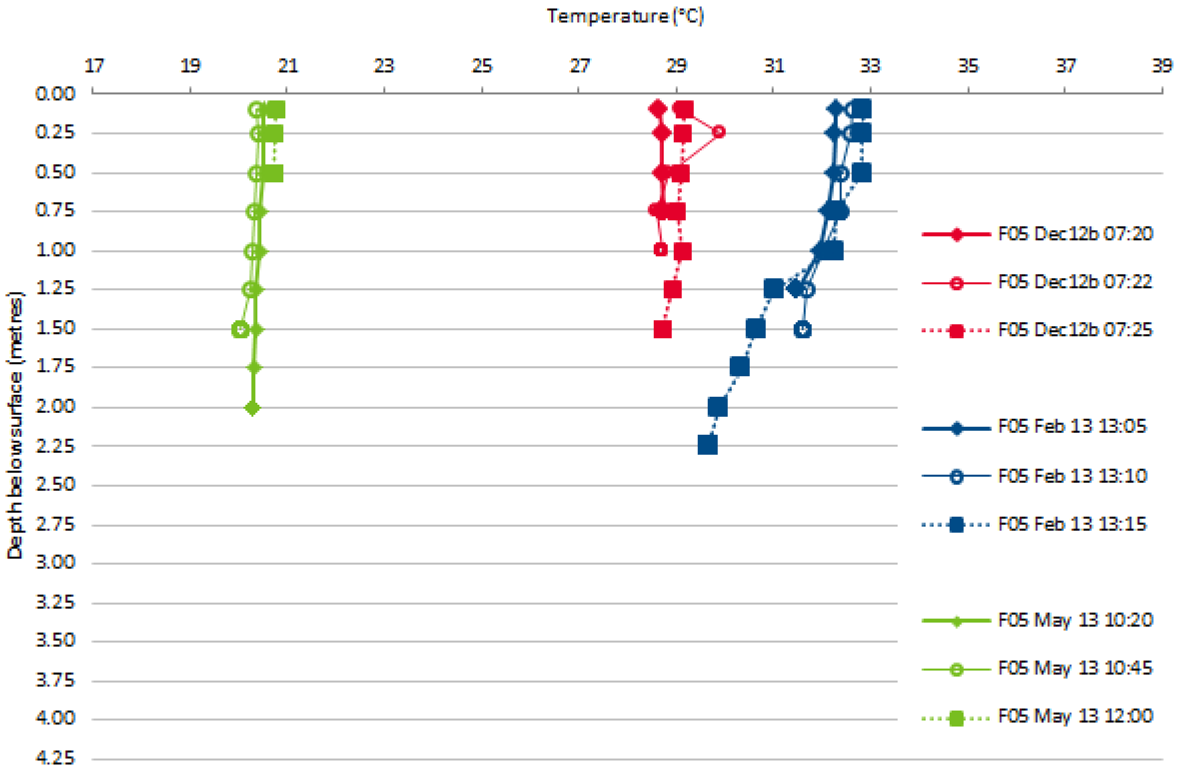
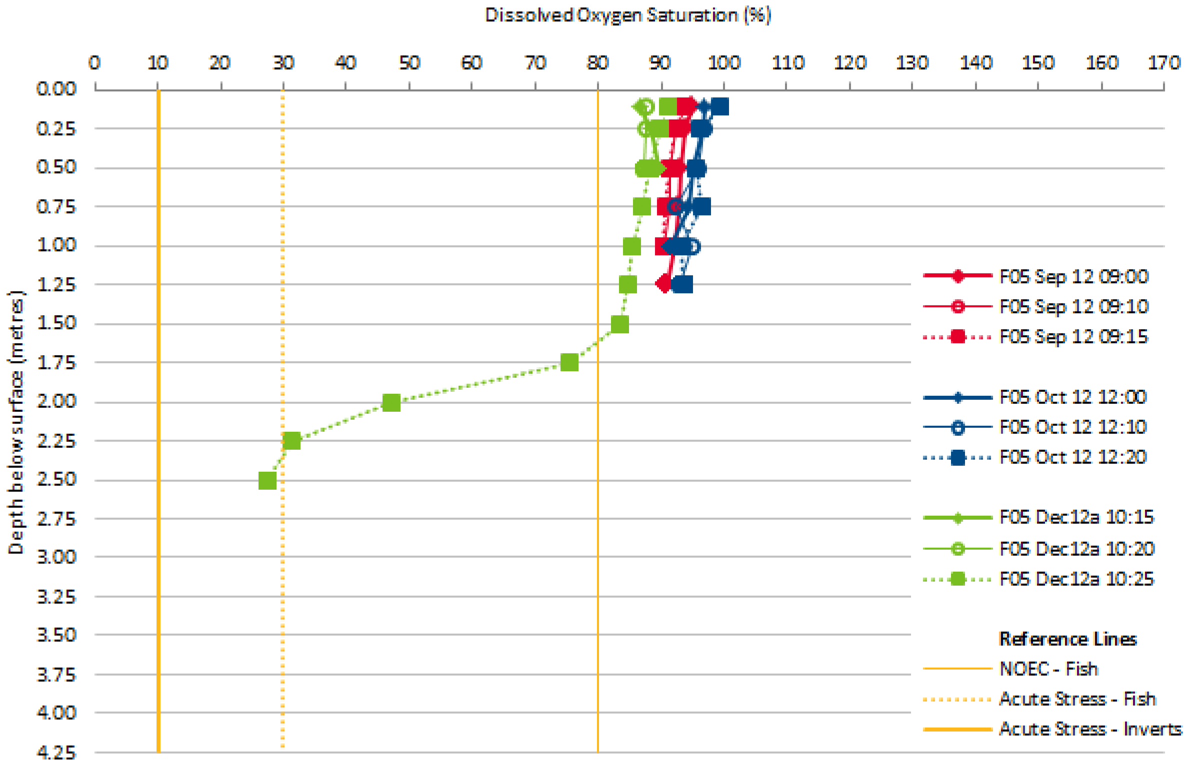


Figure 37 Temperature vertical water column profiles at waterhole F05. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



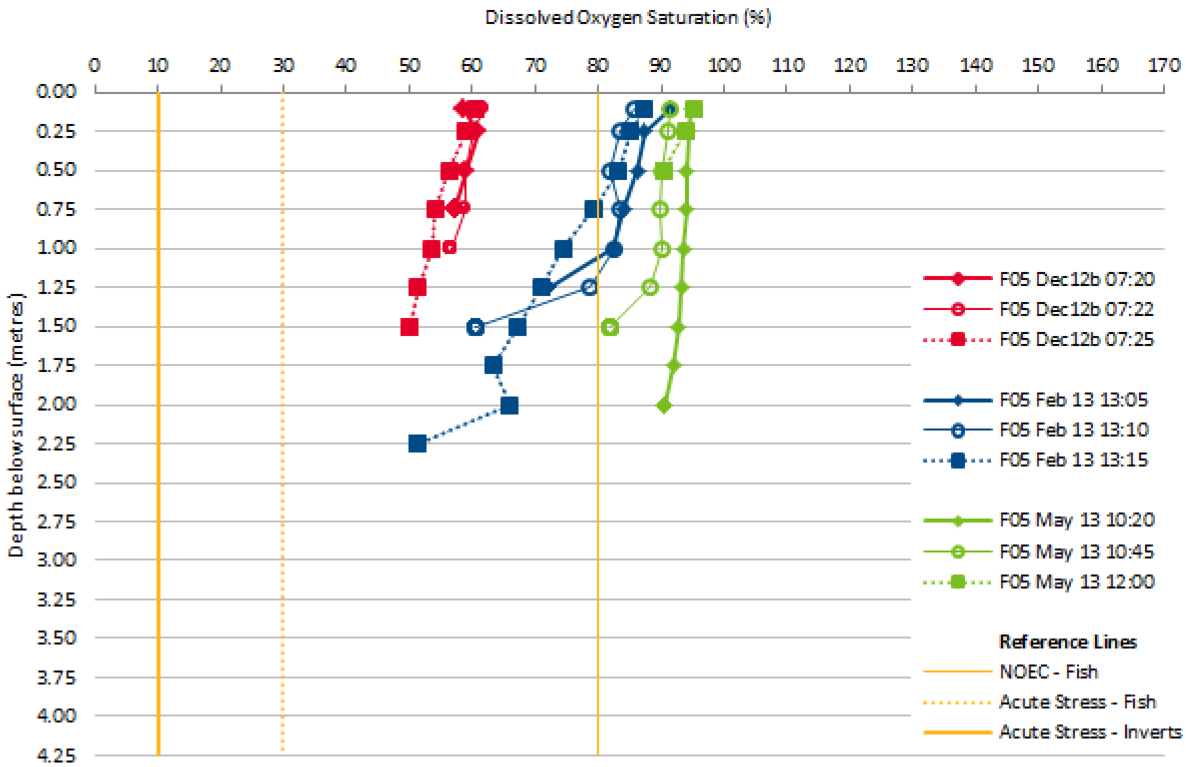
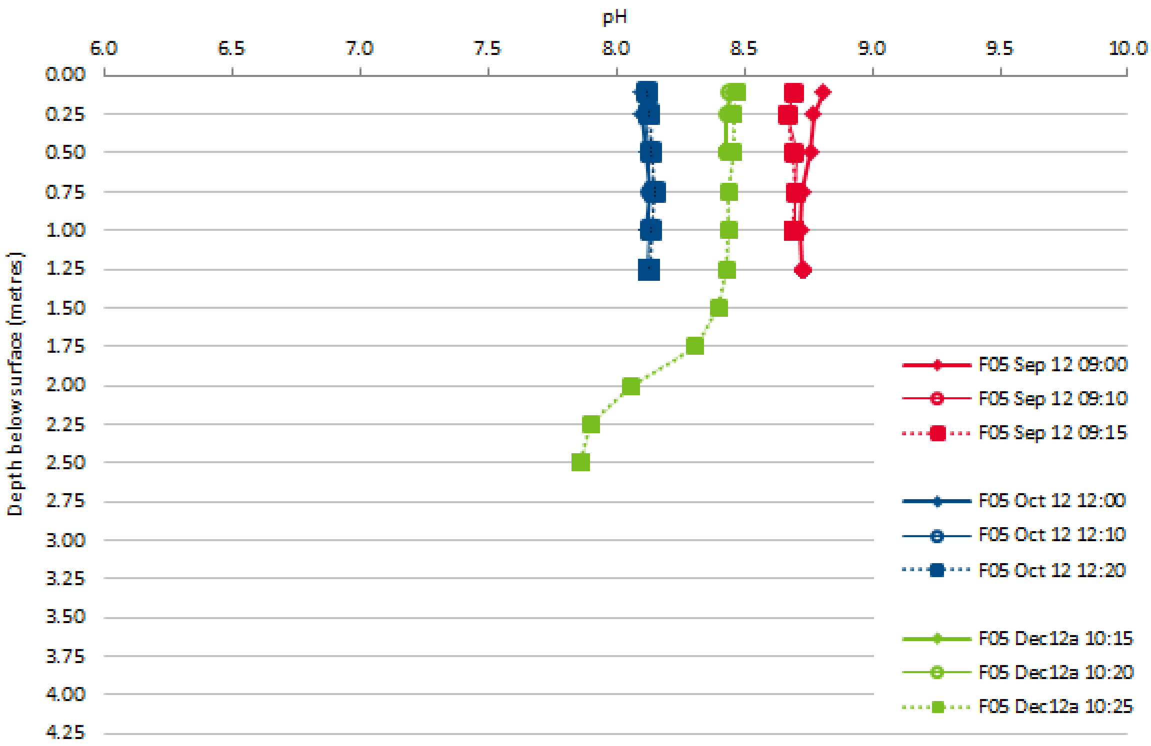


Figure 38 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F05. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



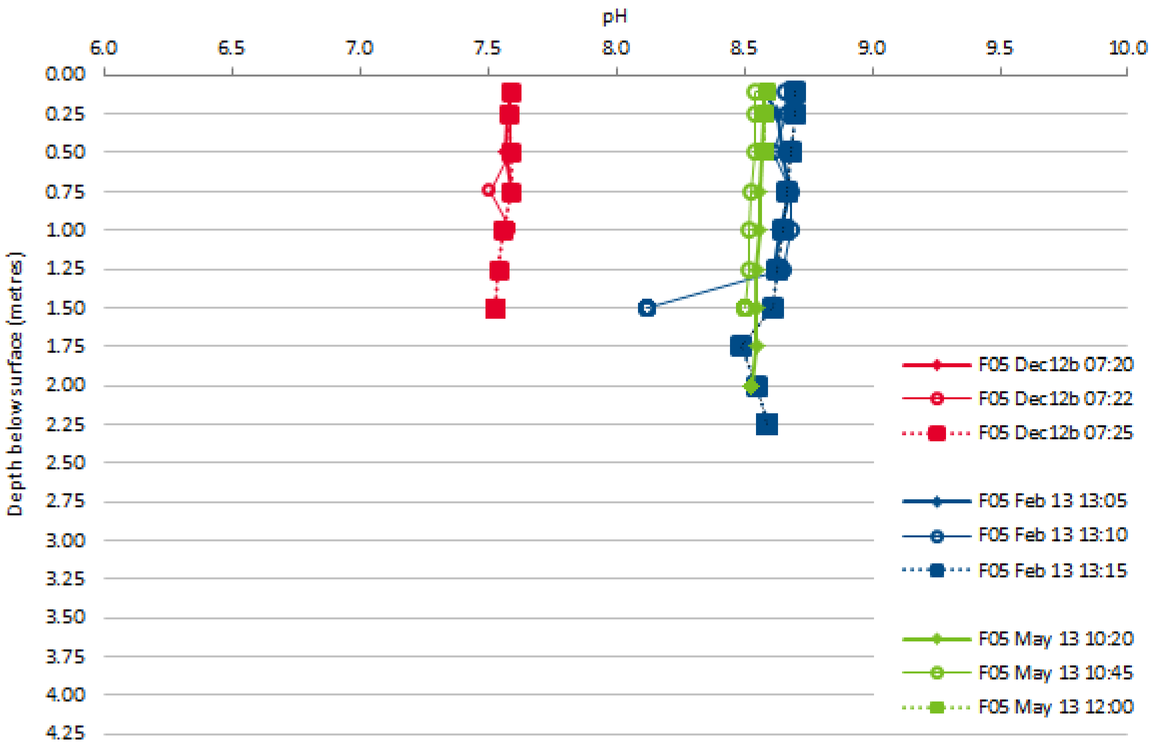
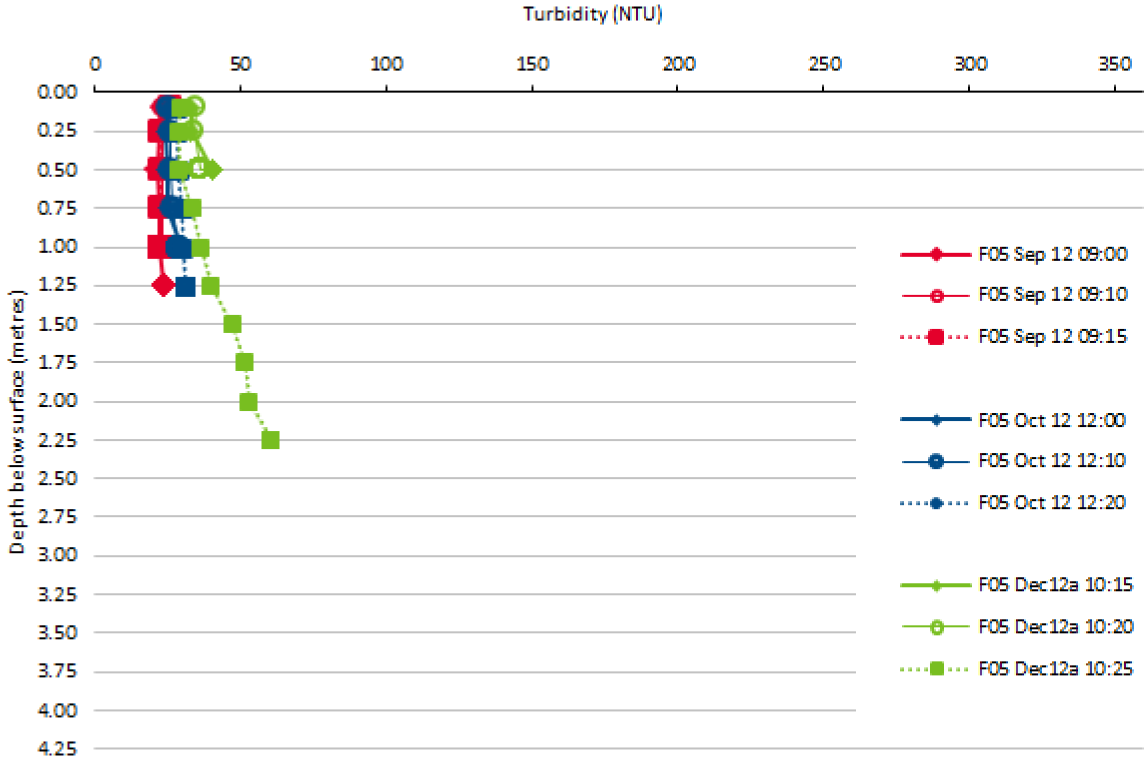


Figure 39 pH vertical water column profiles at waterhole F05. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



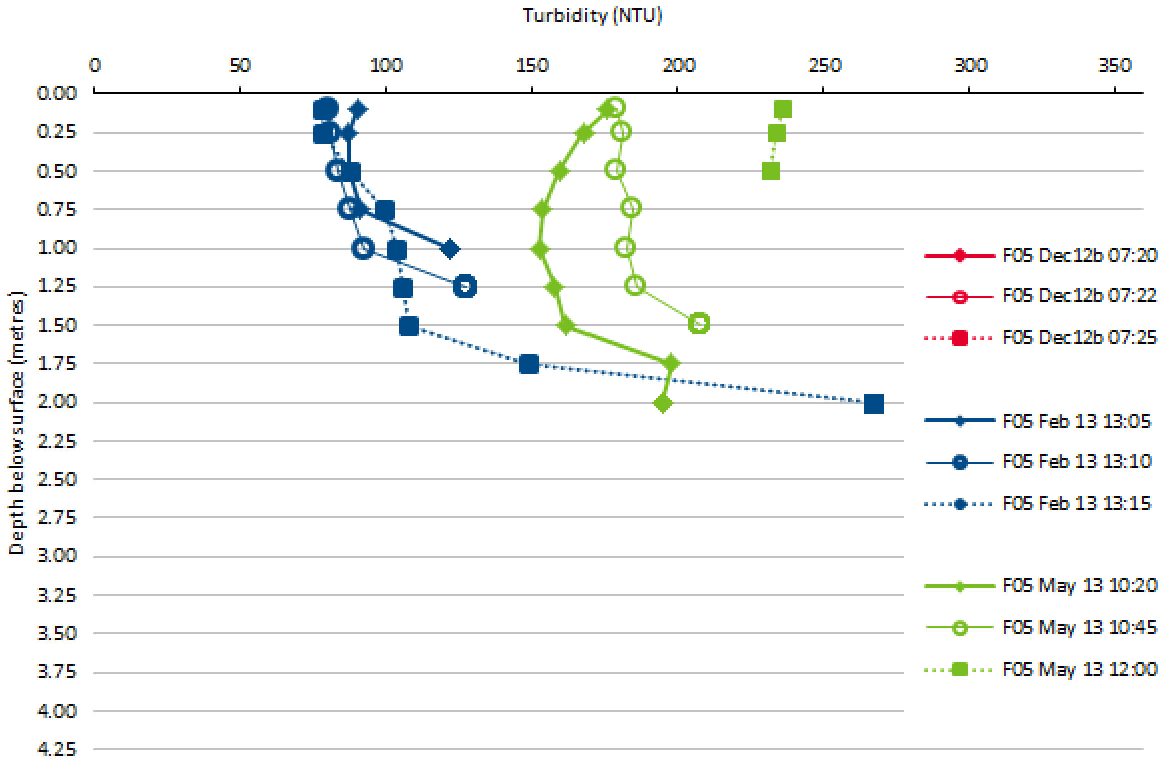
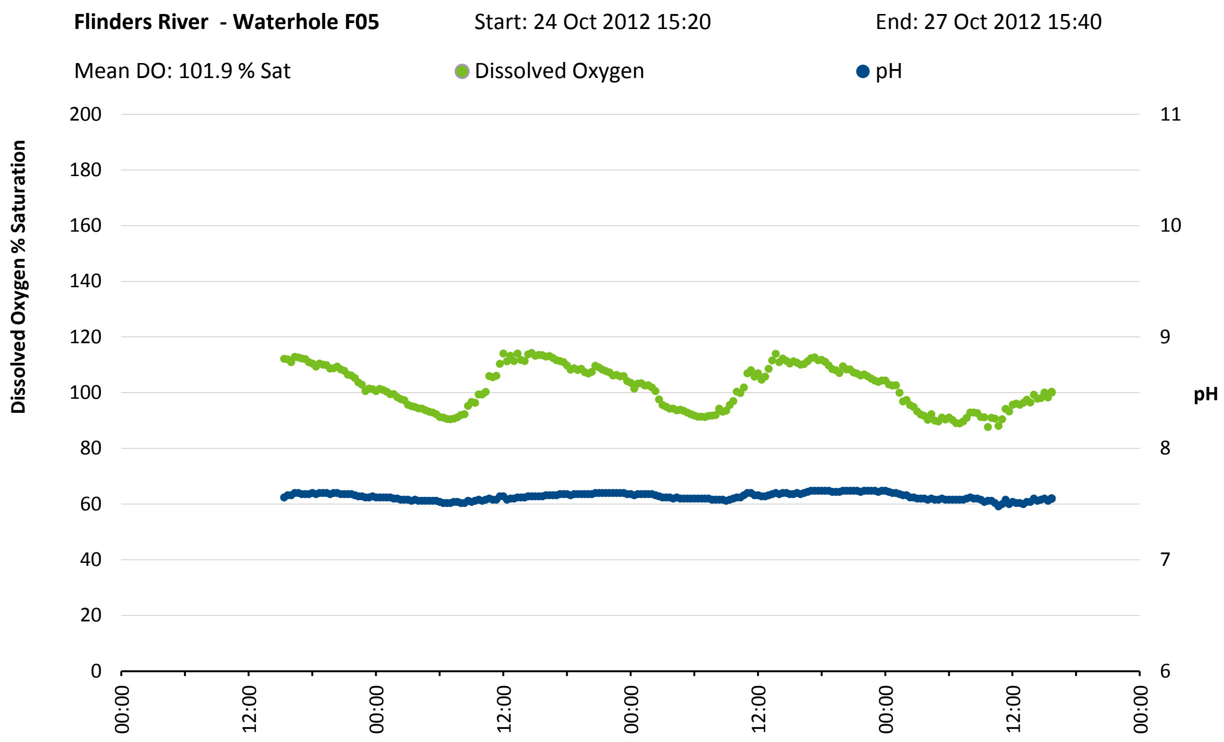


Figure 40 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F05. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



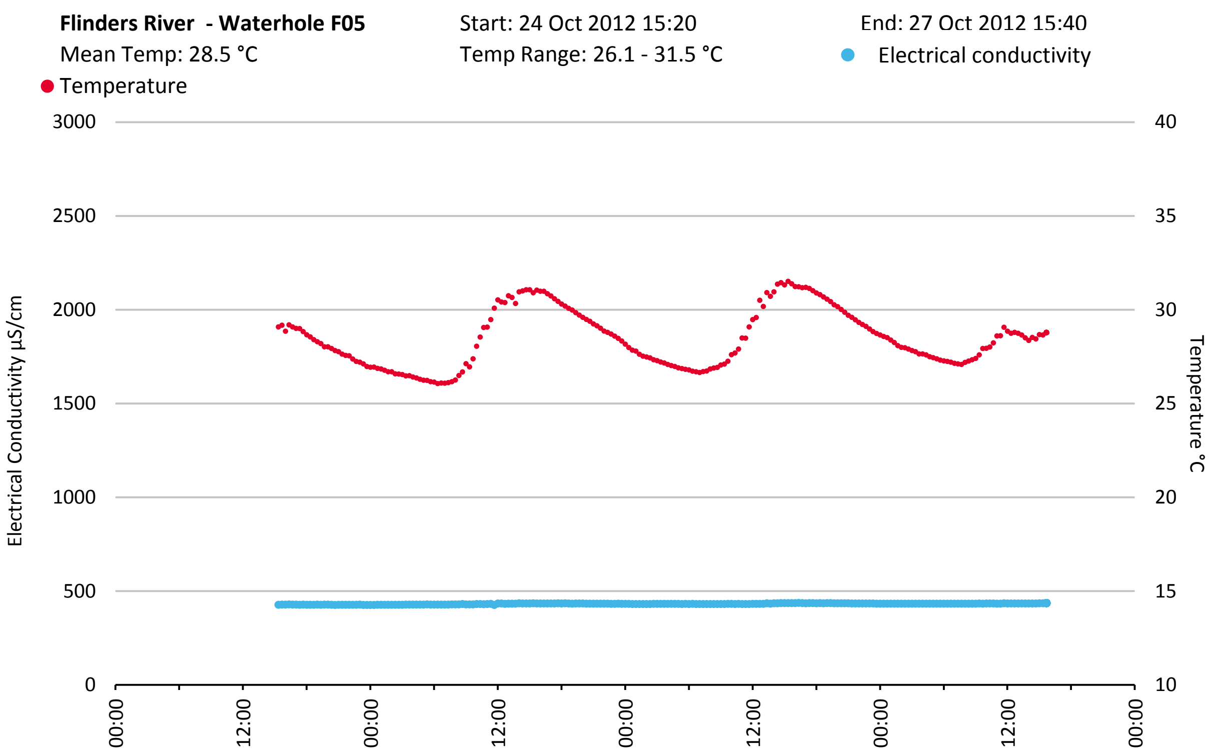
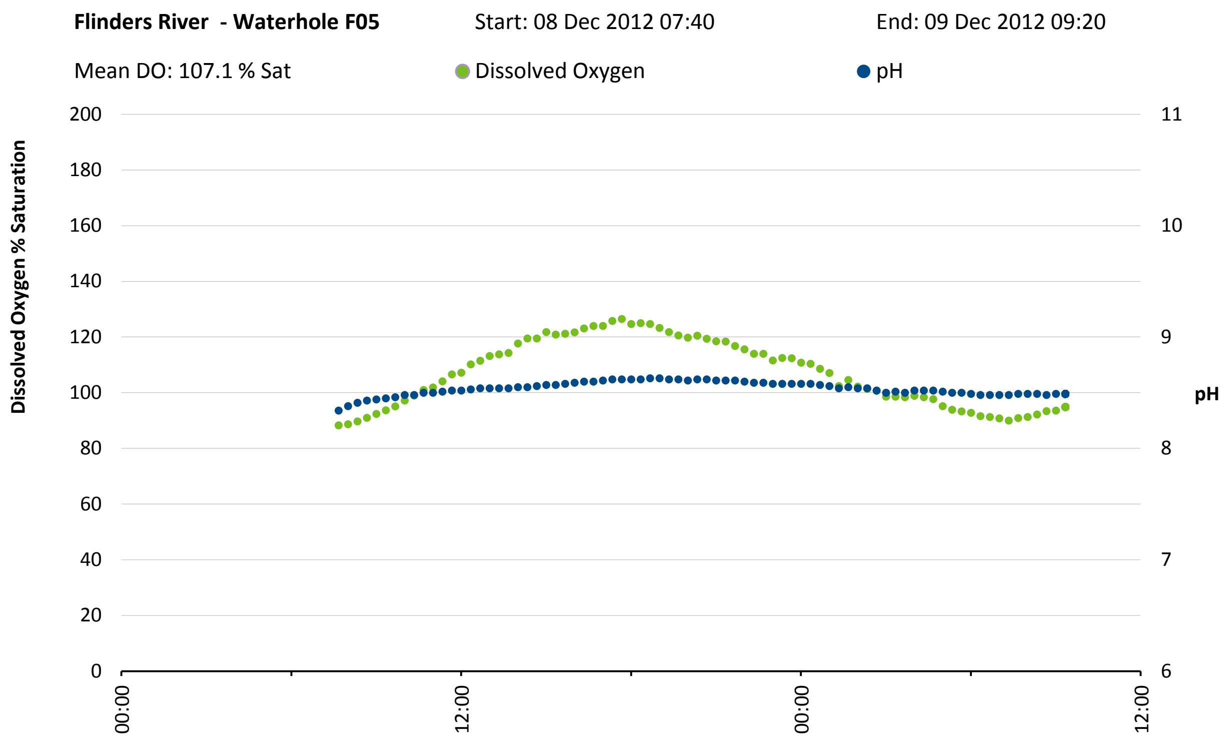


Figure 41 Diel physico chemical data for waterhole F05, Oct 2012



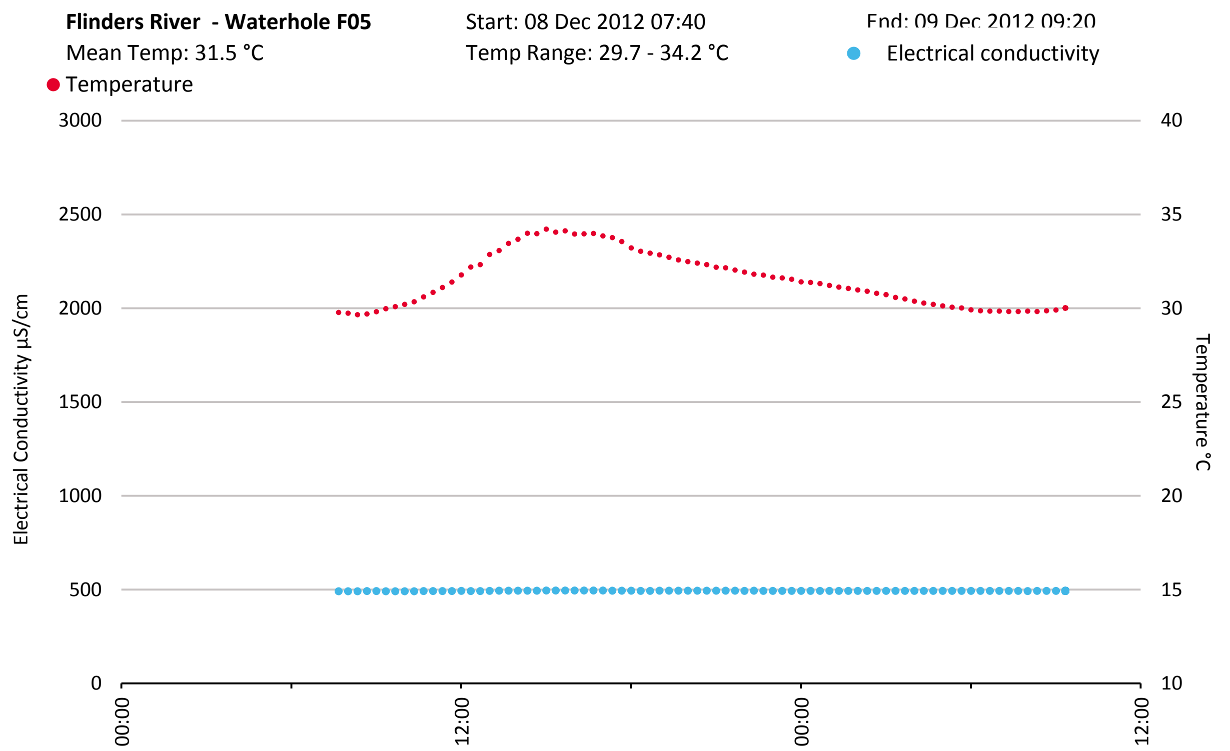


Figure 42 Diel physico chemical data for waterhole F05, Dec 2012

WATERHOLE F06

FEATURE	DESCRIPTION
Waterhole	F06
Catchment	Flinders River
Watercourse	Off channel waterway
Waterhole location	-20.546916°, 142.196974°
Waterhole elevation	~ 140 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Recon trip: Aug 2012
	Survey 1: 8-Sept-12
	Survey 5: 9-Dec-12
	Survey 9: 31-May-13
Instream habitats	Silty substrate.
Riparian zone	Riparian tree species density is low and composed dominantly of *Acacia* species. Groundcover is sparse.
Waterhole depth changes	This waterhole became dry during early September 2012 and remained dry during the remainder of the Assessment period.
Other notes	Cattle tracks evident throughout the riparian zone.

a)

b)

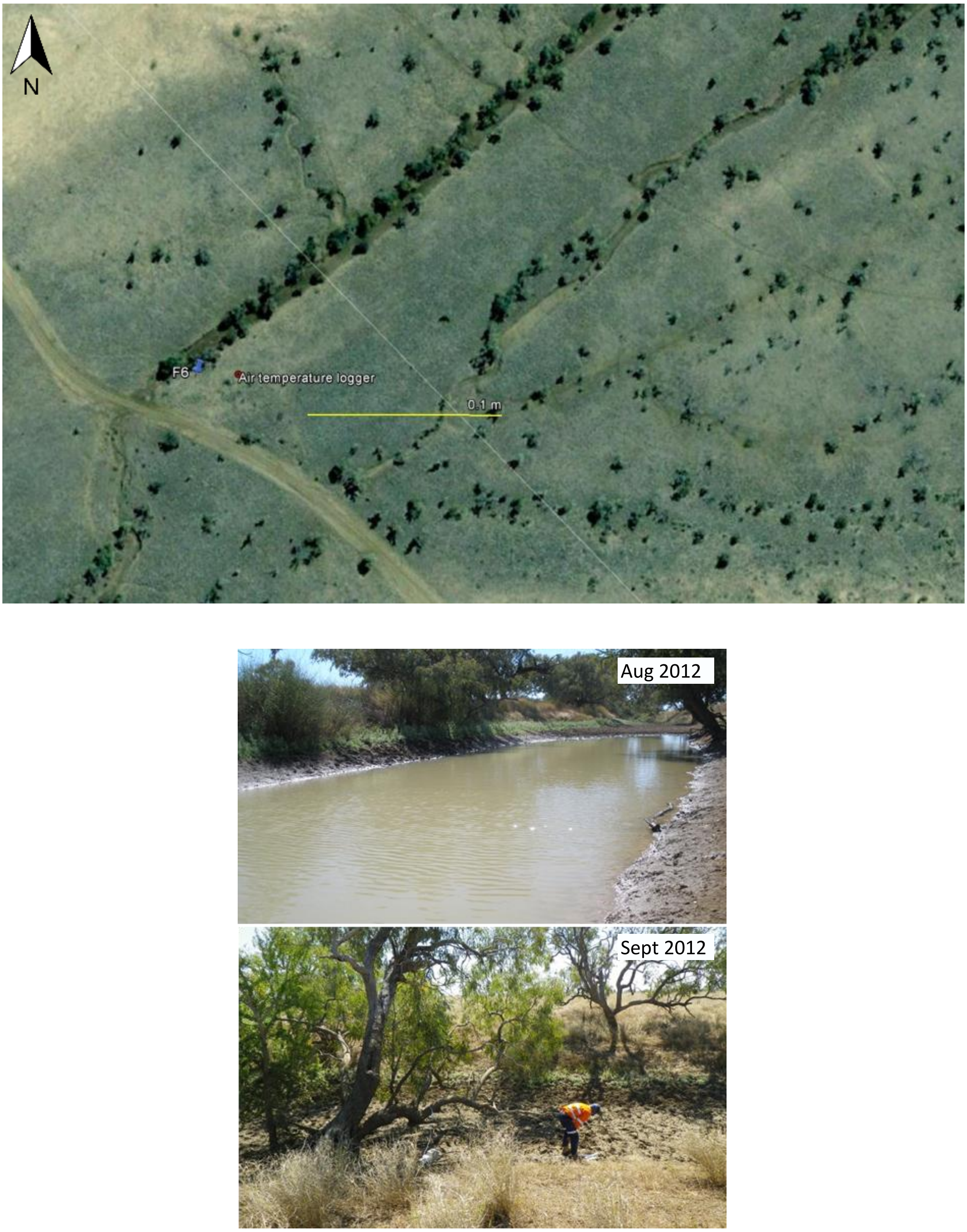


Figure 43 a) GoogleEarth 2005 aerial view of F06. b) Top: F06 during Aug 2012. Bottom: Sept 2012. This waterhole dried quickly after commencement of the project

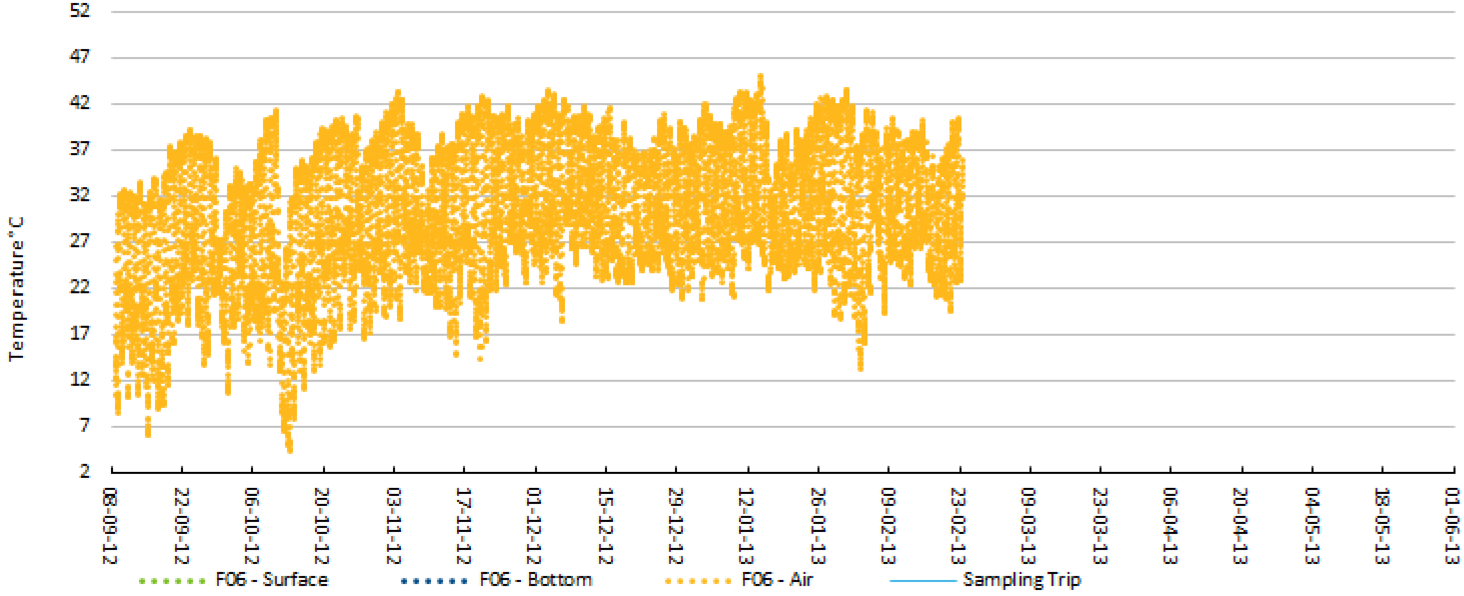


Figure 44 Long term temperature logger data for waterhole F06. Waterhole dried shortly after commenced of the Assessment and remained dry

WATERHOLE F07

FEATURE	DESCRIPTION
Waterhole	F07
Catchment	Flinders River
Waterhole location	-19.973491°, 141.521455°
Waterhole elevation	~ 100 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 9-Sept-12
	Survey 2: 25-Oct-12
	Survey 5: 11-Dec-12
	Survey 6: 20-Dec-12
	Survey 7: 15-Jan-13
	Survey 8: 22-Feb-13
	Survey 9: 30-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~3800 m^2
	Waterhole volume: ~3400 m^3
	Wetted perimeter: ~ 420 m
	Maximum depth: 1.82 m
	Average depth: 0.9 m
	Waterhole length: 200 m
Instream habitats	A silty waterhole with some bedrock evident in the upstream and mid sections. Steep, largely bare lower waterhole banks. Both epilithic and planktonic algal density remained low throughout the Asssessment. Directly downstream from the waterhole the river spreads out across several smaller channels during flow events. Large *Melaleuca* trees grow mid channel.
Riparian zone	Lower bank sections remained bare throughout the Assessment, and overall groundcover is low across the riparian zone. Thistles were present in low densities. *Acacia* and *Melaleuca* species dominate the canopy species, however overall canopy cover is relatively low and offers little shade across the waterhole.
Waterhole depth changes	Water depth declined steadily to December 2012. Maximum depth increased by 1 m during January 2013 then reduced steadily again to May 2013.
Other notes	Cattle access damage is evident along most of riparian area, with high levels of bank and instream activity evident at the downstream end of the waterhole. This waterhole experienced a post wet season flow event during May 2013.

a)

b)

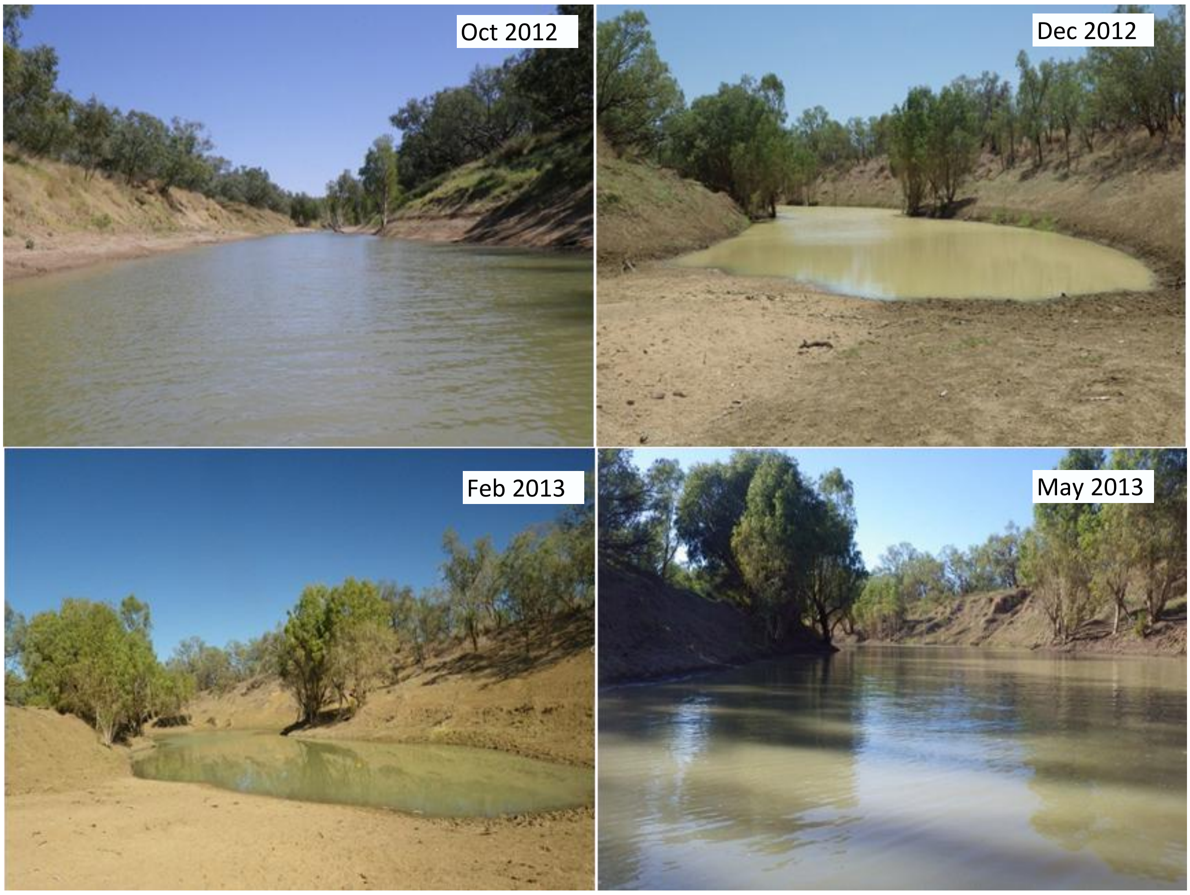


Figure 45 a) GoogleEarth 2006 aerial view of F07. b) Left to right: 1) Upstream from mid channel. 2). Upstream from mid channel. 3) Upstream from mid channel. 4) Upstream from mid channel

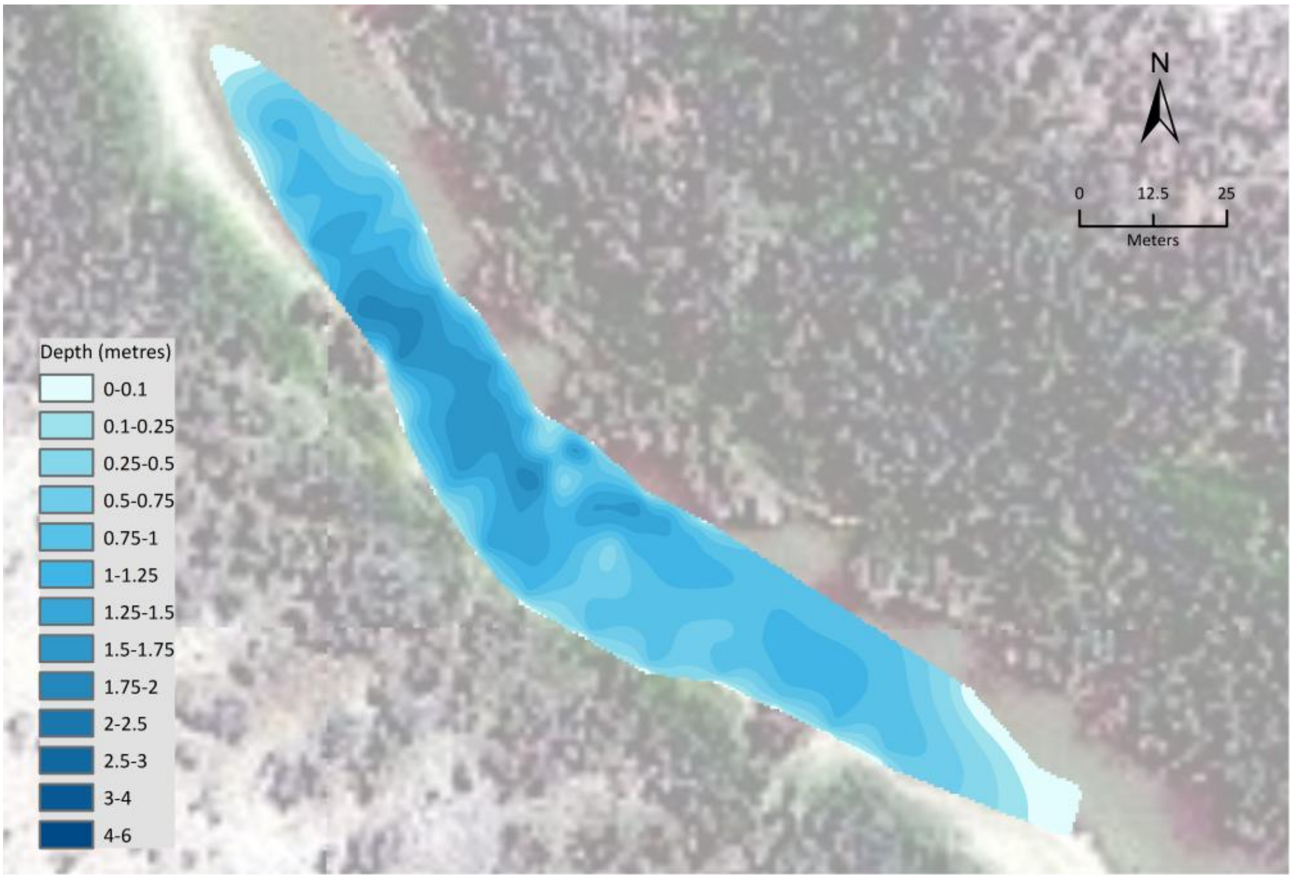


Figure 46 Bathymetry map of waterhole F07. Depth and waterhole perimeter data generated from data collected Oct 2012

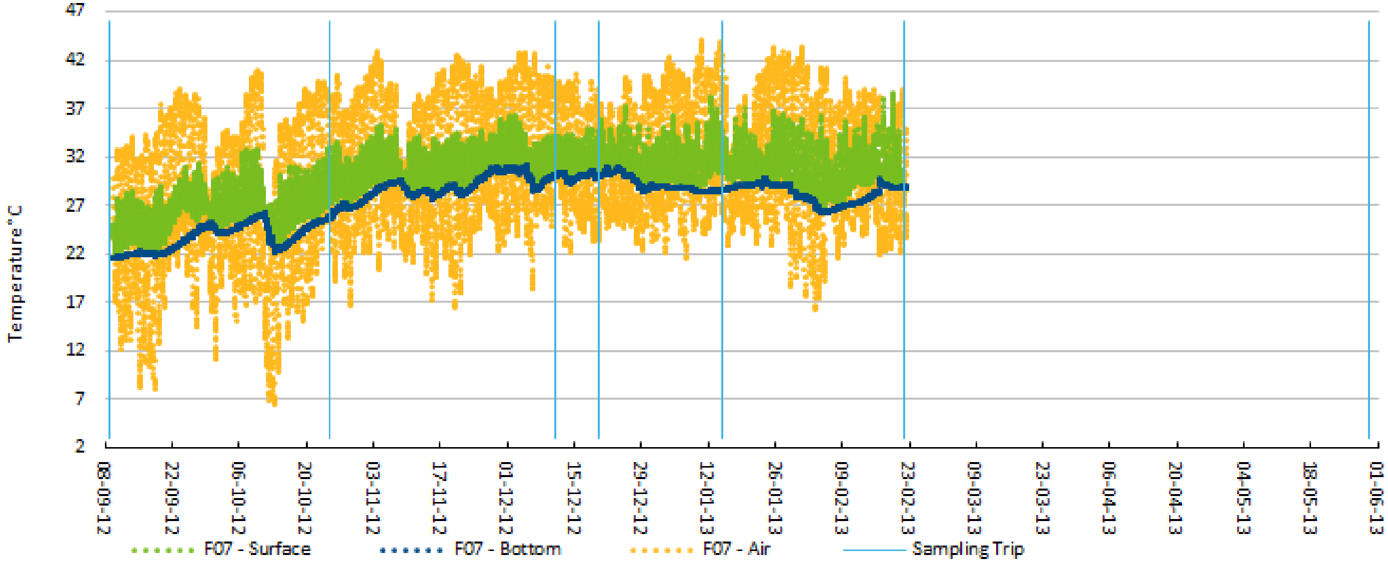
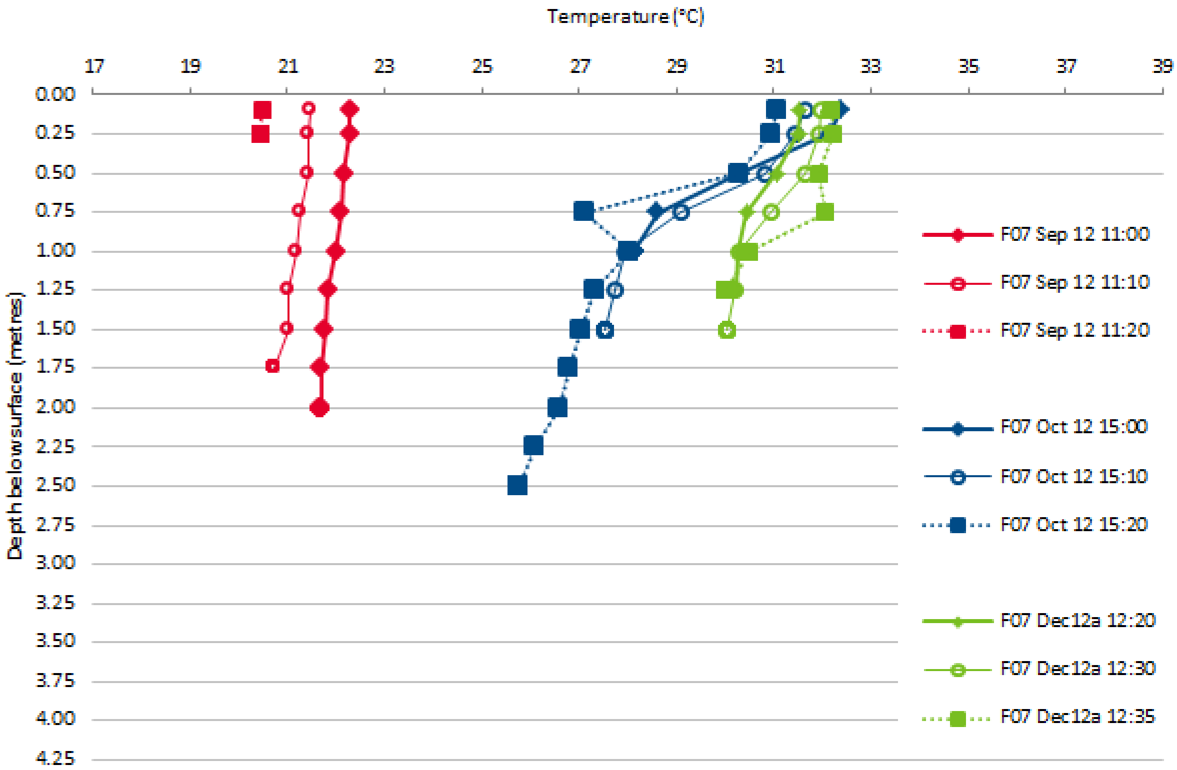


Figure 47 Long term temperature logger data for waterhole F07. Logger malfunction following February 2013

Table 6 Continuous water and air temperature logger summary statistics for each survey at waterhole F07.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5°C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Sep 12	10-09-12 00:15	19-09-12 00:15	9	8.1	23.0	34.5	22.0	24.5	28.5	21.5	21.9	22.3	0.0	2.6	6.6	93.2	80.0	66.7
Oct 12	19-10-12 00:15	01-11-12 00:15	13	15.2	29.6	40.3	25.5	28.8	33.5	24.2	26.0	27.5	0.1	2.8	7.2	97.9	92.1	77.7
Nov12b	17-11-12 00:15	23-11-12 00:15	6	16.5	31.2	42.5	28.4	30.7	34.5	28.0	28.6	29.2	-0.1	2.2	6.0	89.1	72.1	57.0
Dec12b	18-12-12 00:15	23-12-12 00:15	5	23.3	29.7	39.7	30.2	32.0	35.8	29.9	30.3	30.9	-0.1	1.7	5.6	79.5	60.7	46.0
Jan 13	12-01-13 00:15	16-01-13 00:15	4	24.6	33.7	44.0	30.1	32.8	38.3	28.5	28.5	28.7	1.6	4.2	9.8	100.0	100.0	100.0
Feb 13	18-02-13 00:15	20-02-13 00:15	2	22.4	28.9	38.0	29.0	31.9	38.6	28.9	29.0	29.2	0.0	3.0	9.7	80.7	63.4	57.2



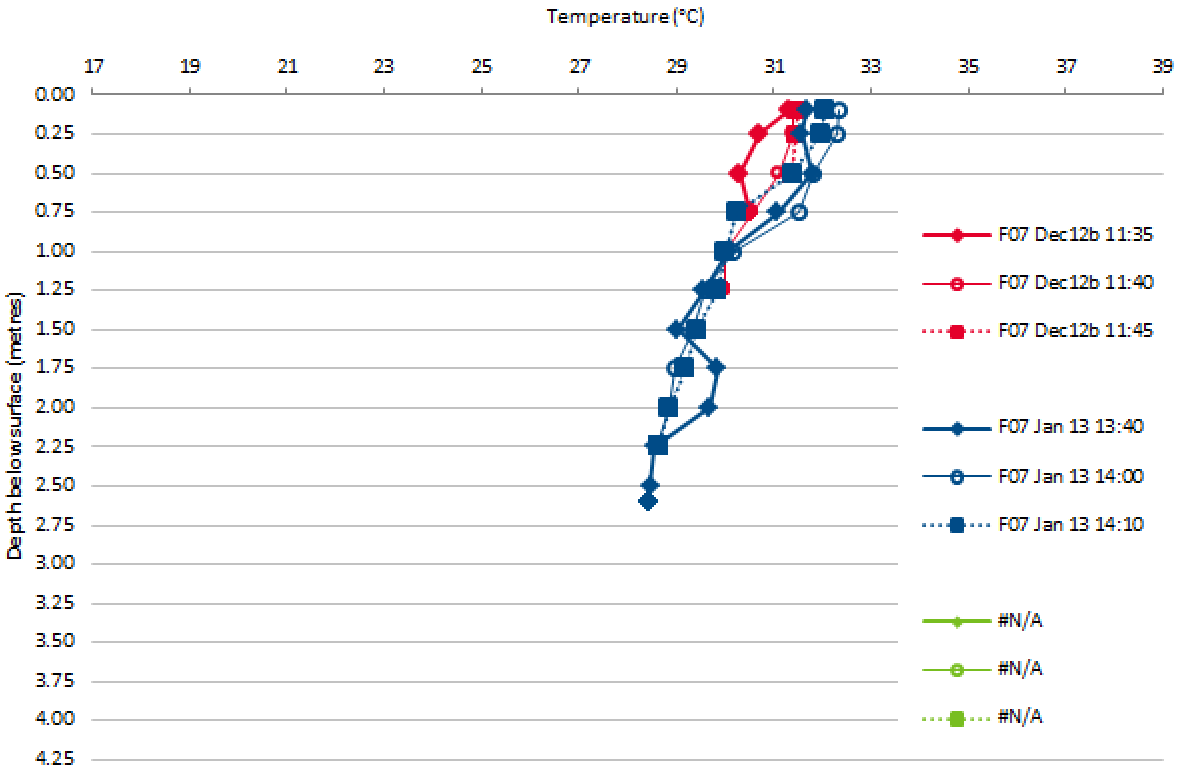


Figure 48 Temperature vertical water column profiles at waterhole F07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

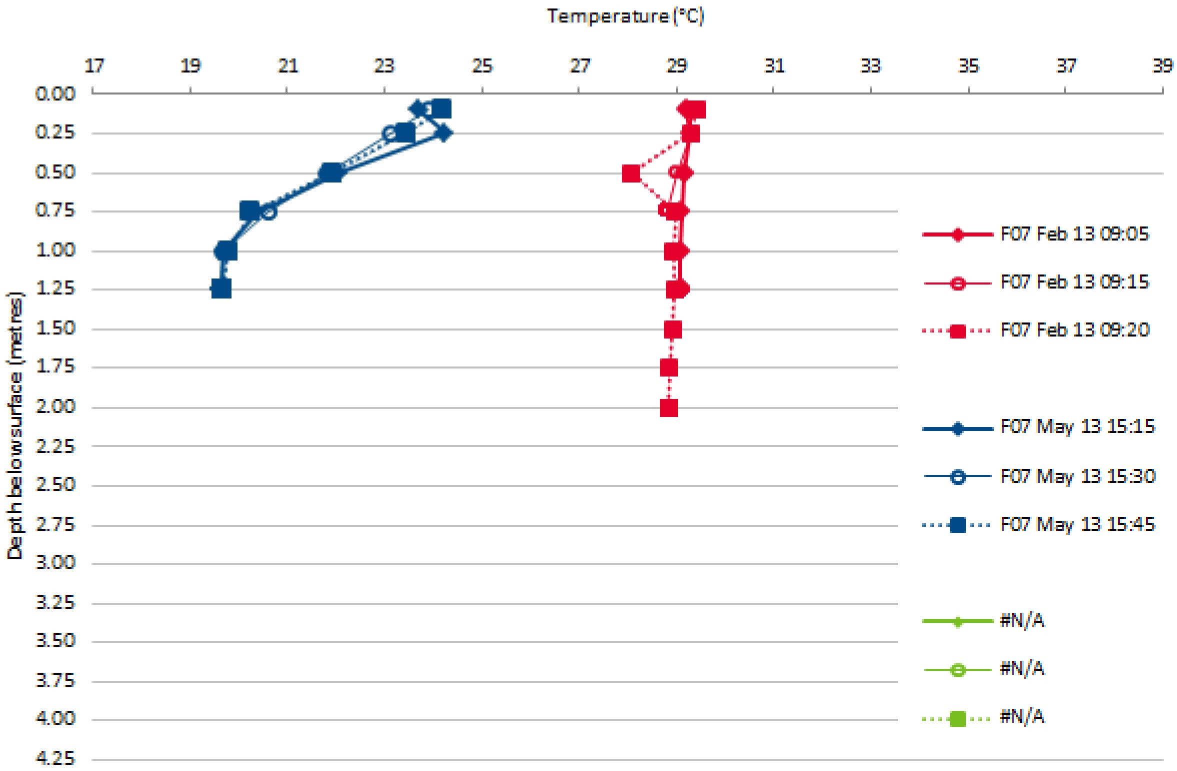
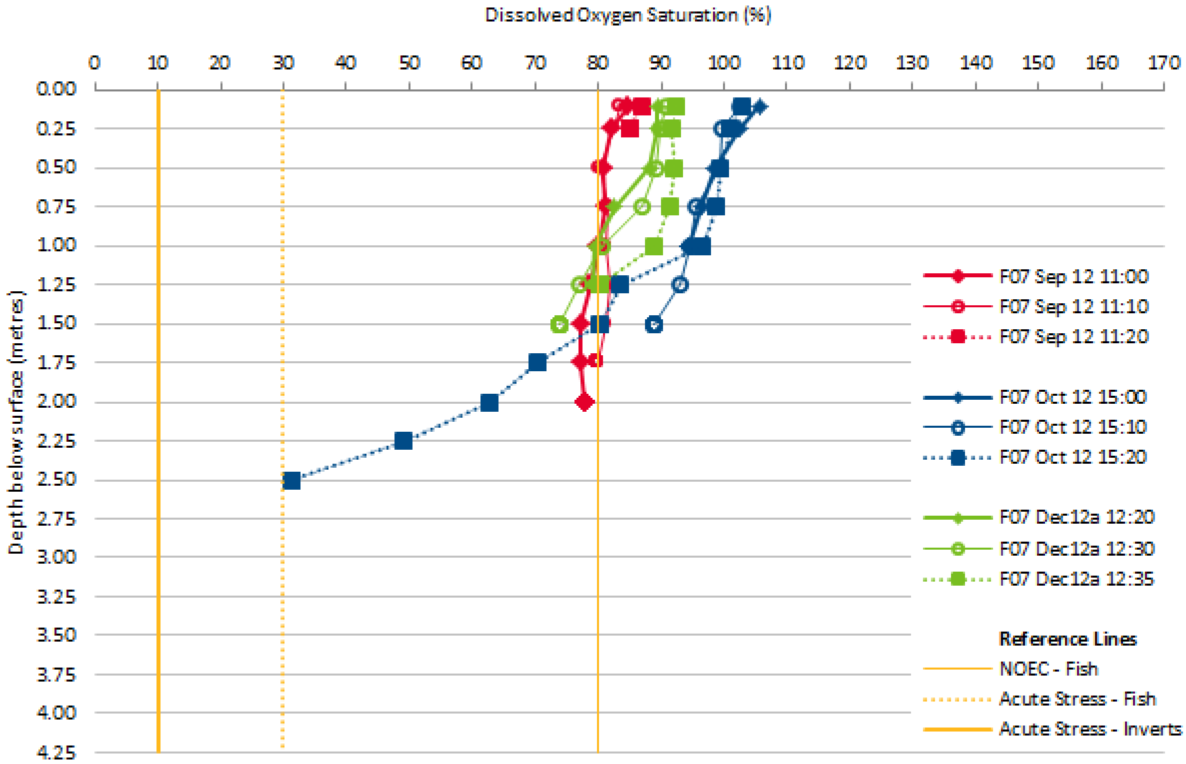


Figure 49 Temperature vertical water column profiles at waterhole F07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



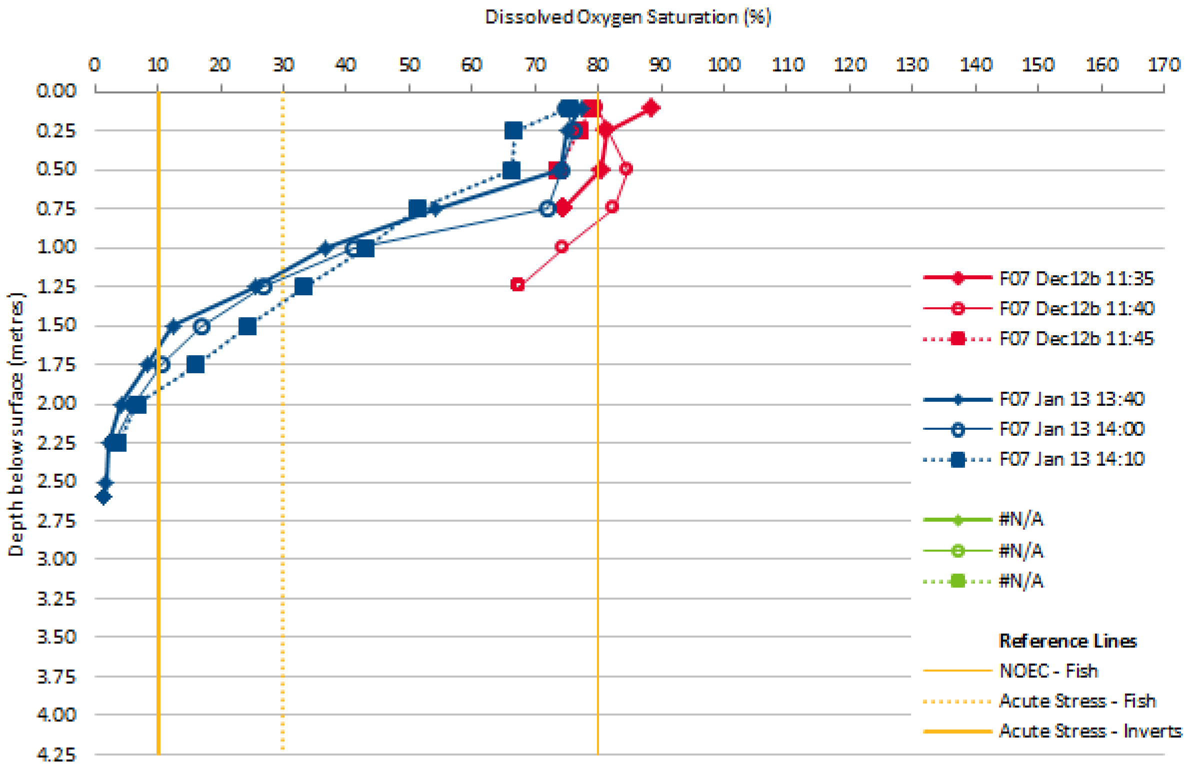


Figure 50 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F07. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

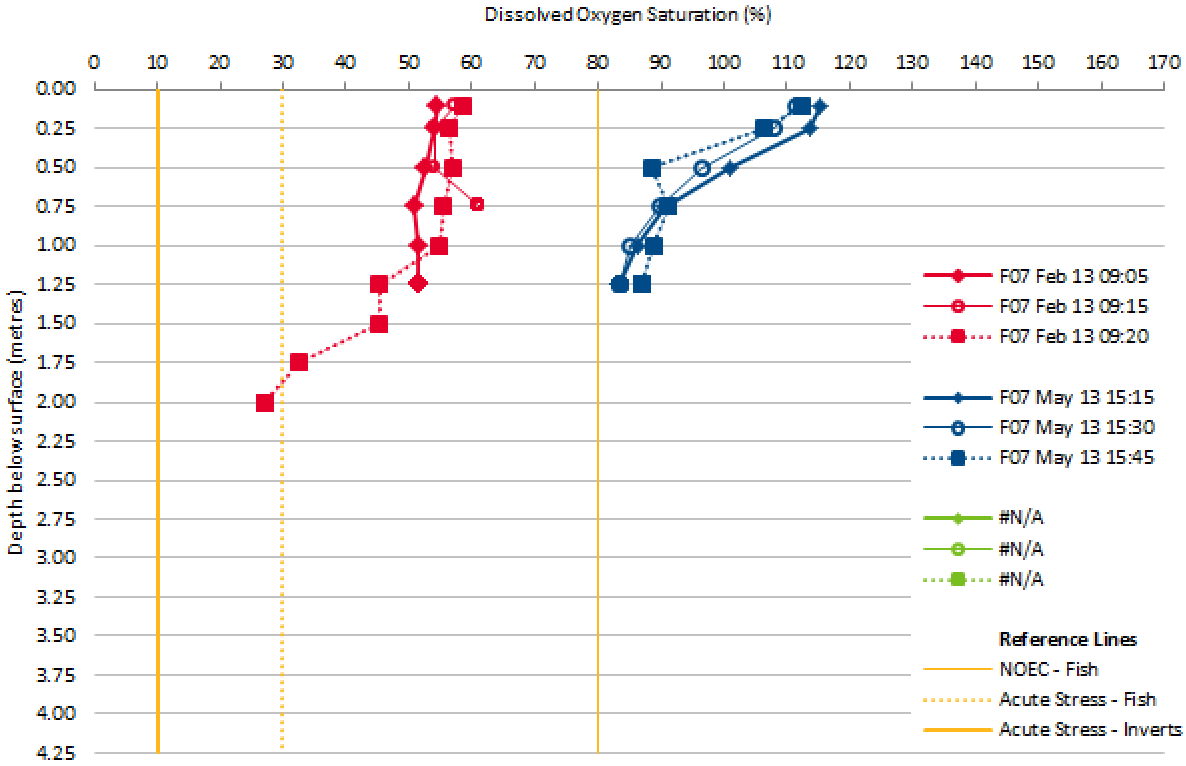
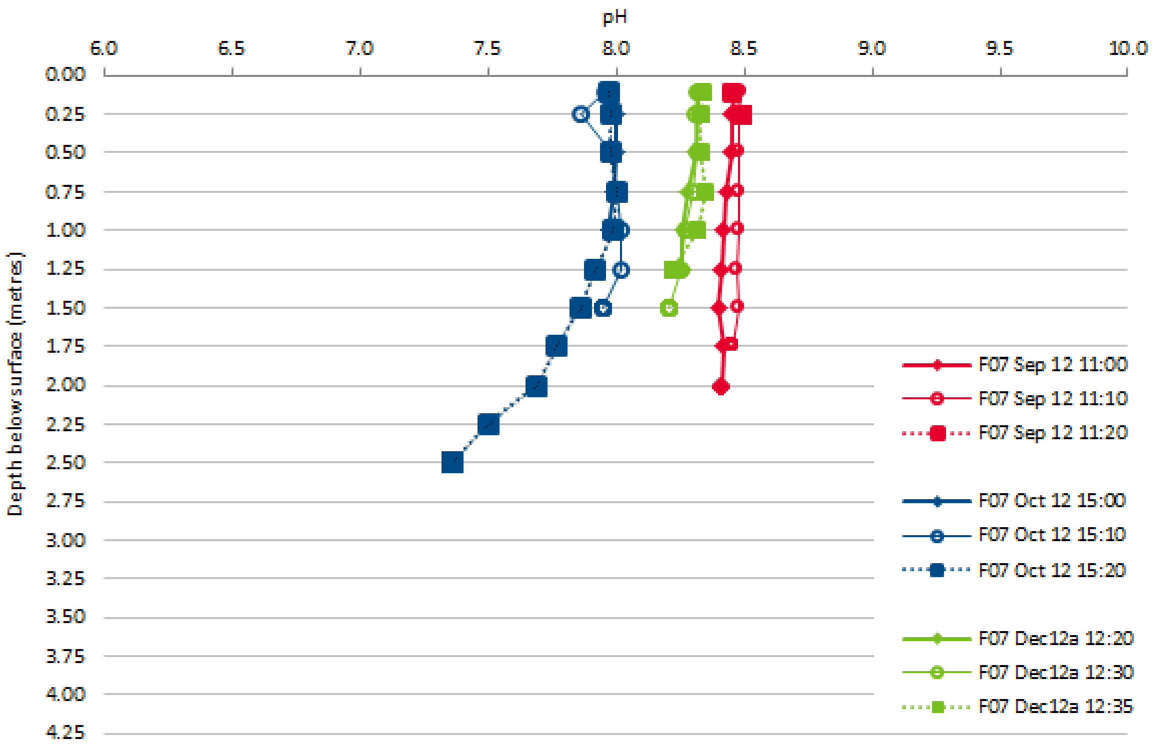


Figure 51 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F07. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



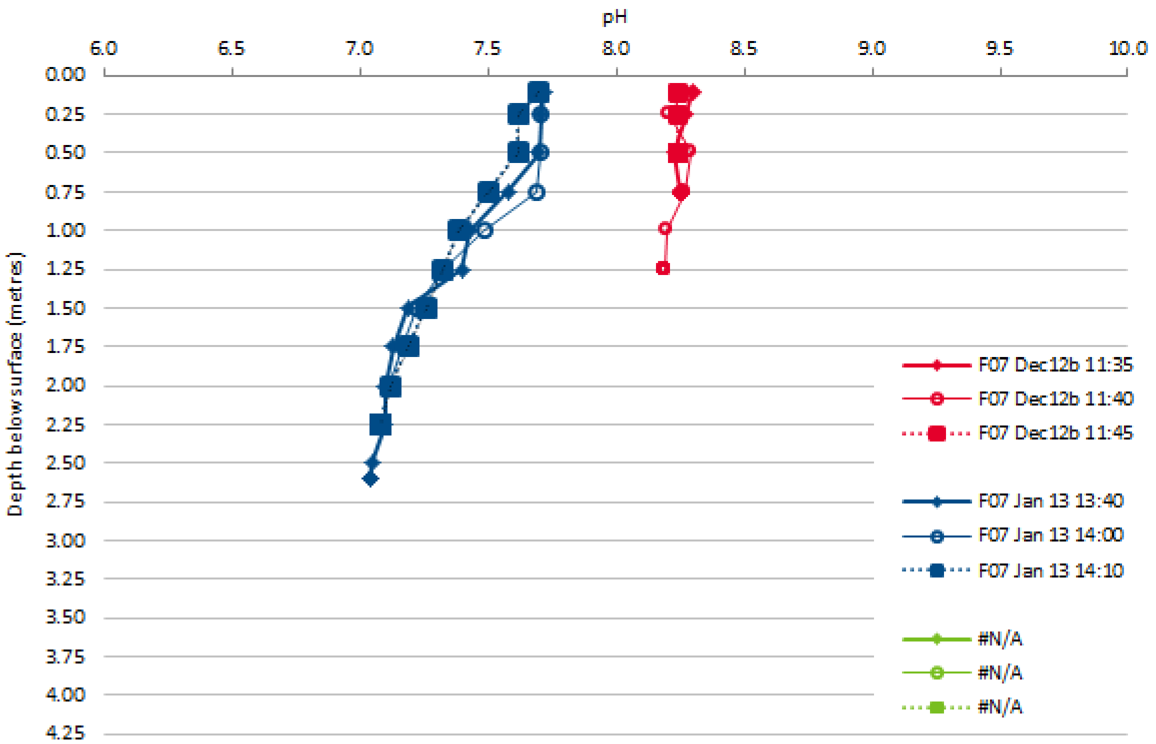


Figure 52 pH vertical water column profiles at waterhole F07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

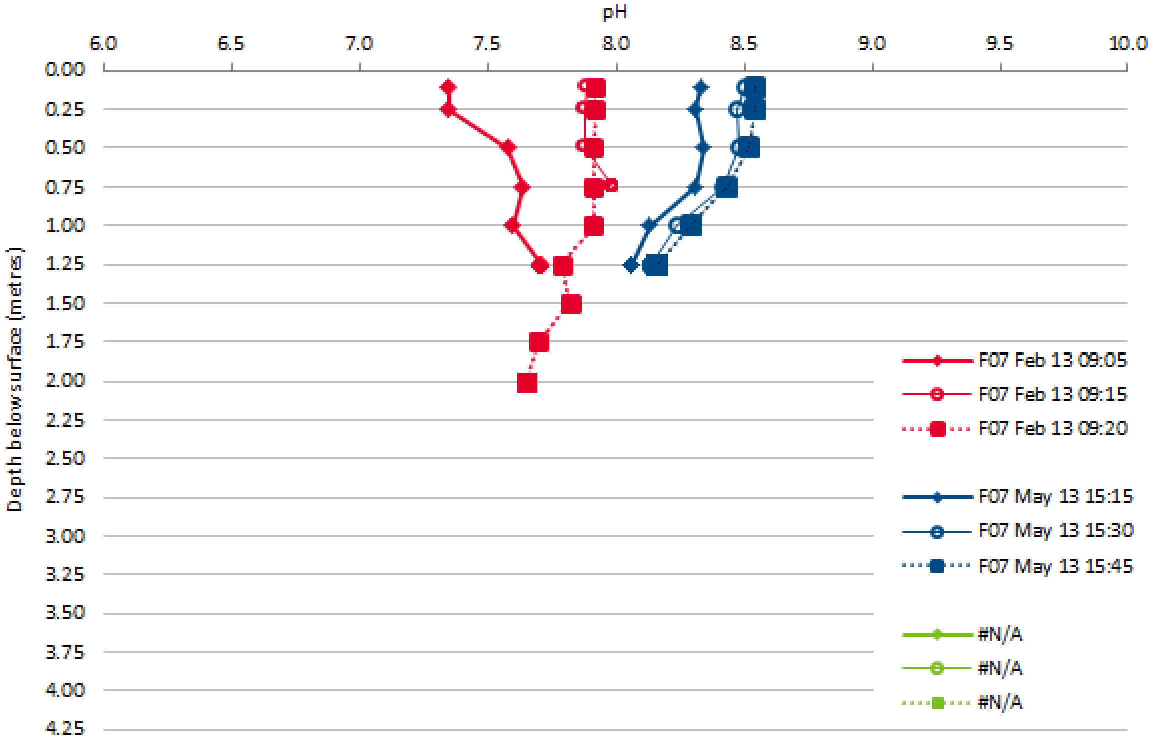
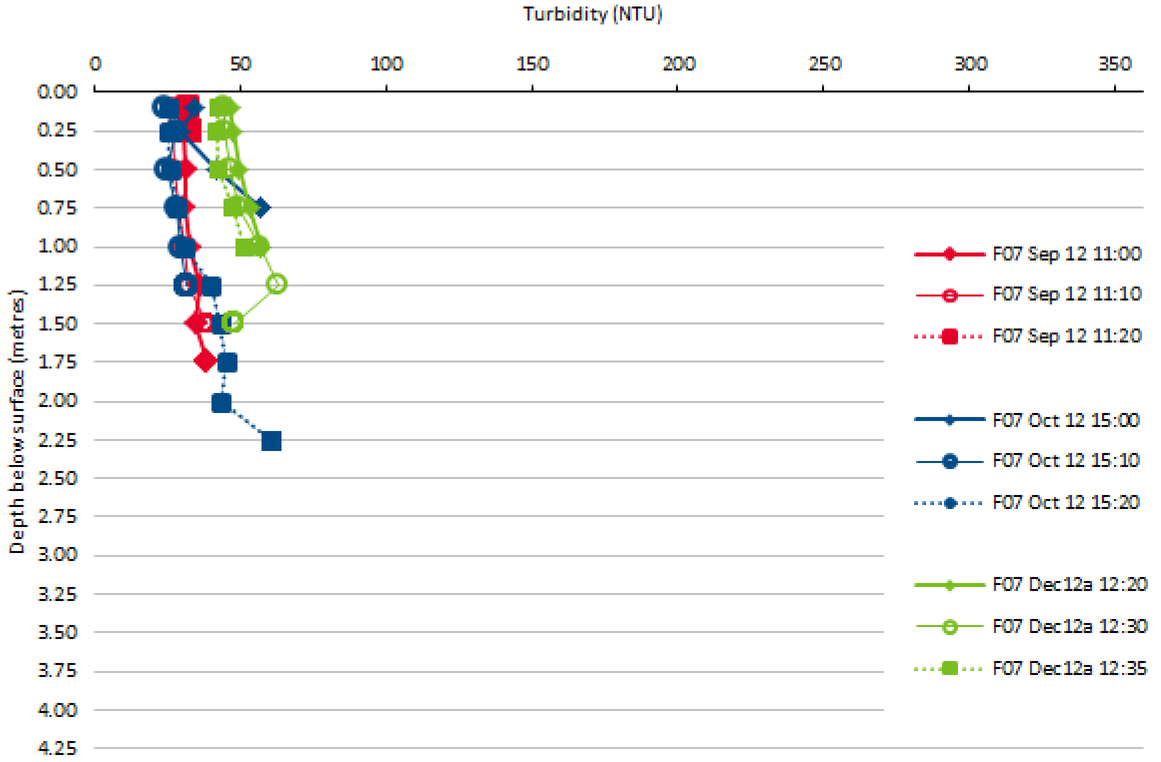


Figure 53 pH vertical water column profiles at waterhole F07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



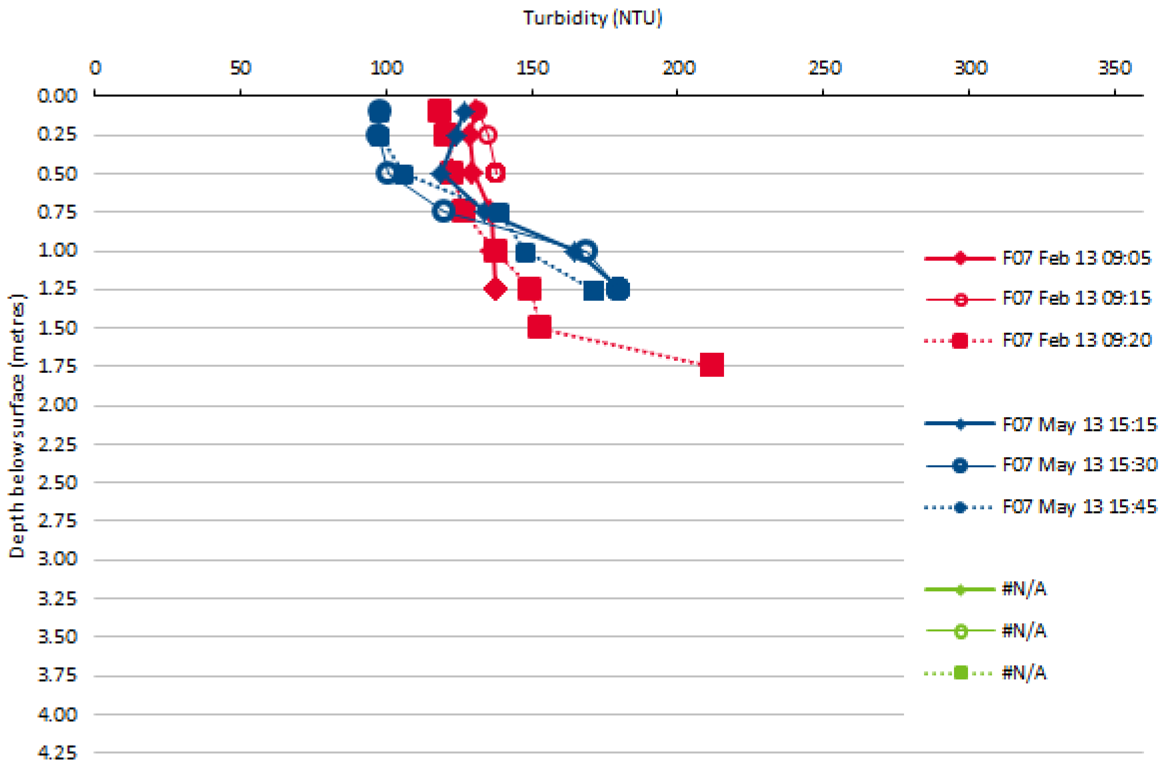
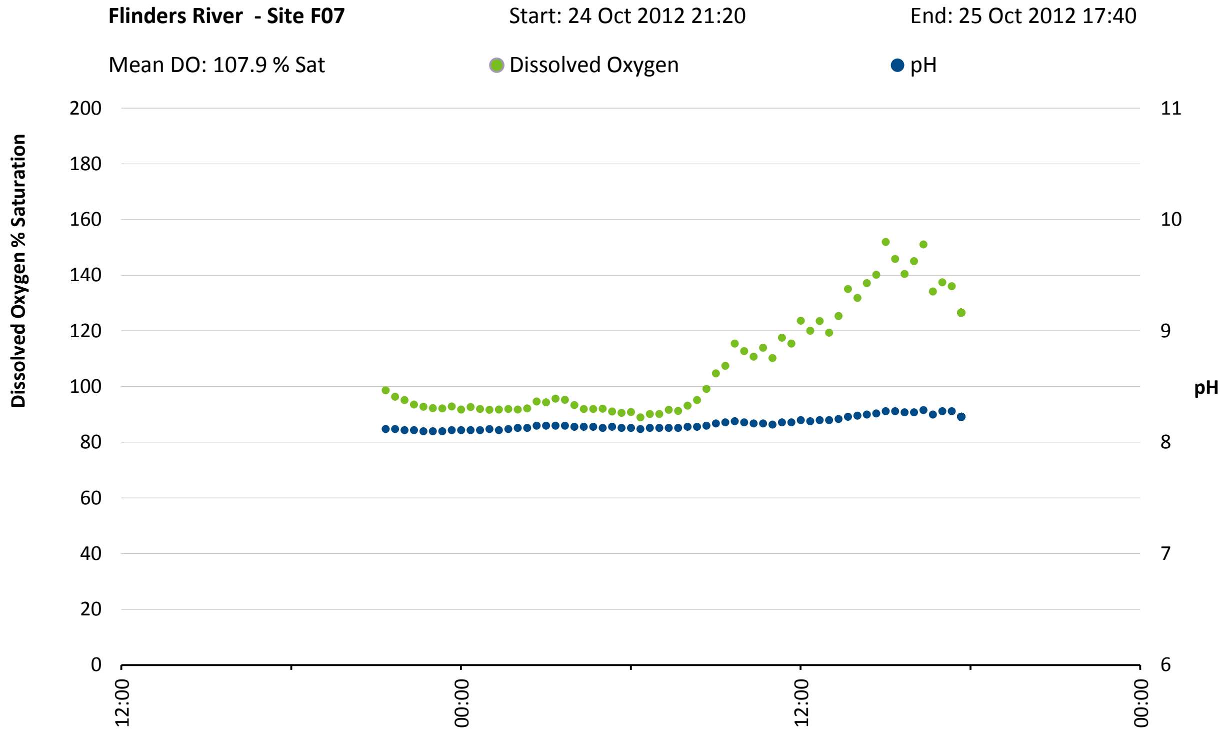


Figure 54 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F05. No turbidity data was collected during Dec 12b or Jan 13 surveys. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



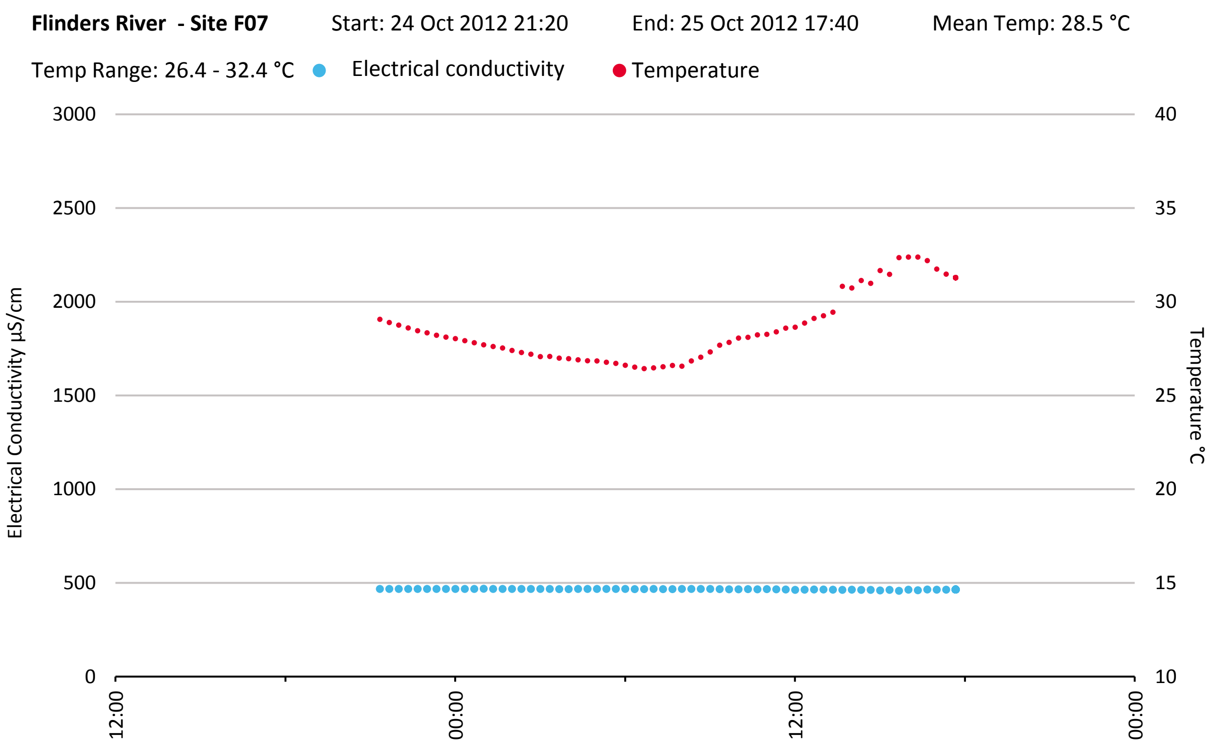
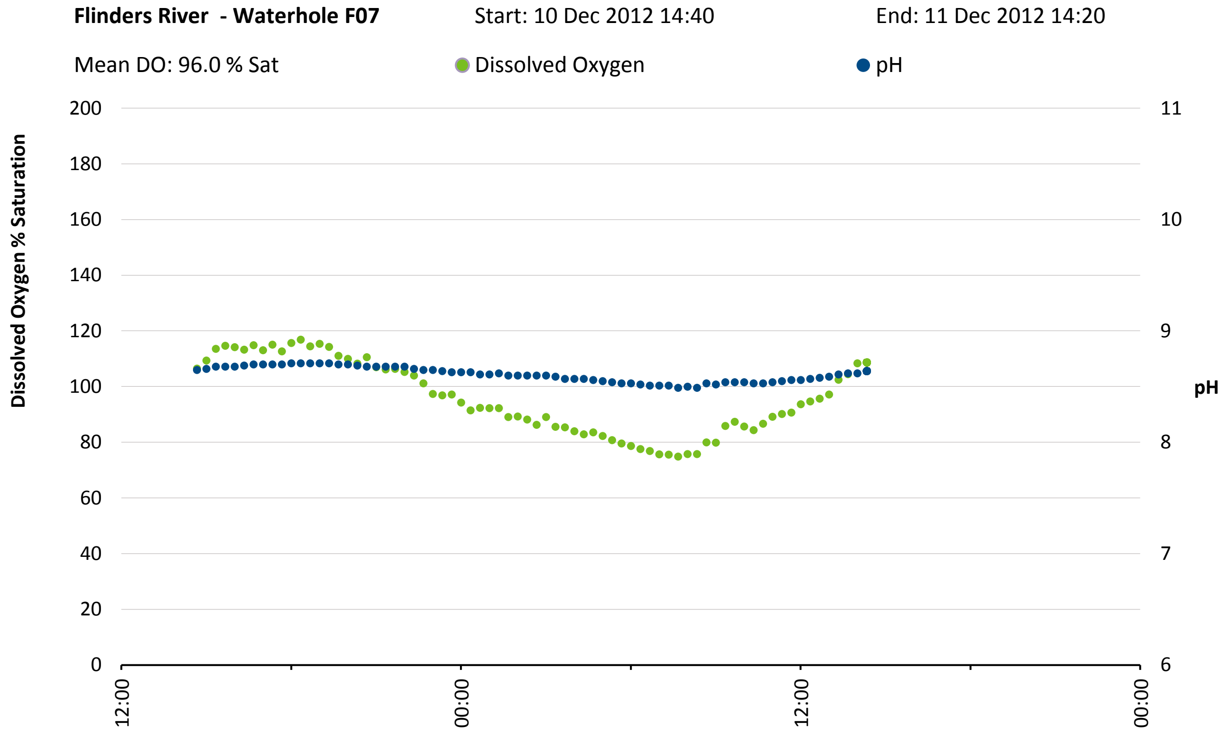


Figure 55 Diel physico chemical data for waterhole F07, Oct 2012



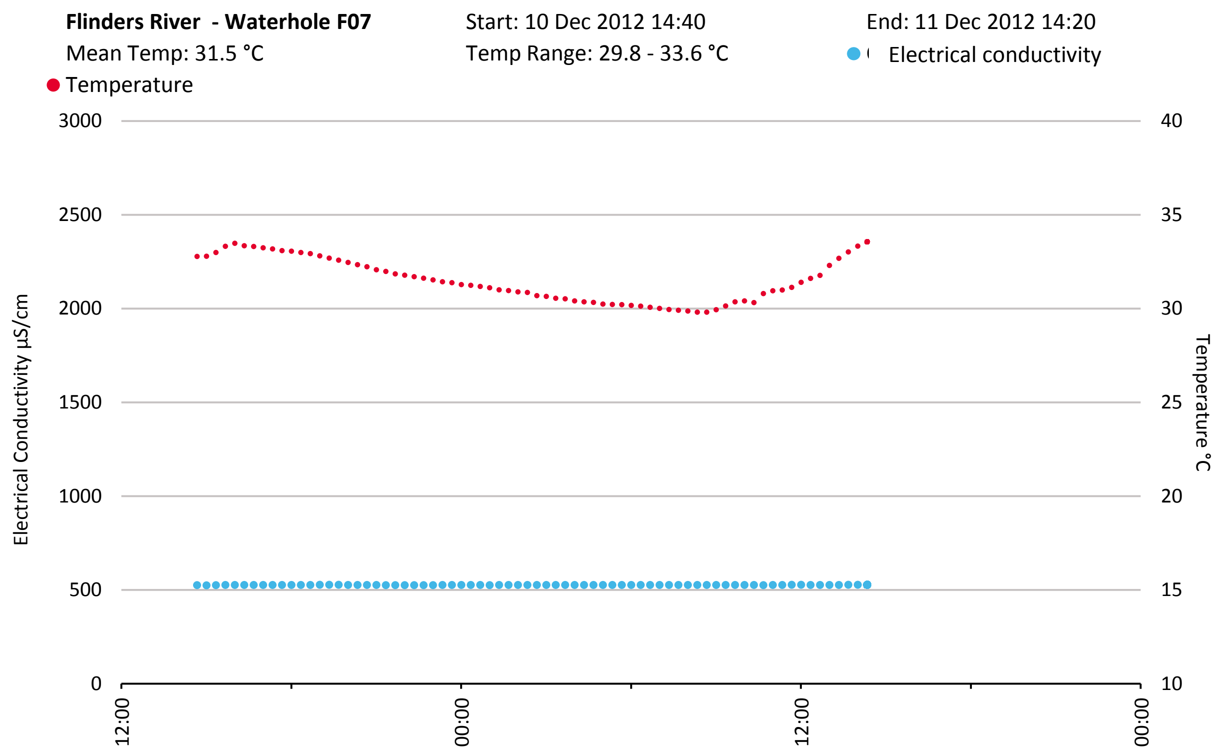
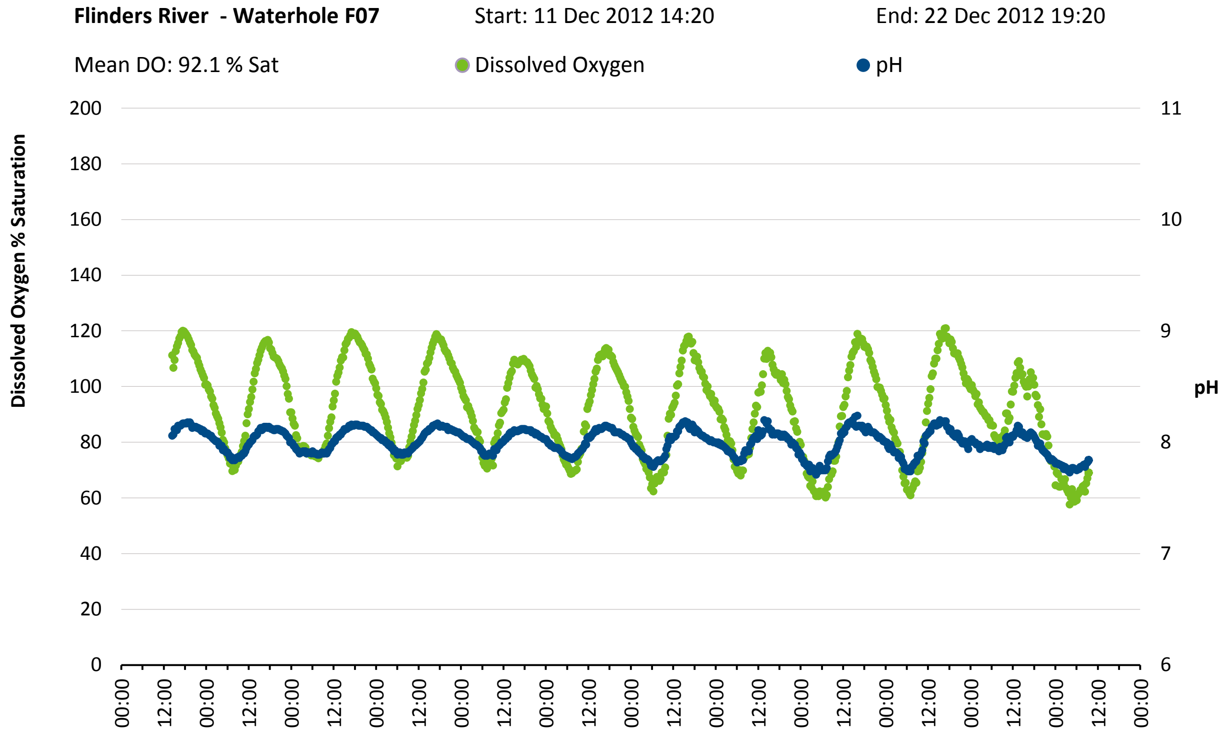


Figure 56 Diel physico chemical data for waterhole F07, Dec 2012



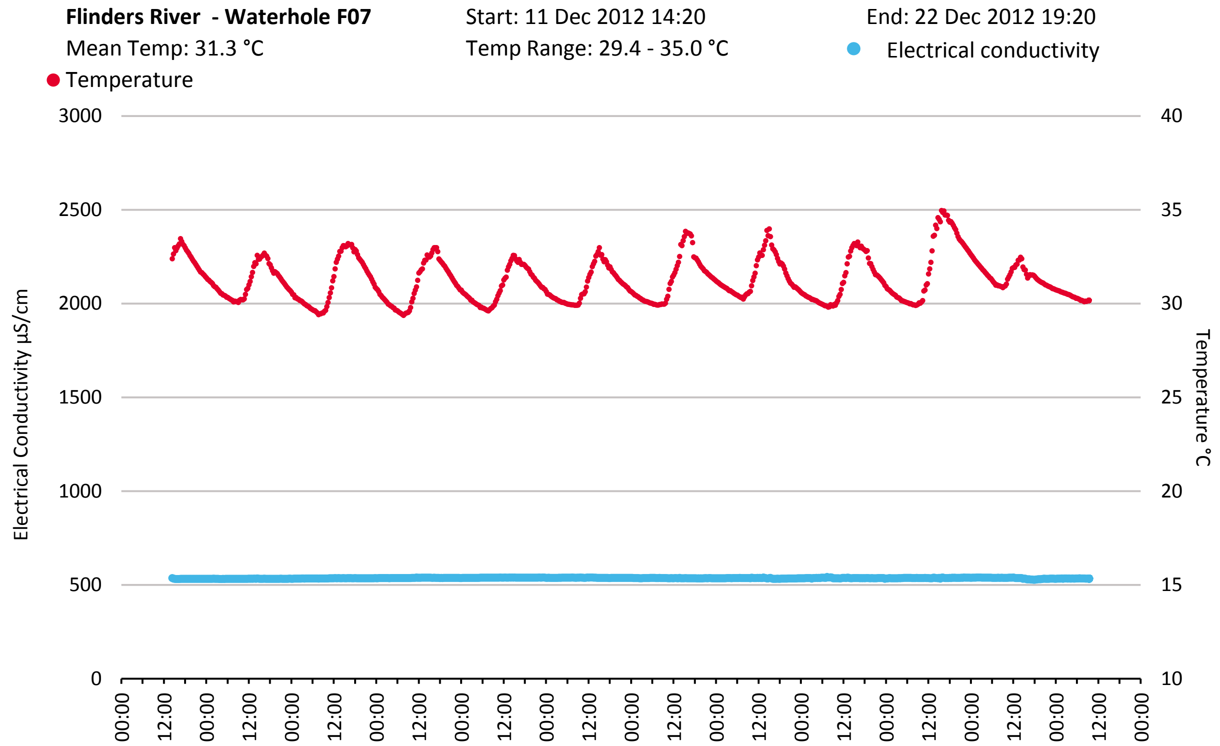
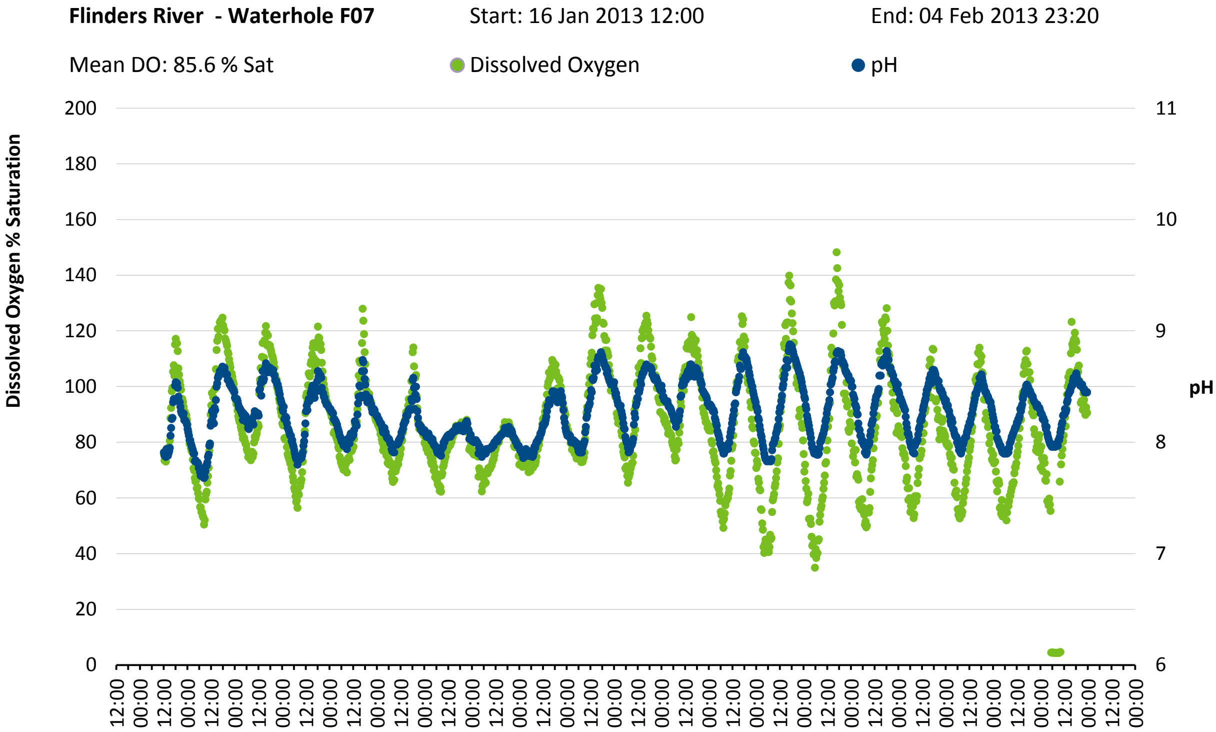


Figure 57 Diel physico chemical data for waterhole F07, Dec 2012. Logger deployed for a longer period of time in an attempt to catch a flow event



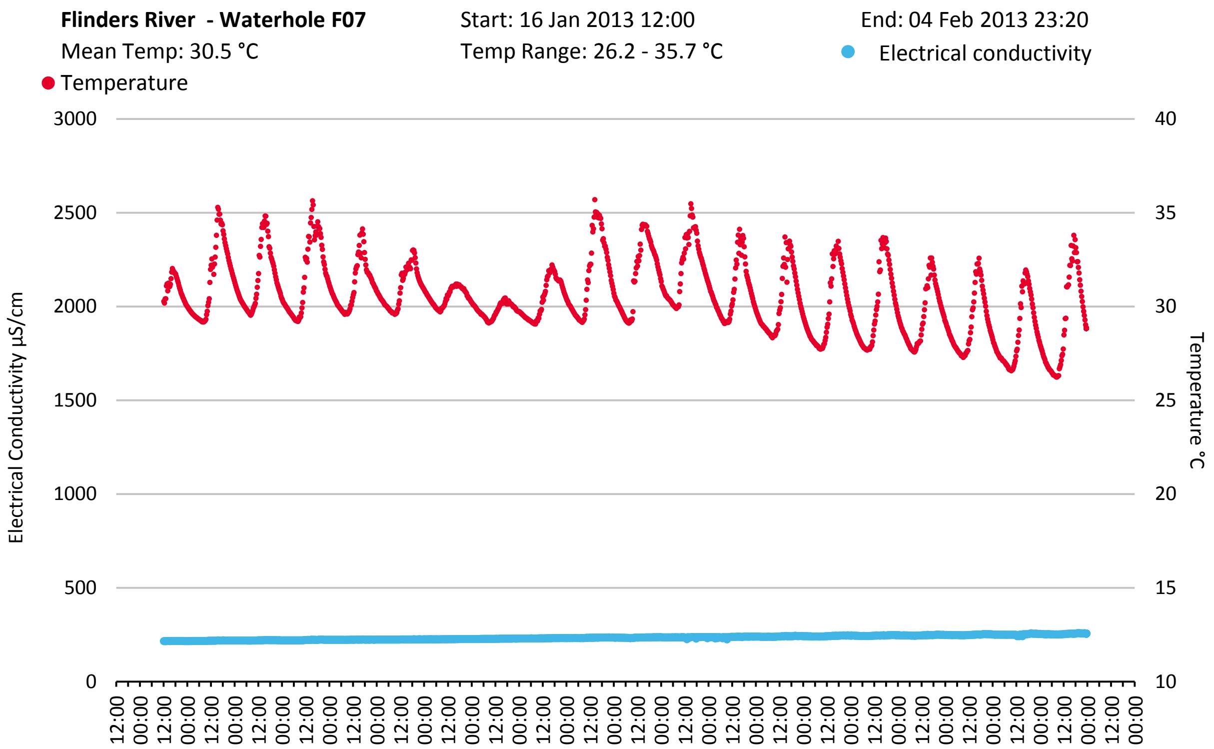


Figure 58 Diel physico chemical data for waterhole F07, Jan-Feb 2013. Logger deployed for a longer period of time in an attempt to catch a flow event

WATERHOLE F08

FEATURE	DESCRIPTION
Waterhole	F08
Catchment	Flinders River
Watercourse	Julia Creek
Waterhole location	-19.973491°, 141.521455°, Dalgonally Station
Waterhole elevation	~ 90 m (GoogleEarth elevation data, ± 30 m accuracy)
Dates surveyed	Survey 1: 9-Sept-12
	Survey 2: 25-Oct-12
	Survey 5: 11-Dec-12
	Survey 6: 20-Dec-12
	Survey 7: 15-Jan-13
	Survey 8: 22-Feb-13
	Survey 9: 30-May-13
Waterhole characteristics (measured from a ~450 m mid waterhole section during Oct 2012)	Surface area: ~25,300 m^2
	Waterhole volume: ~34,400 m^3
	Wetted perimeter: ~ 970 m
	Maximum depth: 2.56 m
	Average depth: 1.4 m
	Waterhole length: 450 m
Instream habitats	A large, silty waterhole, confined at the downstream end by a low barrage. Waterhole banks have a gradual incline. *Myriophyllum* sp. density was high along the waterhole margins, where the gradual bank slope provides adequate depth for colonisation. *Persicaria decipiens* were present in low numbers along waterhole margins. Algae were scarce across the Assessment, likely due to high turbidity.
Riparian zone	Couch grasses are present in the riparian zone, however high cattle access has removed the majority of the groundcover at this waterhole. *Acacia* species and scattered *Melaleuca* trees line the waterhole, but overall the riparian vegetation is narrow and low density.
Waterhole depth changes	Water depth declined steadily across the Assessment period.
Other notes	High levels of cattle traffic are evident along the waterhole. The downstream end of the waterhole is contained by the McIntyre weir and a road crossing. The waterhole was measured from GoogleEarth 2003 imagery to provide surface area and perimeter measurements for the entire waterhole area. Surface area was calculated at ~377,900 m^2, wetted perimeter at ~ 12,122 m.

a)

b)

Figure 59 a) GoogleEarth 2003 aerial view of F08. b) Left to right: 1) From left bank. 2) Couch grasses extending into the waterway. 3) Low water level, left bank. 4) Dense *Myriophyllum* growth, left bank

Figure 60 Bathymetry map of waterhole F08. Depth and waterhole perimeter data generated from data collected Oct 2012. This waterhole extended upstream and downstream from this mapped area

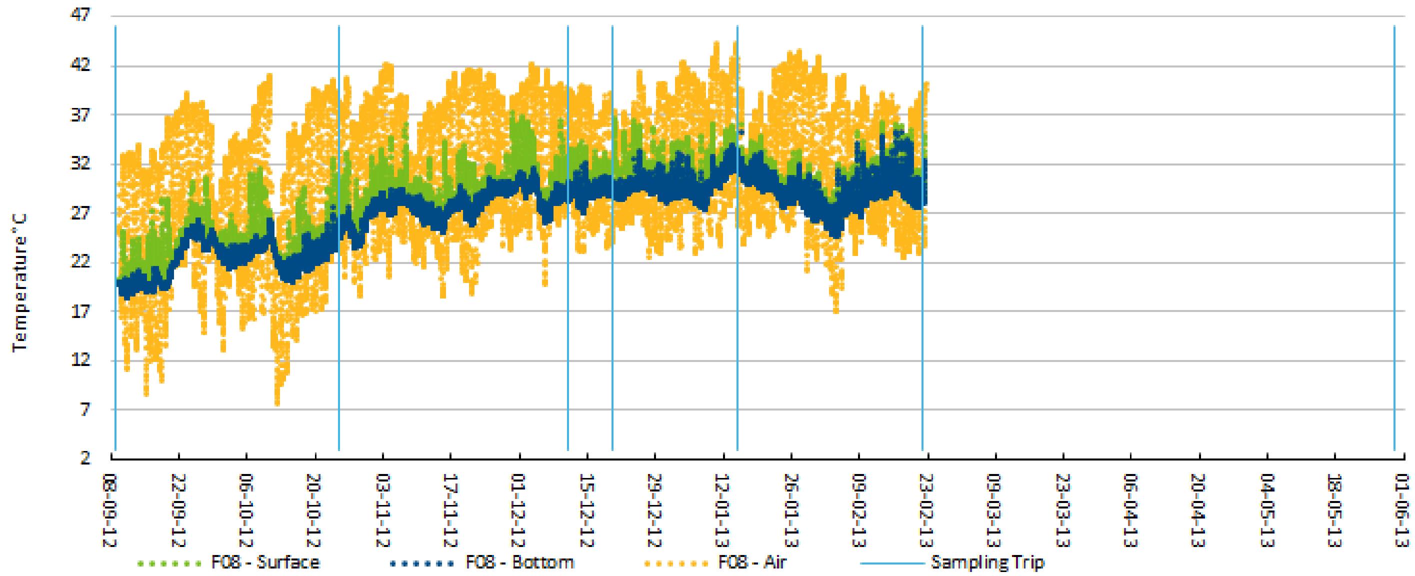
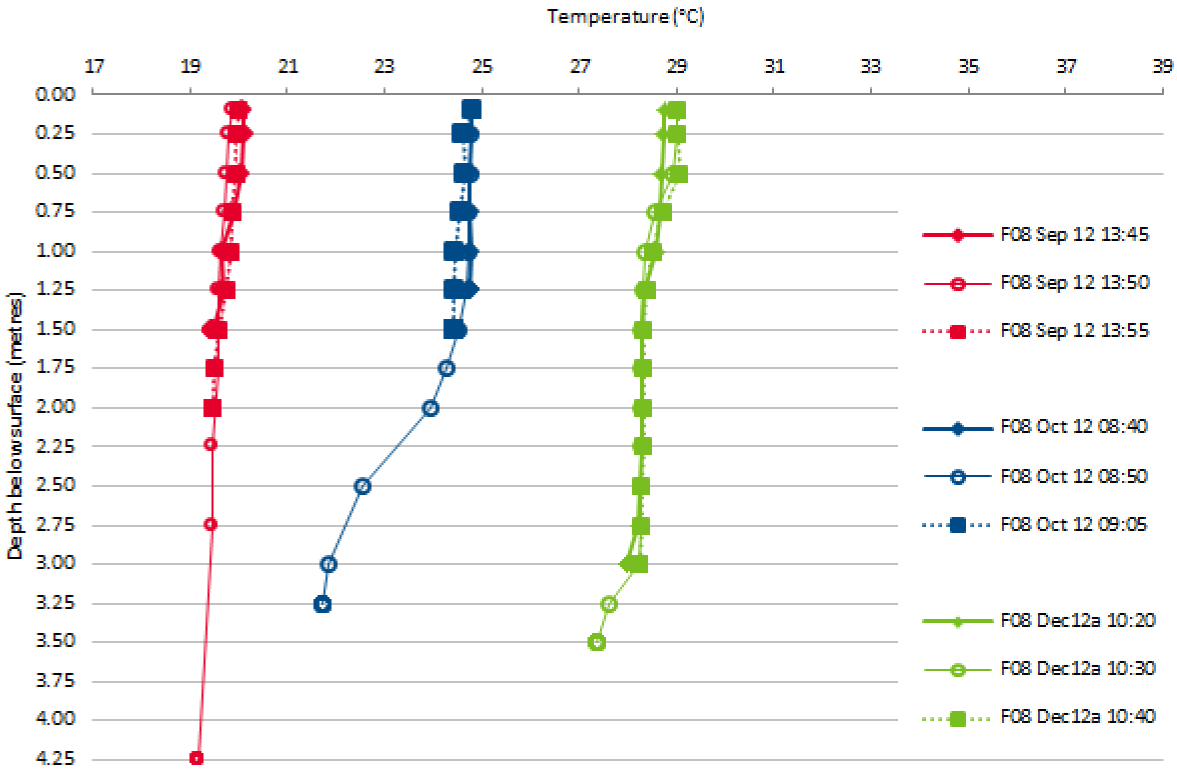


Figure 61 Long term temperature logger data for waterhole F08. Logger malfunction following February 2013

Table 7 Continuous water and air temperature logger summary statistics for each survey at waterhole F08.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5°C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Sep 12	10-09-12 00:15	14-09-12 00:15	4	11.1	23.6	34.0	18.7	20.6	25.0	18.5	19.6	21.2	0.0	1.1	6.0	43.3	30.8	24.9
Oct 12	25-10-12 00:15	28-10-12 00:15	3	20.5	30.6	40.8	24.6	27.1	33.1	24.4	25.7	27.7	0.0	1.4	7.3	56.0	40.3	31.9
Dec12a	10-12-12 00:15	13-12-12 00:15	3	26.7	33.5	39.7	28.5	30.3	33.5	28.3	29.2	31.1	0.0	1.2	4.0	54.4	40.1	31.3
Dec12b	20-12-12 00:15	23-12-12 00:15	3	24.2	30.3	37.4	28.6	30.4	36.7	28.4	29.2	30.4	0.0	1.3	7.1	43.8	29.0	26.7
Jan 13	14-01-13 00:15	17-01-13 00:15	3	23.9	32.2	44.2	30.5	32.1	36.1	30.3	31.7	35.3	-0.1	0.4	2.5	33.2	14.0	4.7
Feb 13	20-02-13 00:15	22-02-13 00:15	2	23.0	31.9	39.3	27.6	29.1	31.4	27.6	28.9	30.7	-0.2	0.3	1.3	32.4	1.4	0.0



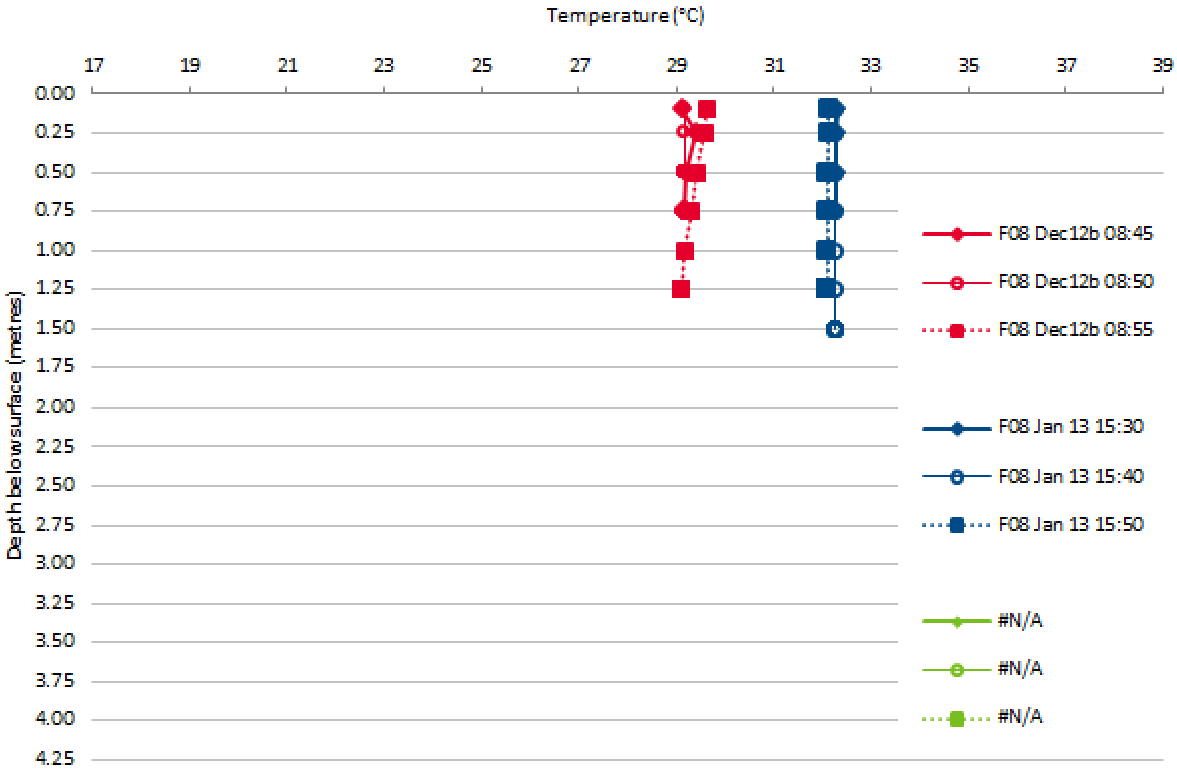


Figure 62 Temperature vertical water column profiles at waterhole F08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

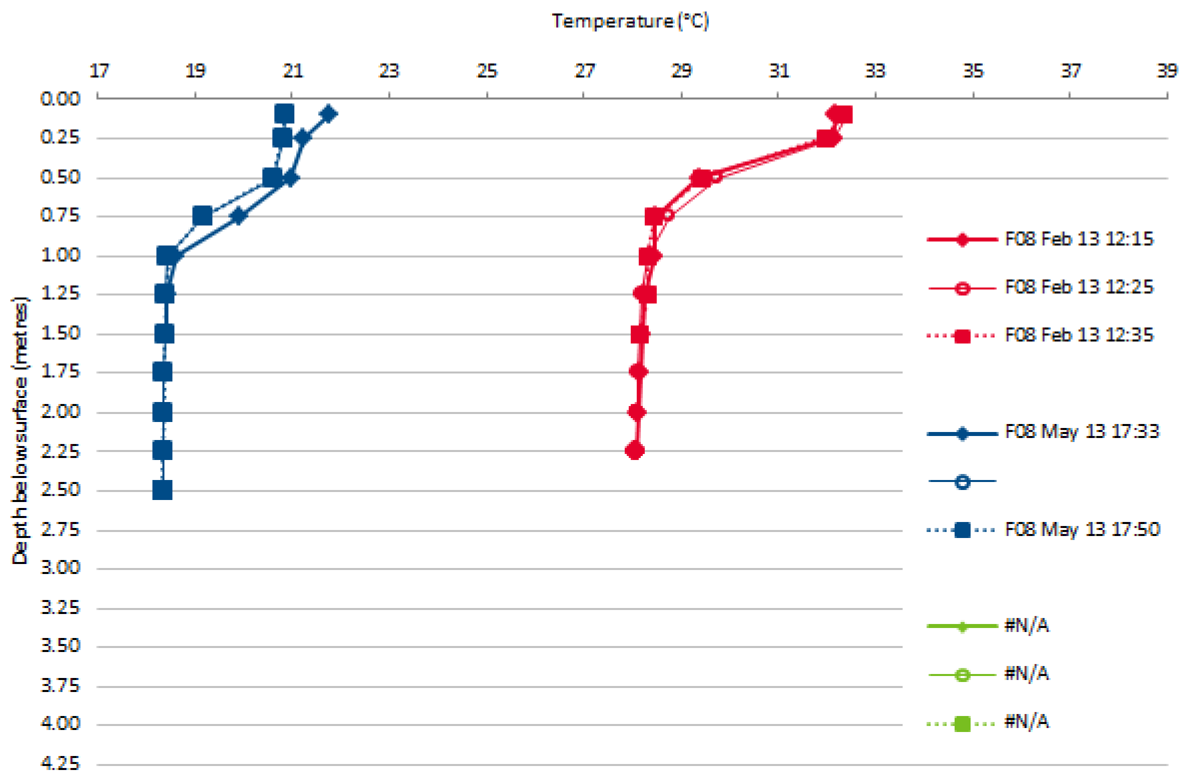


Figure 63 Temperature vertical water column profiles at waterhole F08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

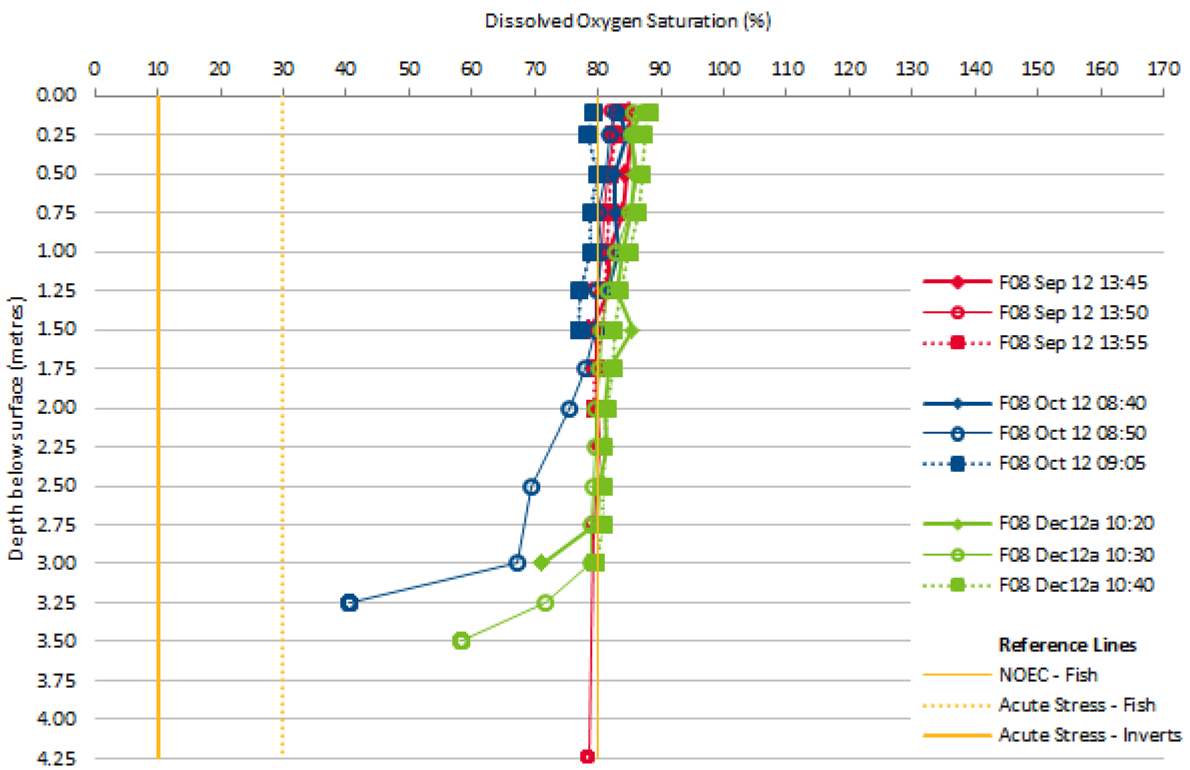
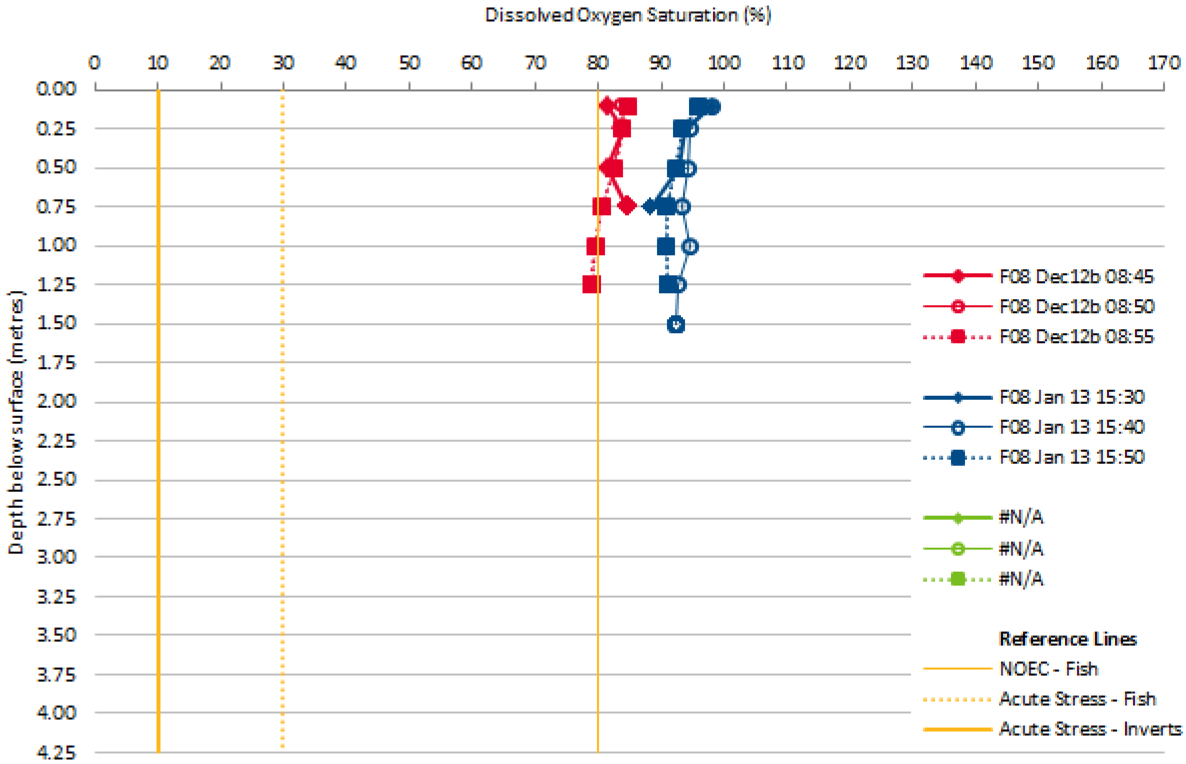


Figure 64 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F08. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



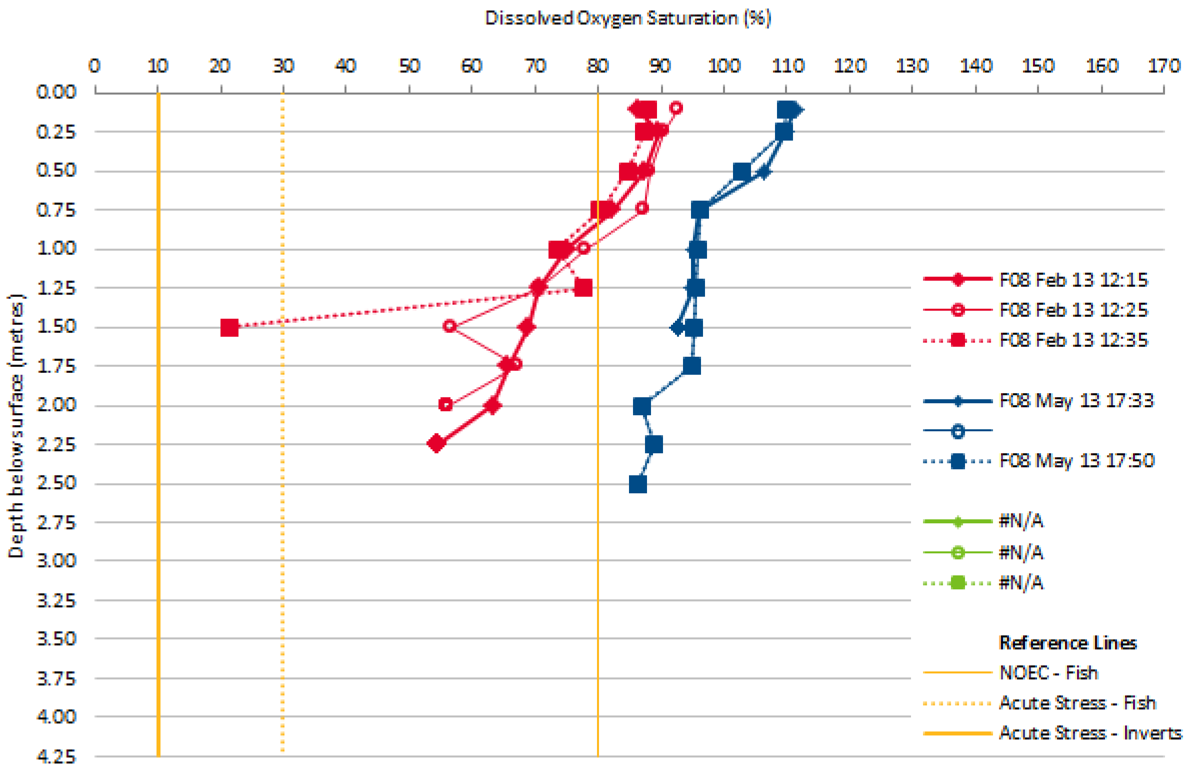
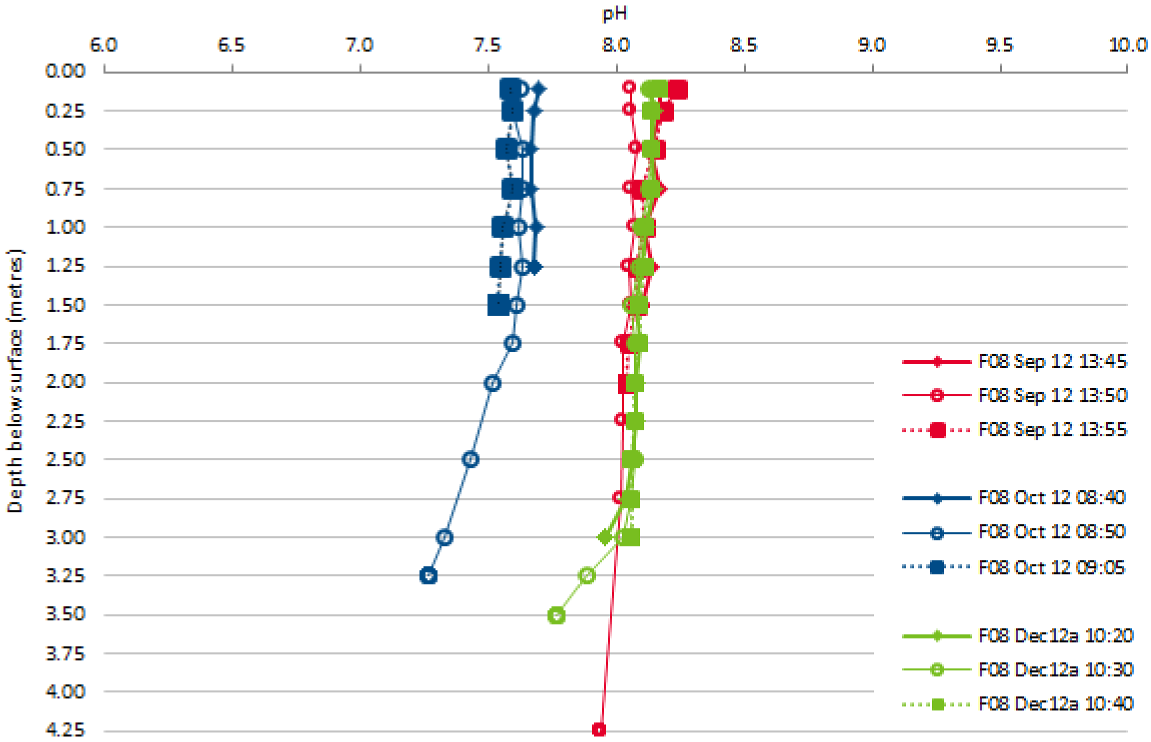


Figure 65 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F08. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



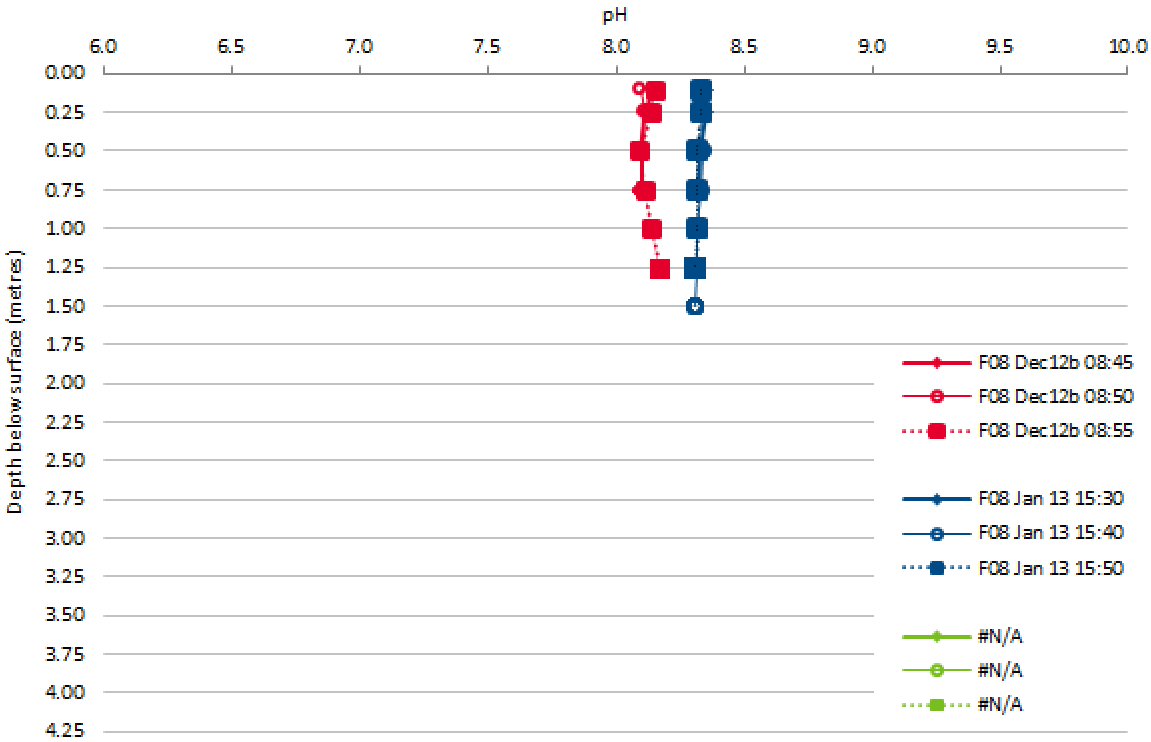


Figure 66 pH vertical water column profiles at waterhole F08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

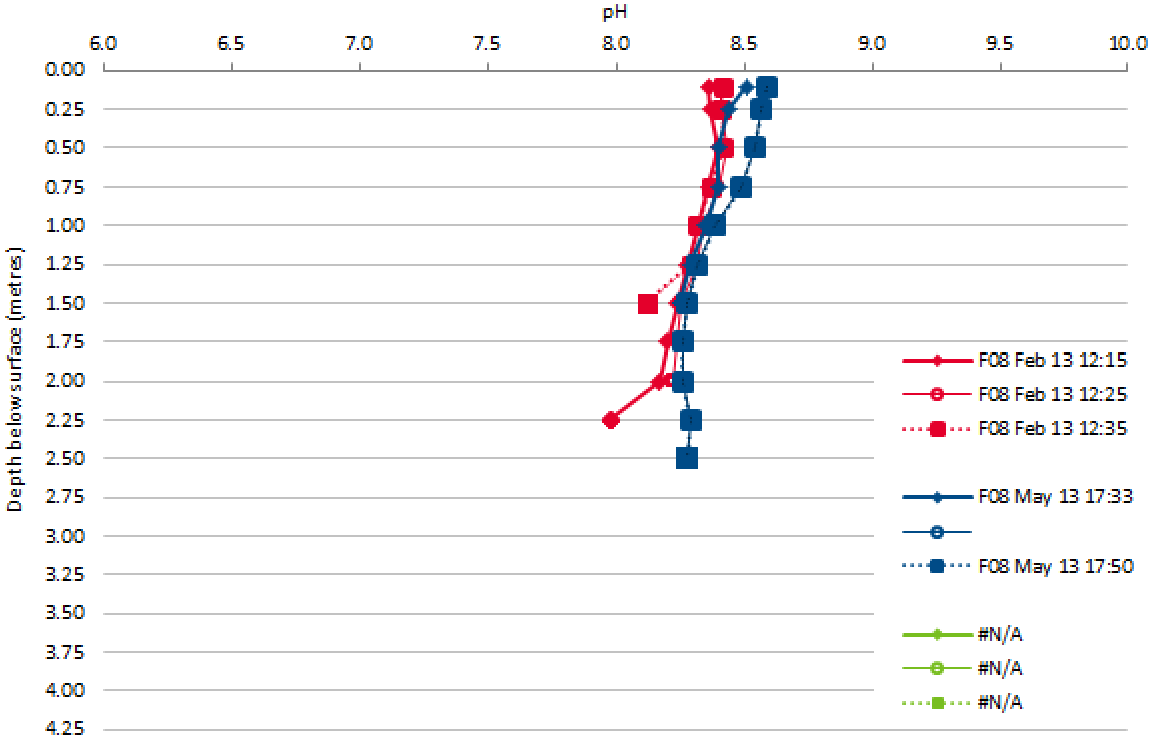
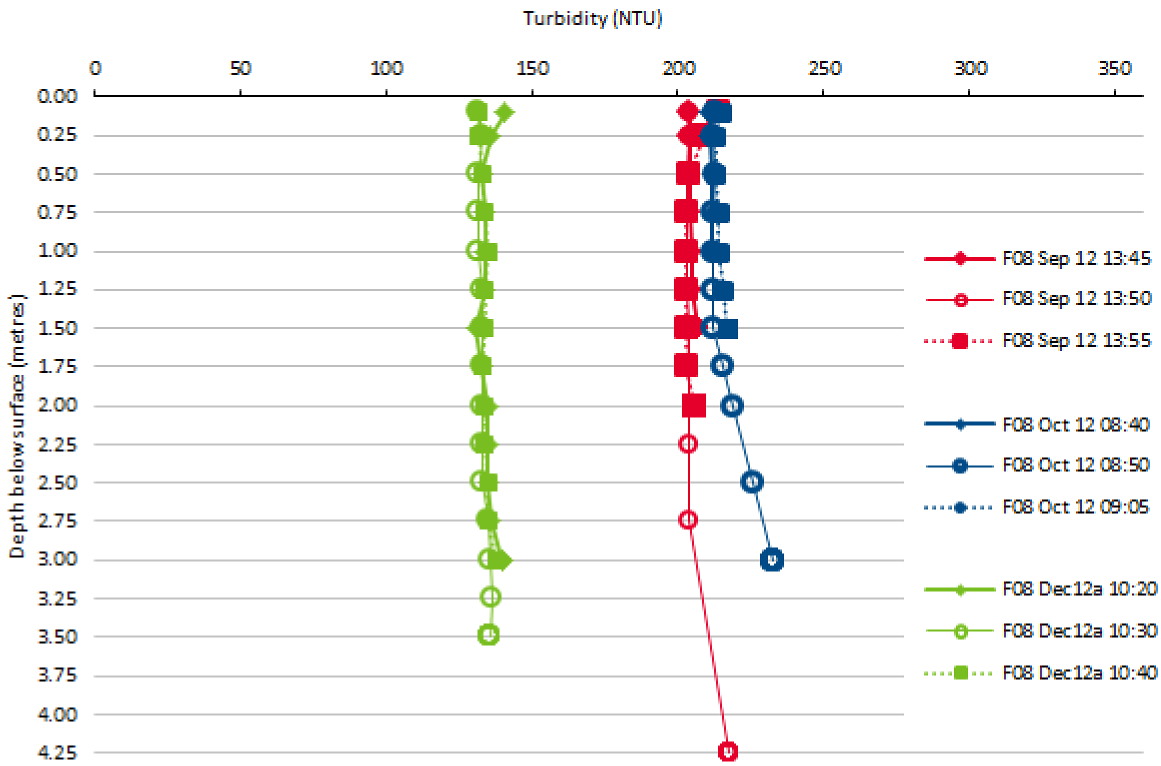


Figure 67 pH vertical water column profiles at waterhole F08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



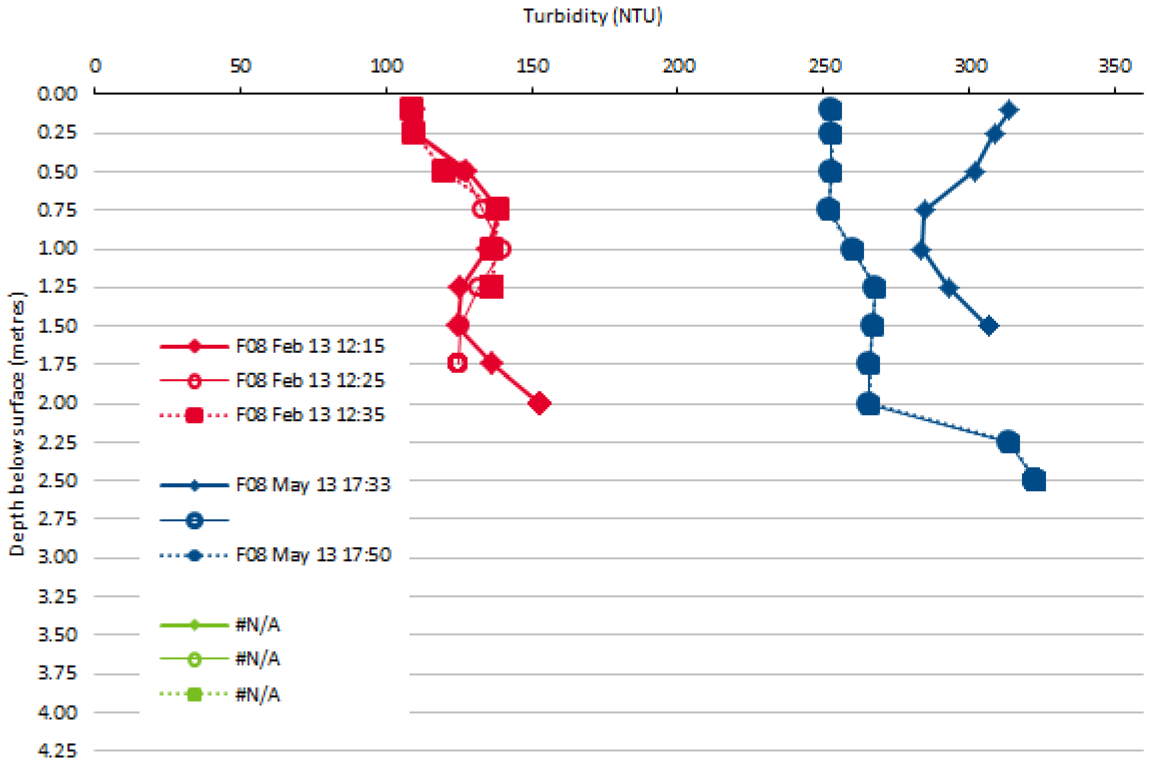
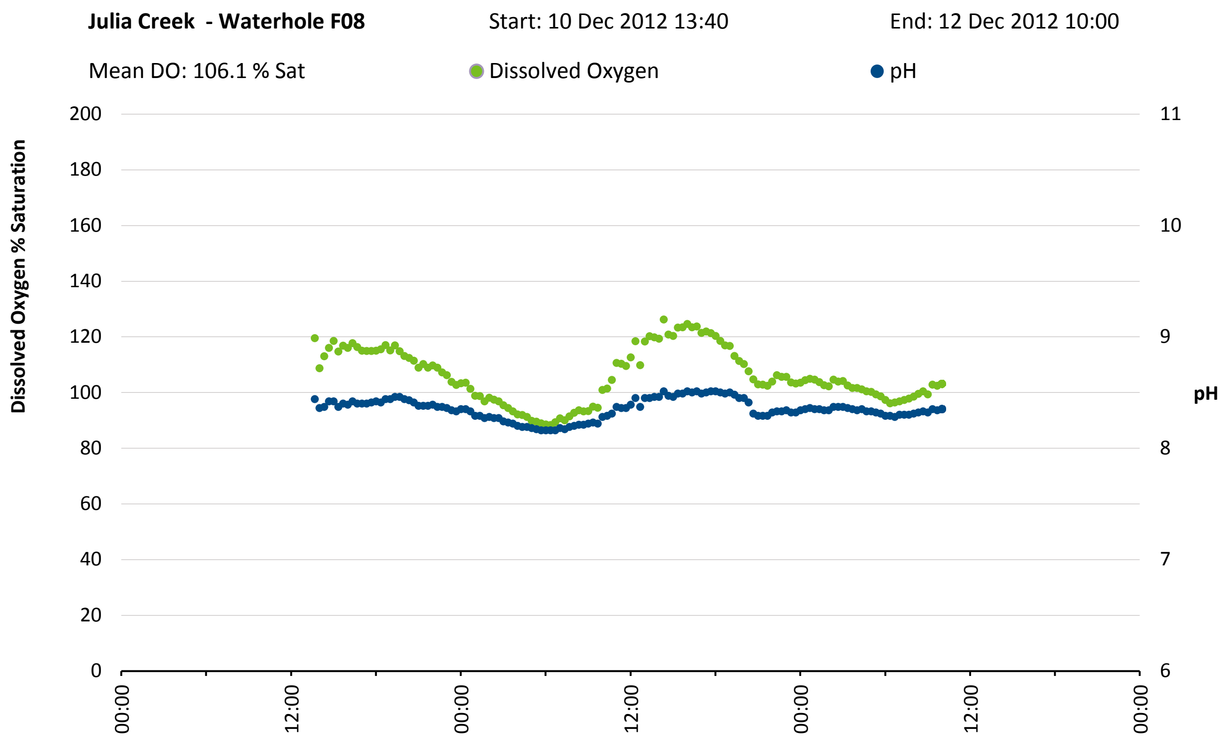


Figure 68 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



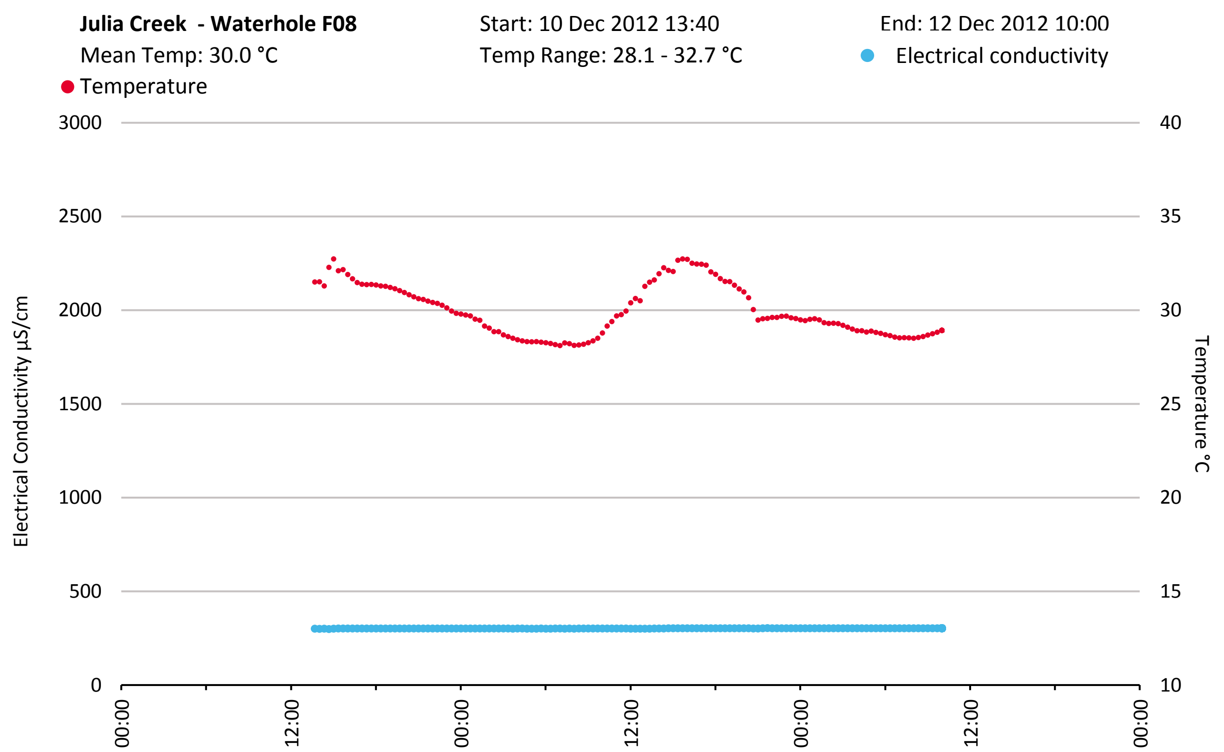
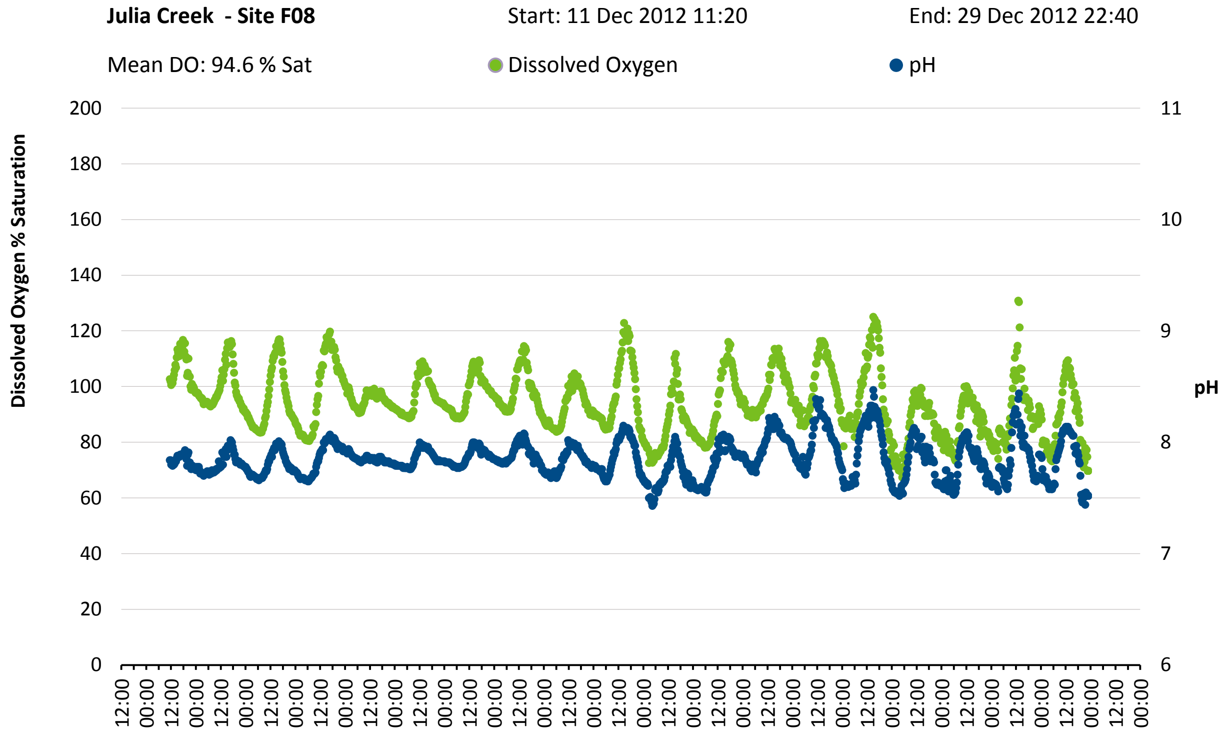


Figure 69 Diel physico chemical data for waterhole F08, Dec 2012



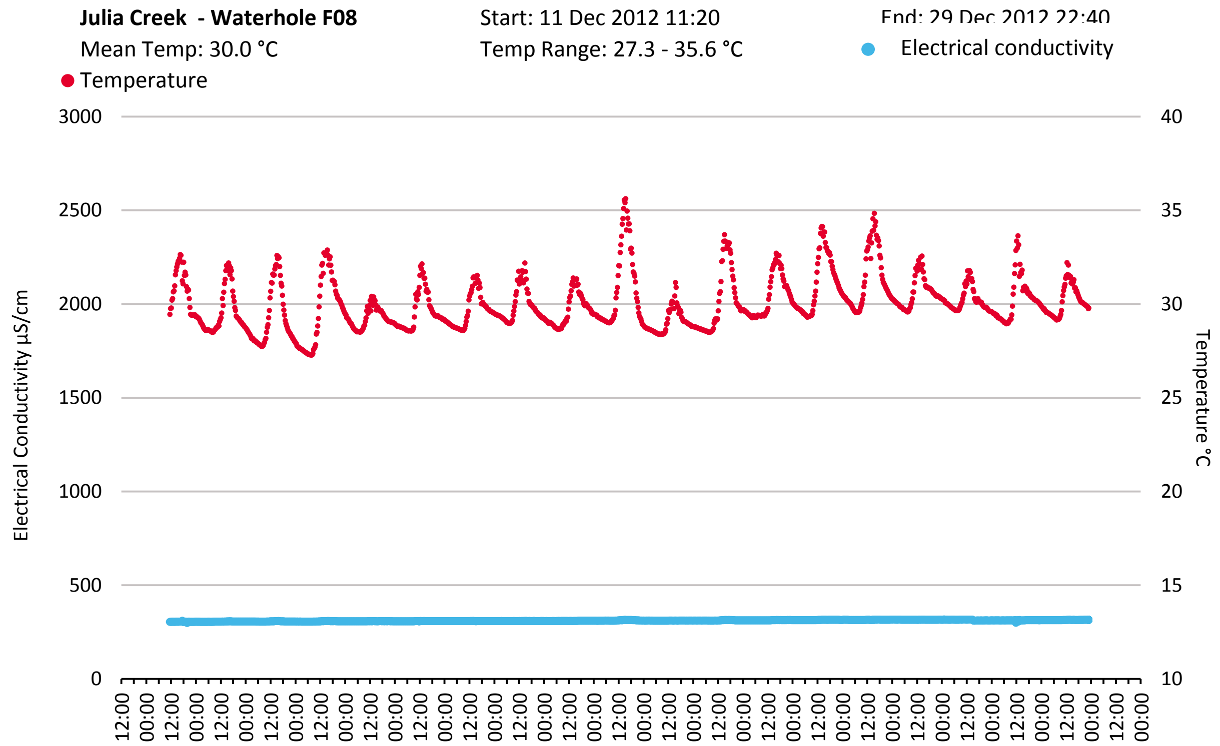


Figure 70 Diel physico chemical data for waterhole F08, Dec 2012. Logger deployed for a longer period of time in an attempt to catch a flow event

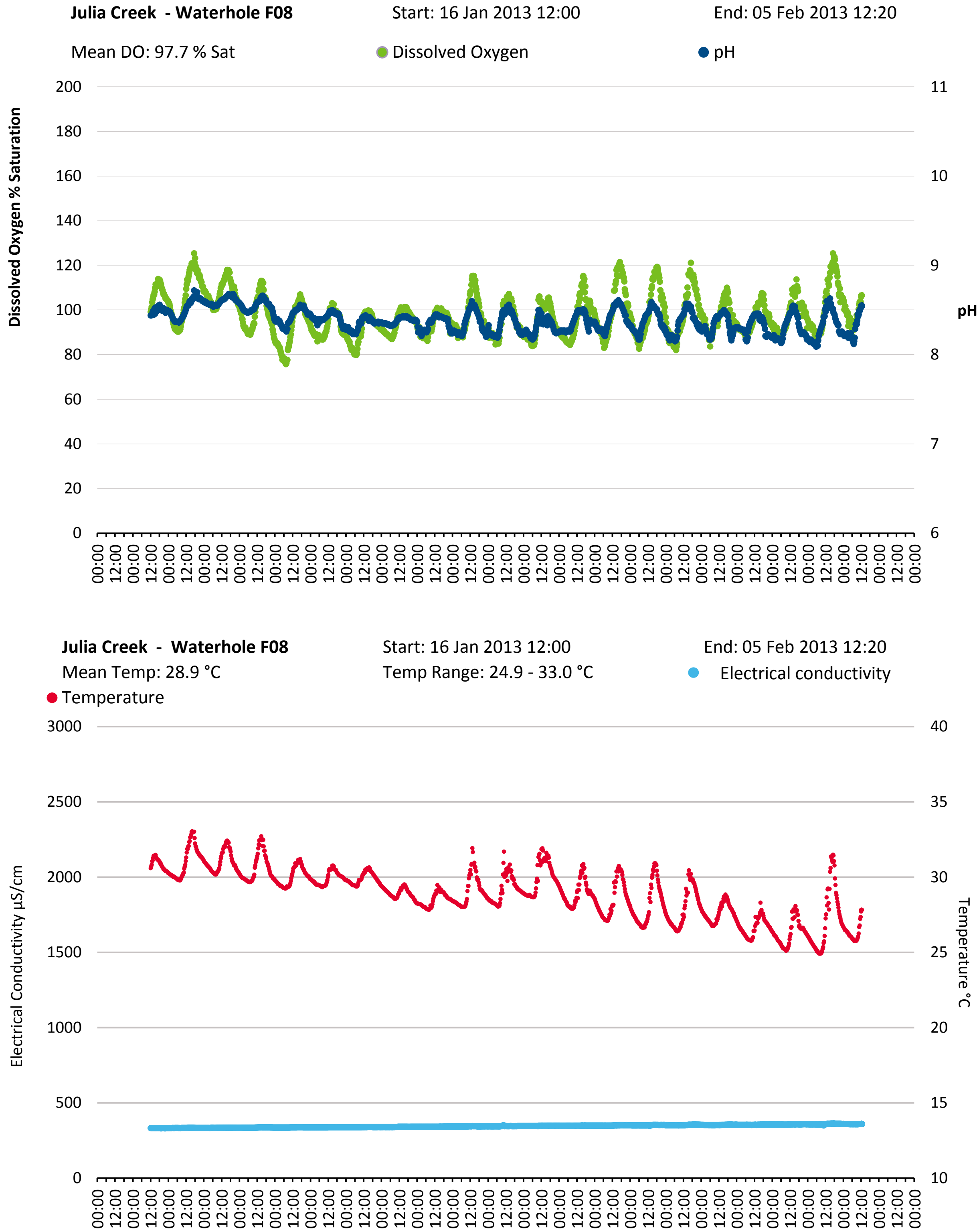


Figure 71 Diel physico chemical data for waterhole F08, Jan-Feb 2013. Logger deployed for a longer period of time in an attempt to catch a flow event

WATERHOLE F09

FEATURE	DESCRIPTION
Waterhole	F09
Catchment	Flinders River
Watercourse	Cloncurry River
Waterhole location	-20.045600°, 141.088433°
Waterhole elevation	~ 100 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 10-Sept-12
	Survey 2: 26-Oct-12
	Survey 5: 10-Dec-12
	Survey 6: 20-Dec-12
	Survey 7: 15-Jan-13
	Survey 9: 30-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~38,000 m^2
	Waterhole volume: ~36,700 m^3
	Wetted perimeter: ~ 1300 m
	Maximum depth: 2 m
	Average depth: 1 m
	Waterhole length: 570 m
Instream habitats	A sand bottom waterhole with bedrock at the downstream end. Steep banks with fallen trees provide woody debris along the right side of the waterhole. Epilithic algal density was moderate. No aquatic macrophytes were identified.
Riparian zone	Riparian cover on the left bank was low due to cattle access points. On the right bank couch grasses offer ground cover, and large *Melaleuca* trees line the bank. Overall canopy cover along this right bank is quite high, and offers significant shade across half the waterhole area.
Waterhole depth changes	Water depth declined steadily to December 2012. Maximum depth increased by 1 m during January 2013 then reduced steadily again to May 2013.
Other notes	Cattle access damage is evident along the right bank and within the waterhole area upstream.

a)

b)

Figure 72 a) GoogleEarth 2003 aerial view of F09. b) Left to right: 1) Rocky substrate, downstream waterhole end. 2) From mounted camera, right bank. 3) Upstream from right bank. 4) From mounted camera

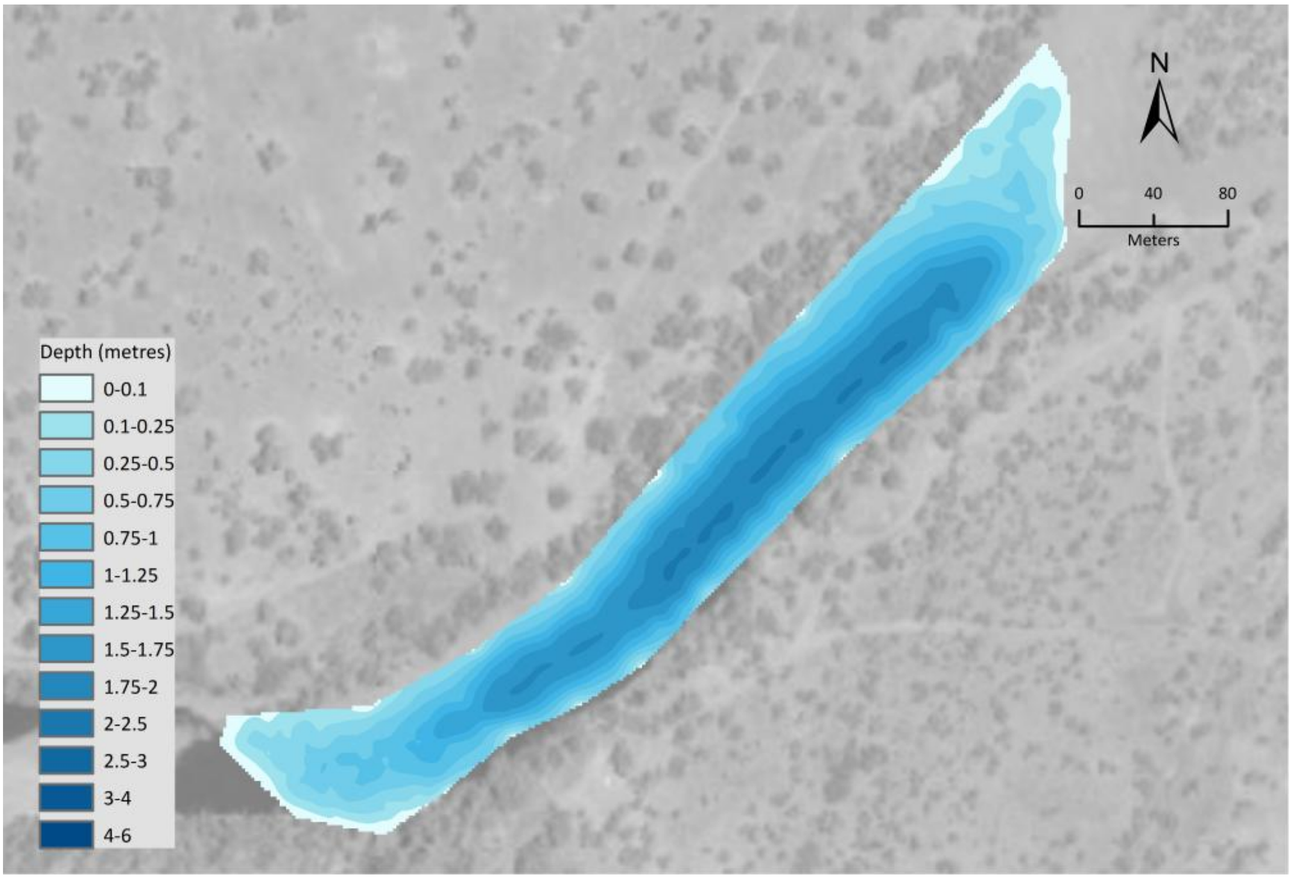


Figure 73 Bathymetry map of waterhole F09. Depth and waterhole perimeter data generated from data collected Oct 2012

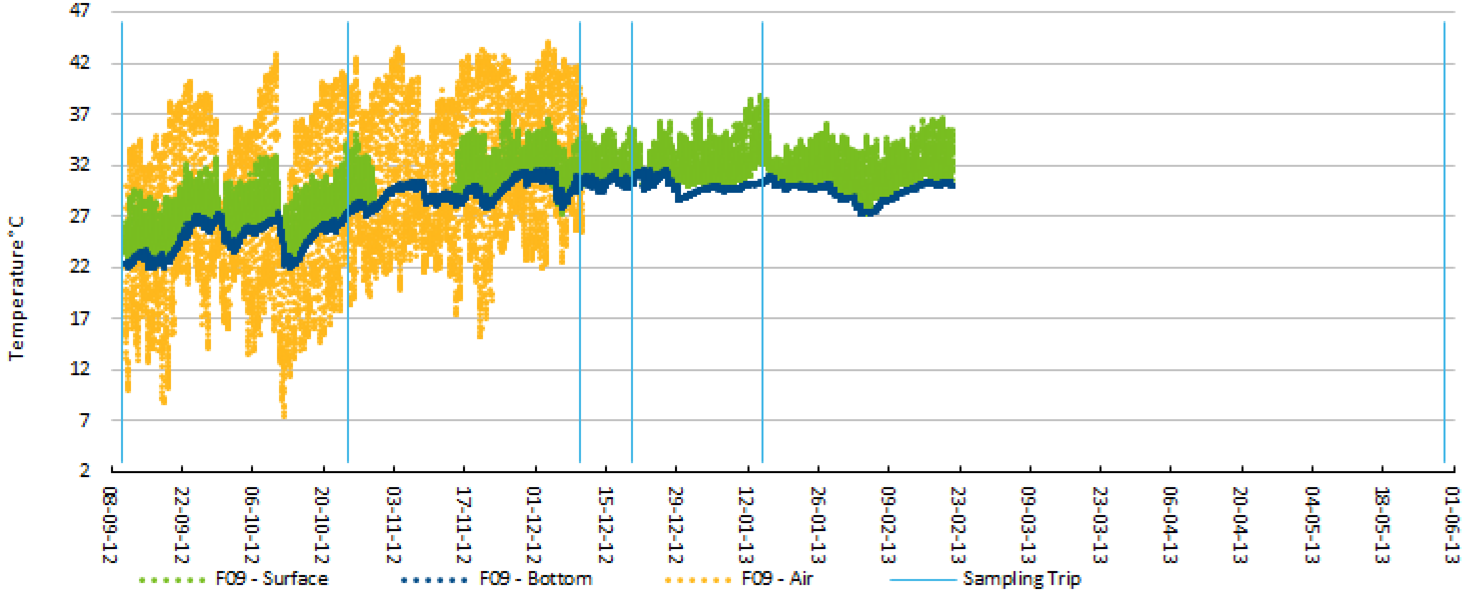
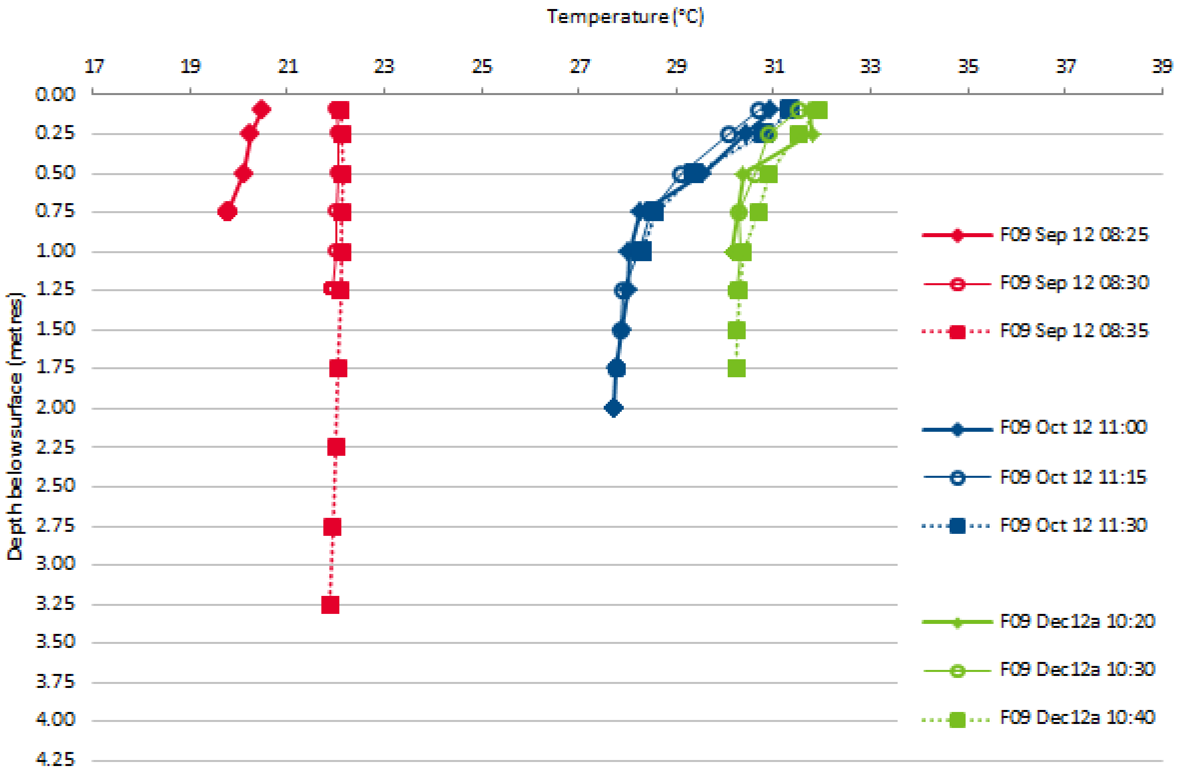


Figure 74 Long term temperature logger data for waterhole F09. Air temperature logger malfunction in December 2012, water loggers in February 2013

Table 8 Continuous water and air temperature logger summary statistics for each survey at waterhole F09.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5°C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Sep 12	12-09-12 00:15	19-09-12 00:15	7	8.8	23.3	34.9	22.2	25.1	29.6	21.9	22.8	23.7	0.1	2.3	6.6	79.0	68.7	58.8
Oct 12	18-10-12 00:15	23-10-12 00:15	5	14.7	28.4	40.4	25.3	27.8	31.6	25.1	25.8	26.6	0.0	1.9	5.7	77.4	63.8	54.3
Dec12a	05-12-12 00:15	08-12-12 00:15	3	22.6	33.5	42.4	27.3	30.5	33.6	27.9	28.9	31.2	-0.6	1.6	5.3	64.5	57.1	50.7
Dec12b	20-12-12 00:15	21-12-12 00:15	1	-	-	-	30.6	32.5	35.4	30.3	30.6	31.1	0.0	1.9	4.9	75.3	60.3	53.4
Jan 13	06-01-13 00:15	14-01-13 00:15	8	-	-	-	29.9	32.7	38.5	29.5	29.9	30.3	0.1	2.9	8.2	94.6	79.7	68.3



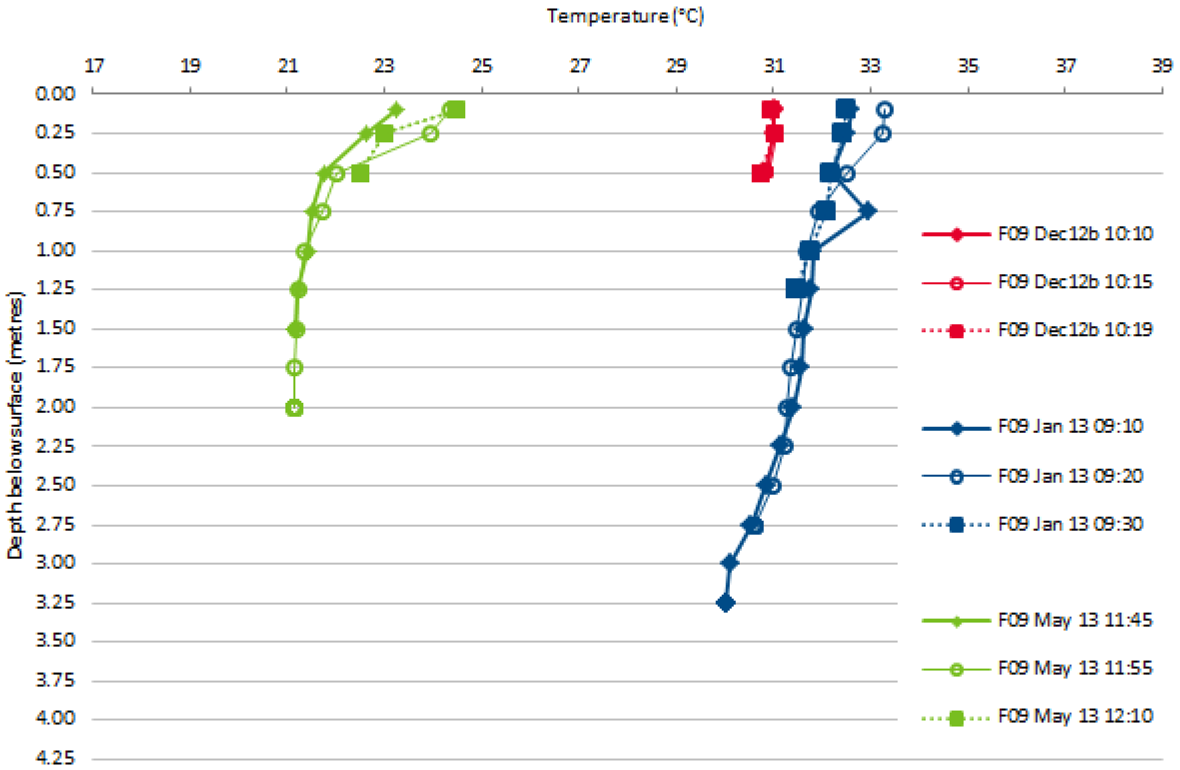
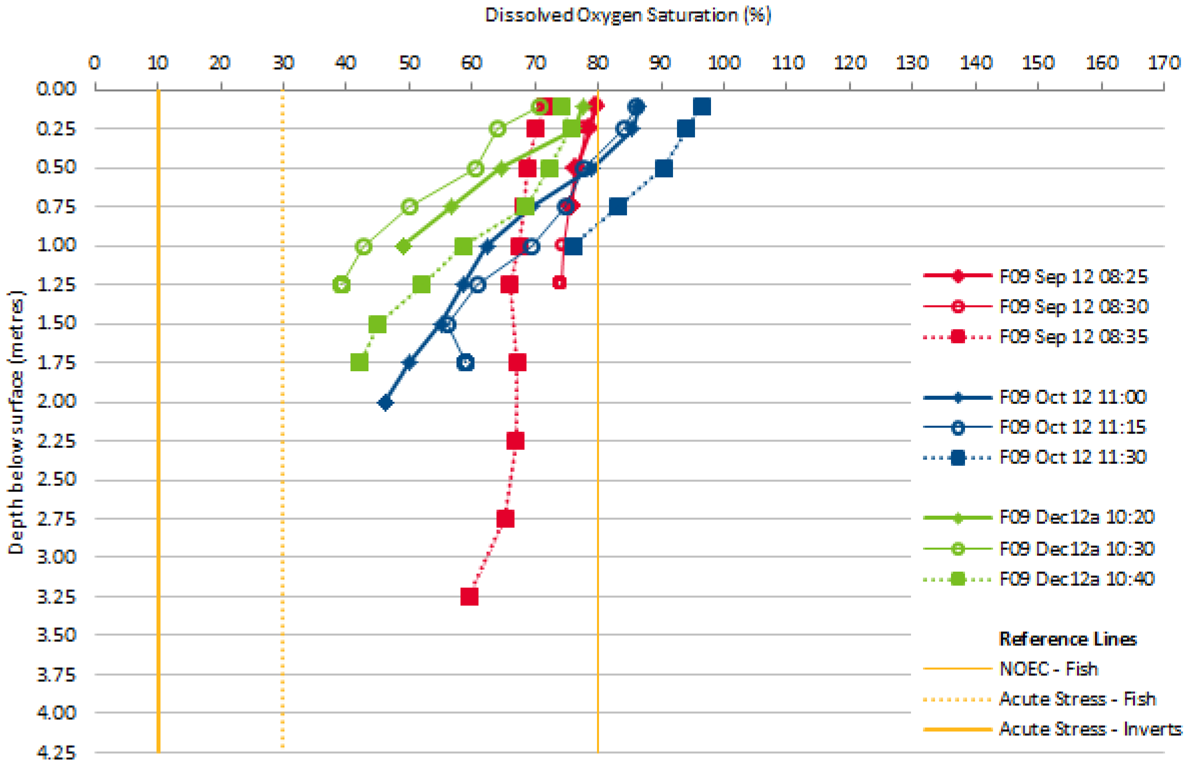


Figure 75 Temperature vertical water column profiles at waterhole F09. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



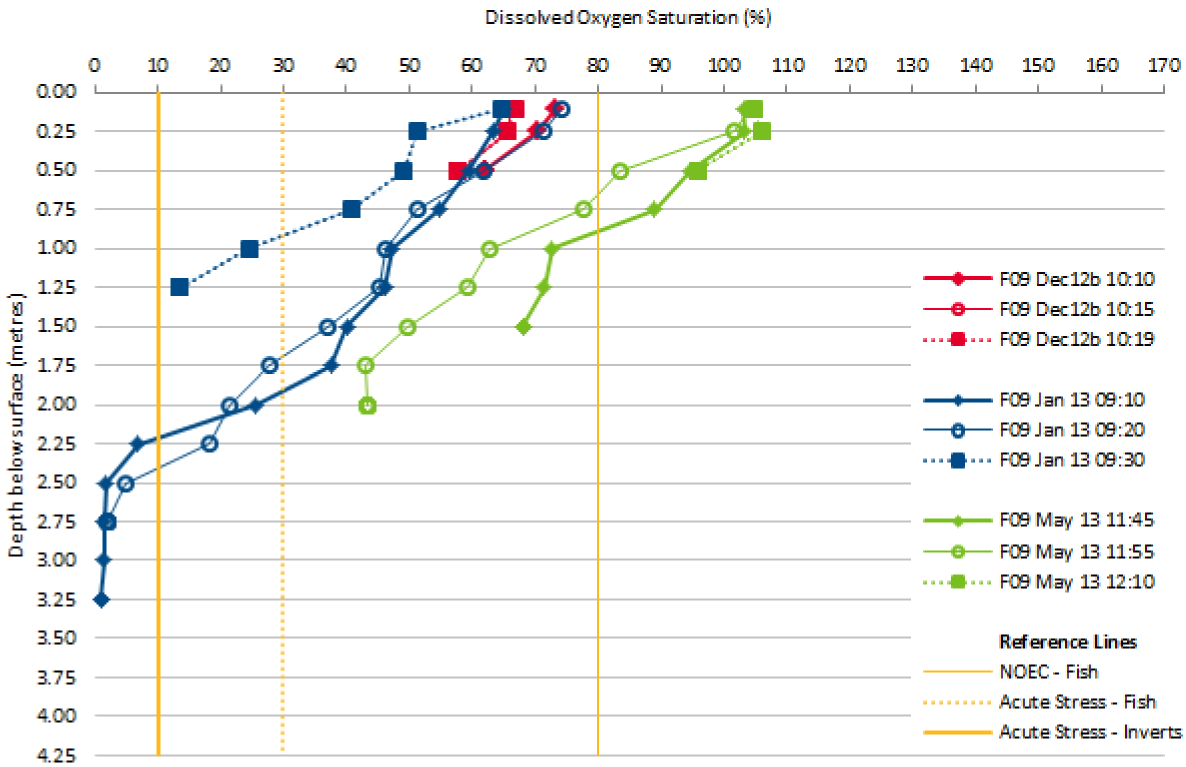
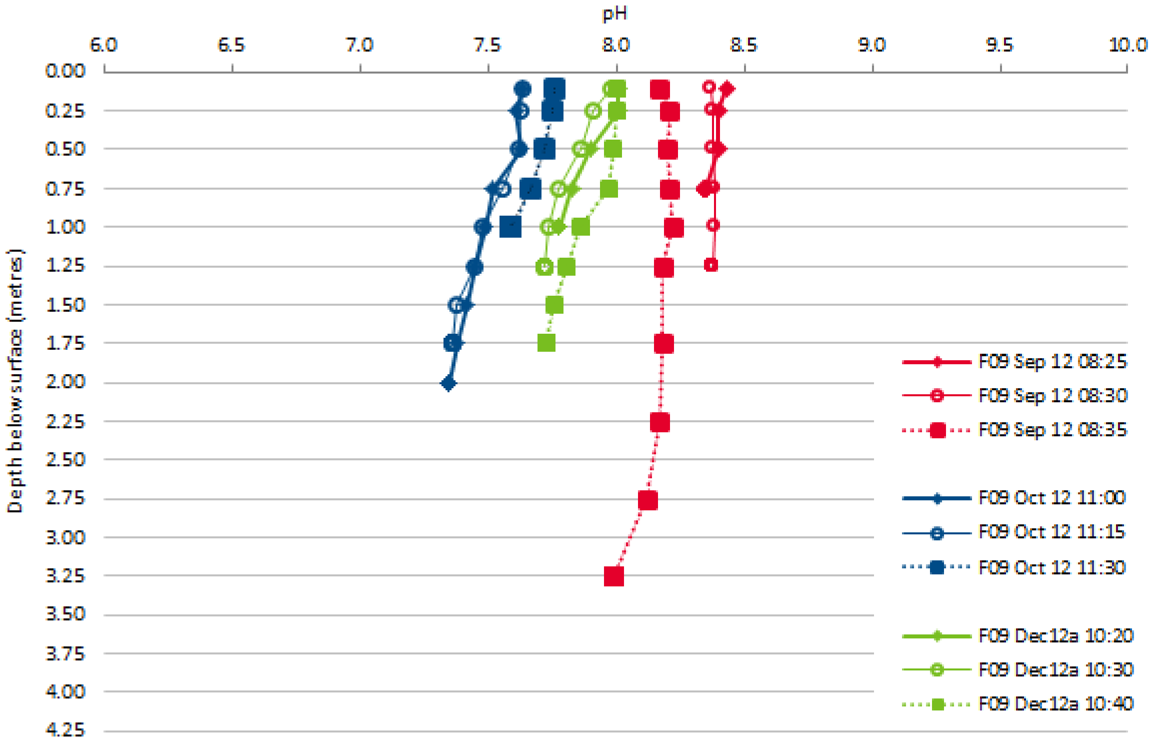


Figure 76 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F09. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



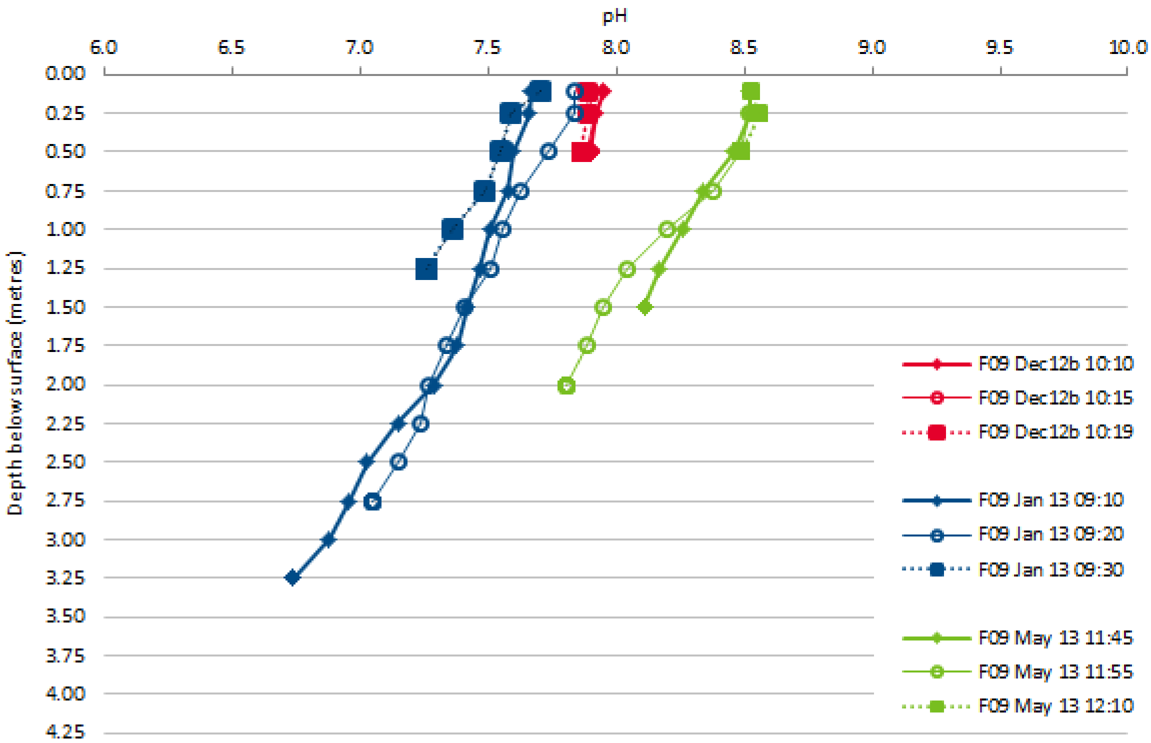
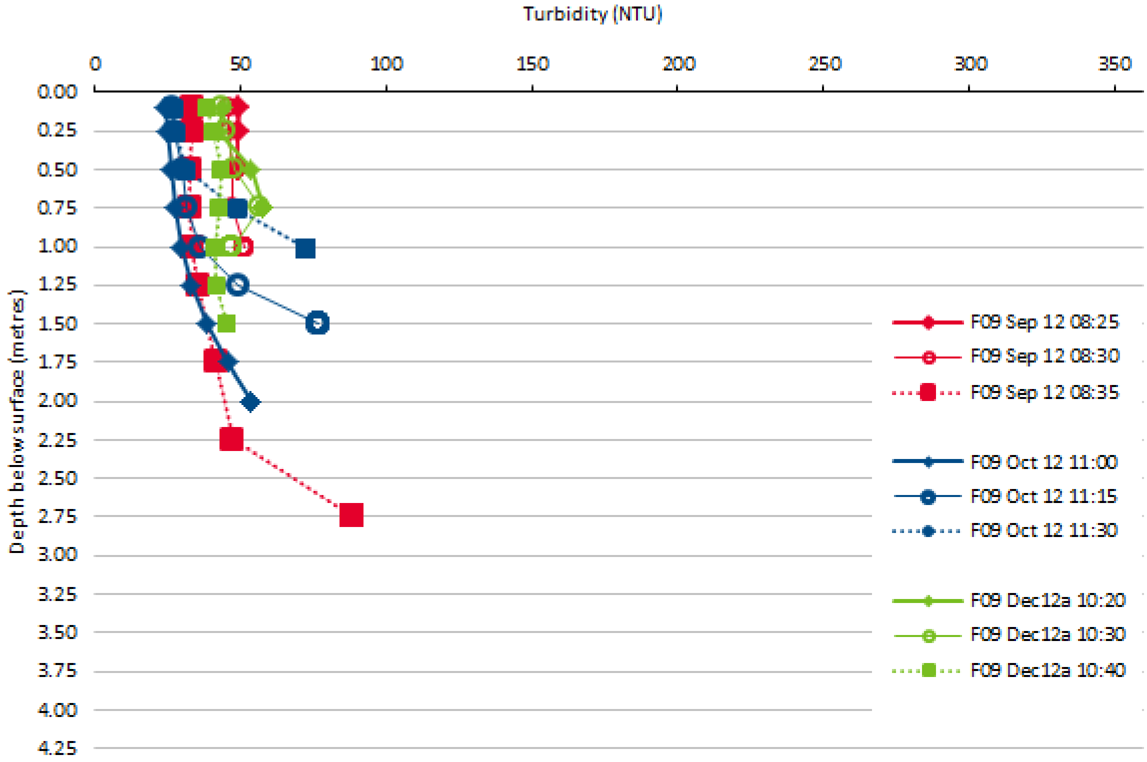


Figure 77 pH vertical water column profiles at waterhole F09. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



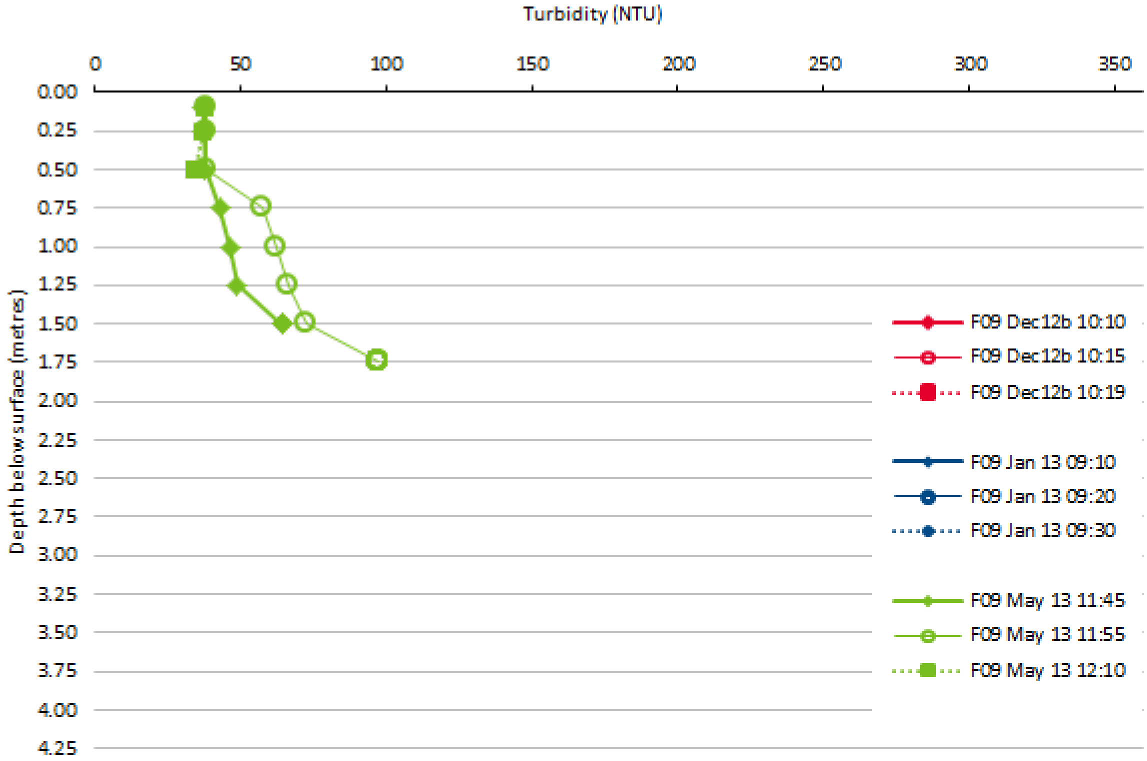


Figure 78 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F09. No turbidity data was collected on surveys Dec 12b or Jan 13. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

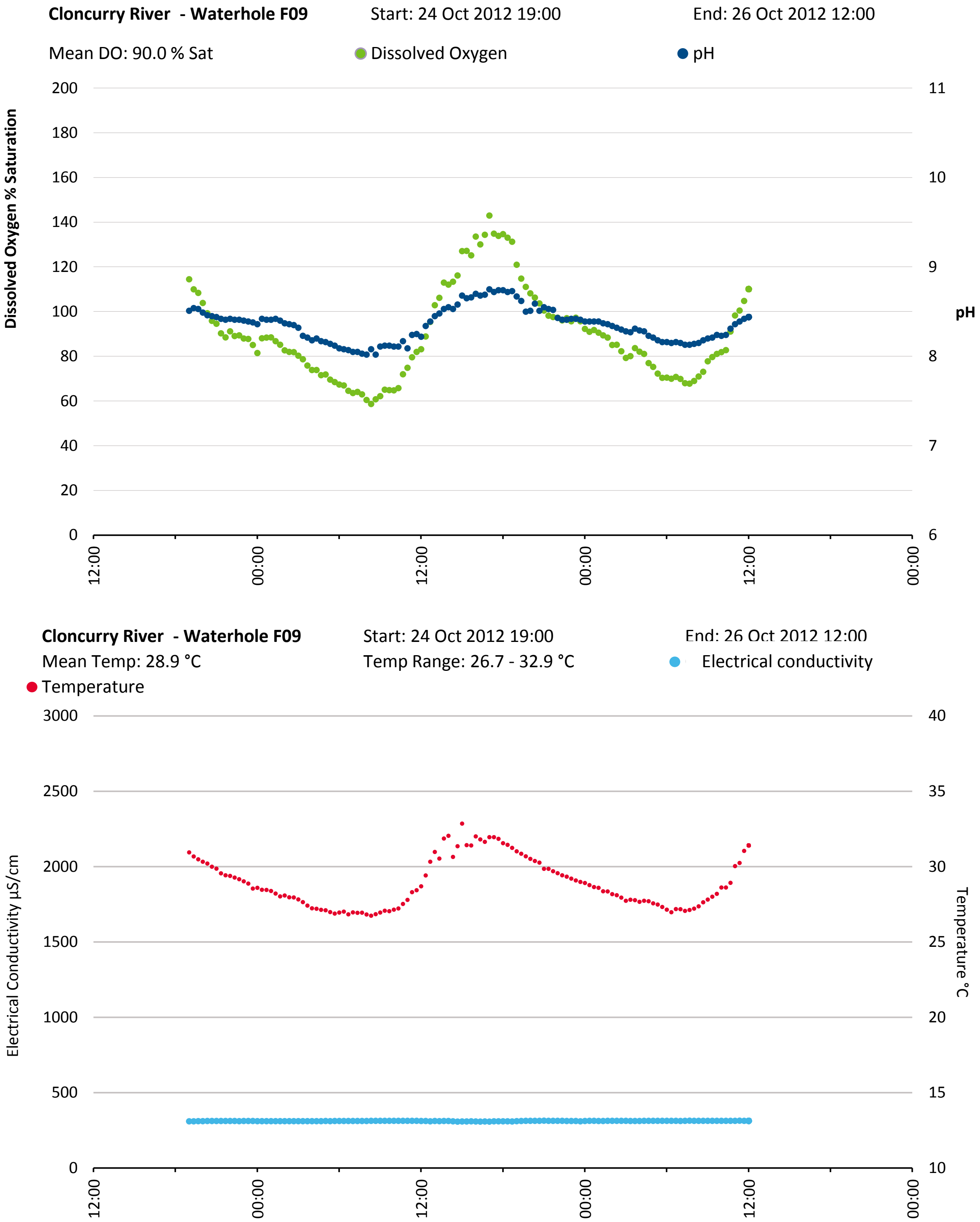
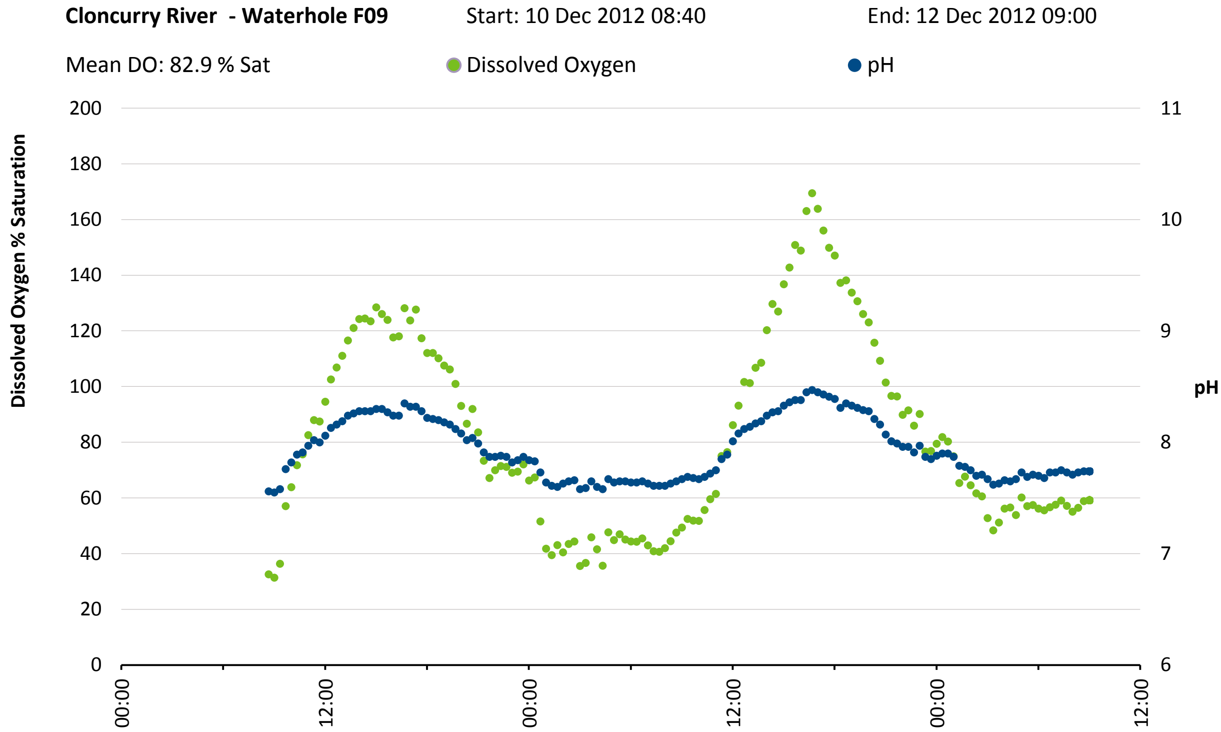


Figure 79 Diel physico chemical data for waterhole F09, Oct 2012



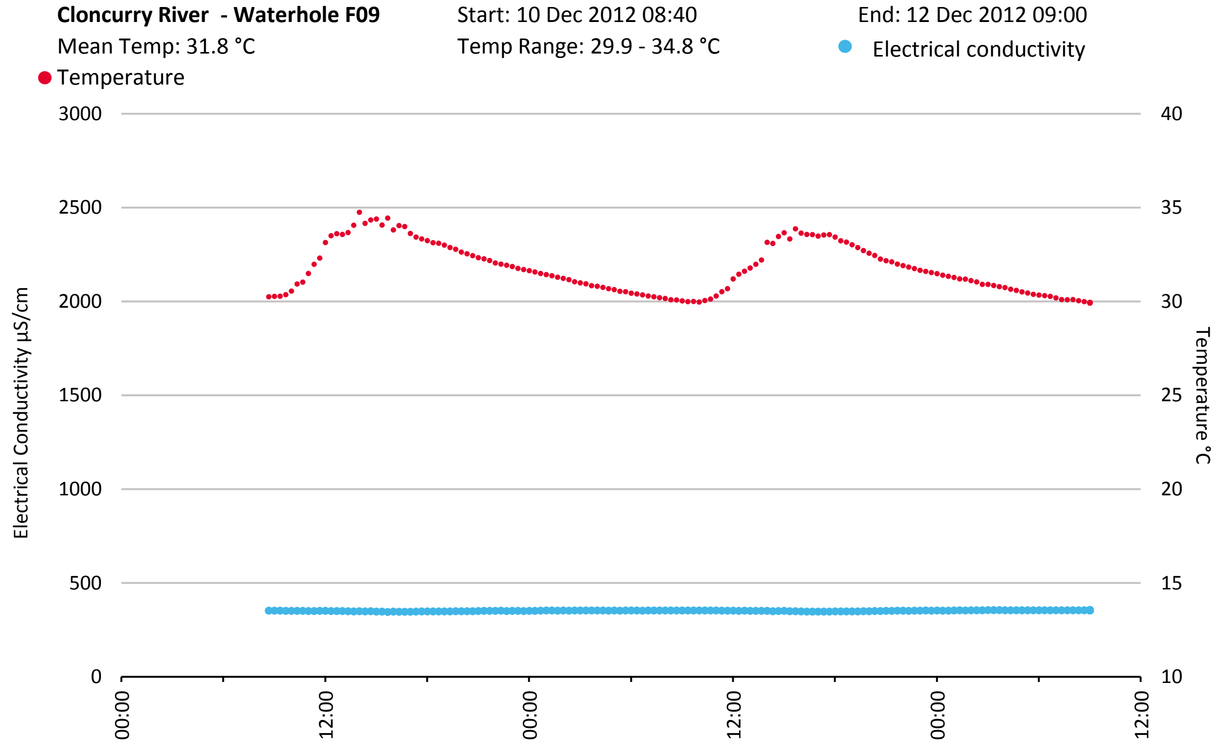


Figure 80 Diel physico chemical data for waterhole F09, Dec 2012

WATERHOLE F10

FEATURE	DESCRIPTION
Waterhole	F10
Catchment	Flinders River
Watercourse	Alick Creek
Waterhole location	-20.780870°, 142.712746°
Waterhole elevation	~ 170 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 1: 8-Sept-12
	Survey 2: 27-Oct-12
	Survey 5: 8-Dec-12
	Survey 9: 31-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~800 m^2
	Waterhole volume: ~80 m^3
	Wetted perimeter: ~ 340 m
	Maximum depth: 0.25 m
	Average depth: 0.1 m
	Waterhole length: 160 m
Instream habitats	A silty, shallow waterhole with a very high biomass of the aquatic macrophyte *Myriophyllum* sp. This waterhole became fully dry mid December 2012.
Riparian zone	A narrow area of riparian vegetation is present, and is dominated by Prickly Acacia (*Acacia nilotica*). Groundcover is very sparse.
Waterhole depth changes	Water depth declined steadily to December 2012. The waterhole remained completely dry from early December until the end of the Assessment period.
Other notes	Cattle access damage was evident along the entire waterhole.

a)

b)

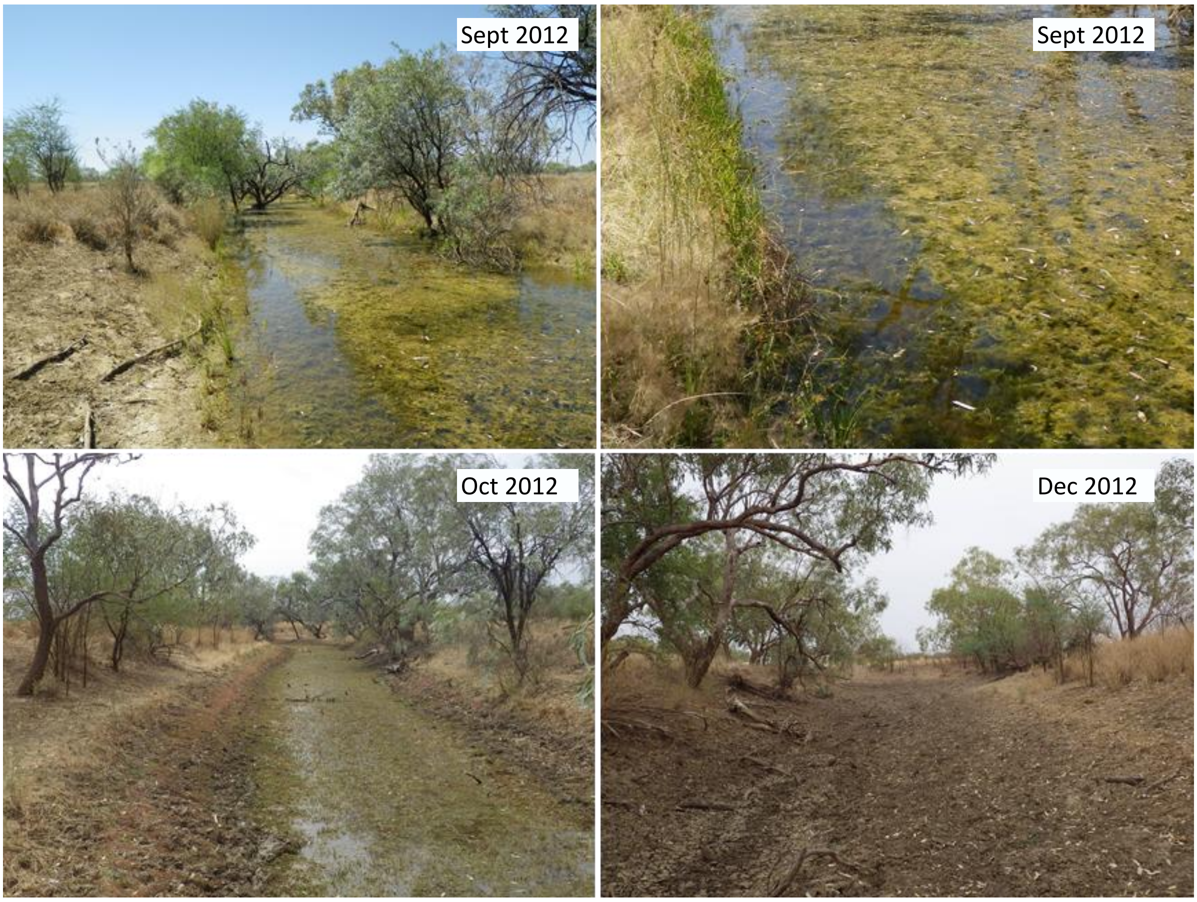


Figure 81 a) GoogleEarth 2005 aerial view of F10. b) Left to right: 1) Looking upstream. 2) Dense *Myriophyllum* sp. and filamentous algae. 3) Looking downstream. 4) Looking upstream

Figure 82 Bathymetry map of waterhole F10. Depth and waterhole perimeter data generated from data collected Oct 2012

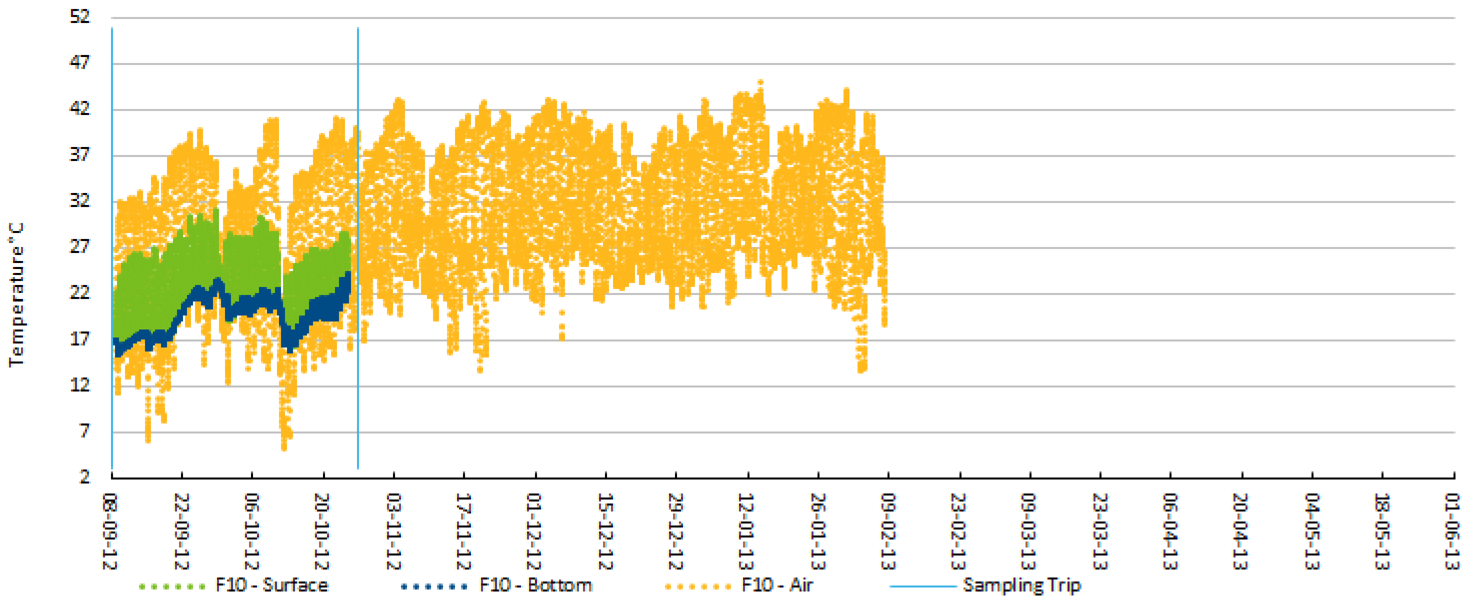


Figure 83 Long term temperature logger data for waterhole F10. Waterhole dried October 2012

Table 9 Continuous water and air temperature logger summary statistics for each survey at waterhole F10.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5°C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Sep 12	10-09-12 00:15	16-09-12 00:15	6	6.1	22.5	33.0	16.2	20.5	26.3	16.0	17.0	18.0	0.0	3.5	9.2	83.6	69.7	63.3
Oct 12	20-10-12 00:15	25-10-12 00:15	5	14.9	29.0	41.1	19.3	23.1	28.5	19.3	21.2	24.1	-0.1	1.9	6.3	54.8	46.8	42.1

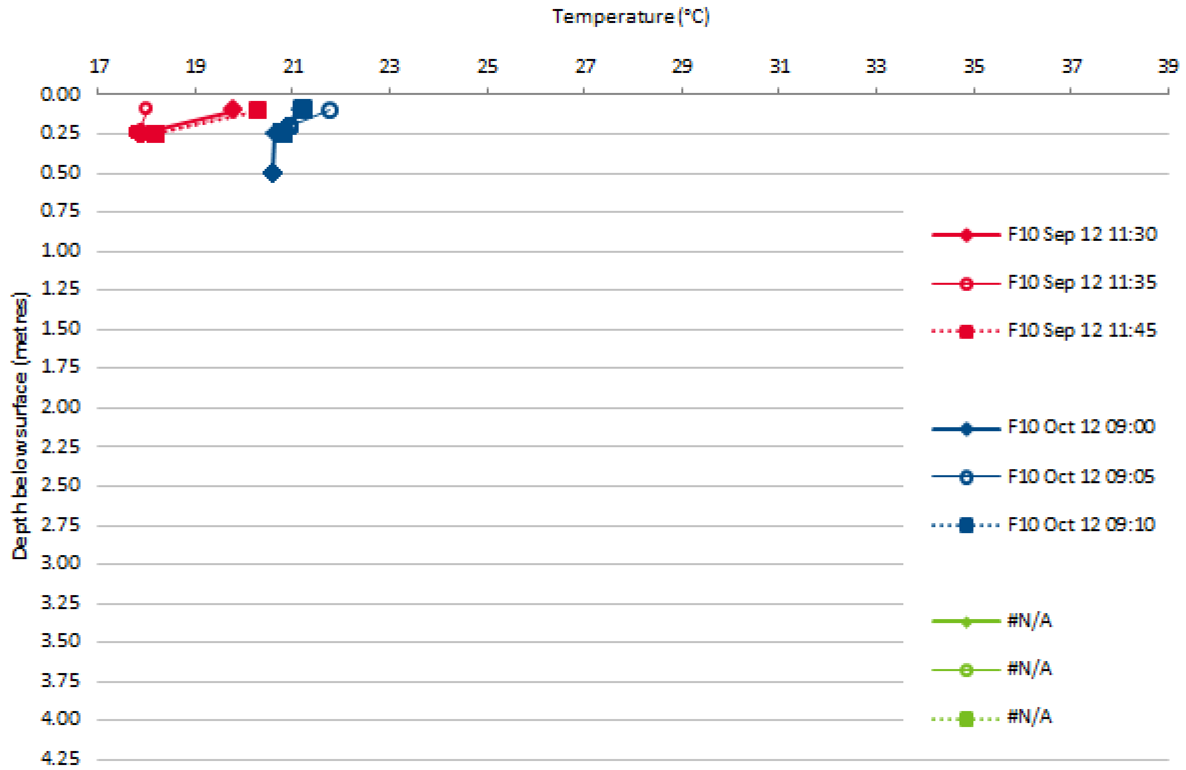


Figure 84 Temperature vertical water column profiles at waterhole F10. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

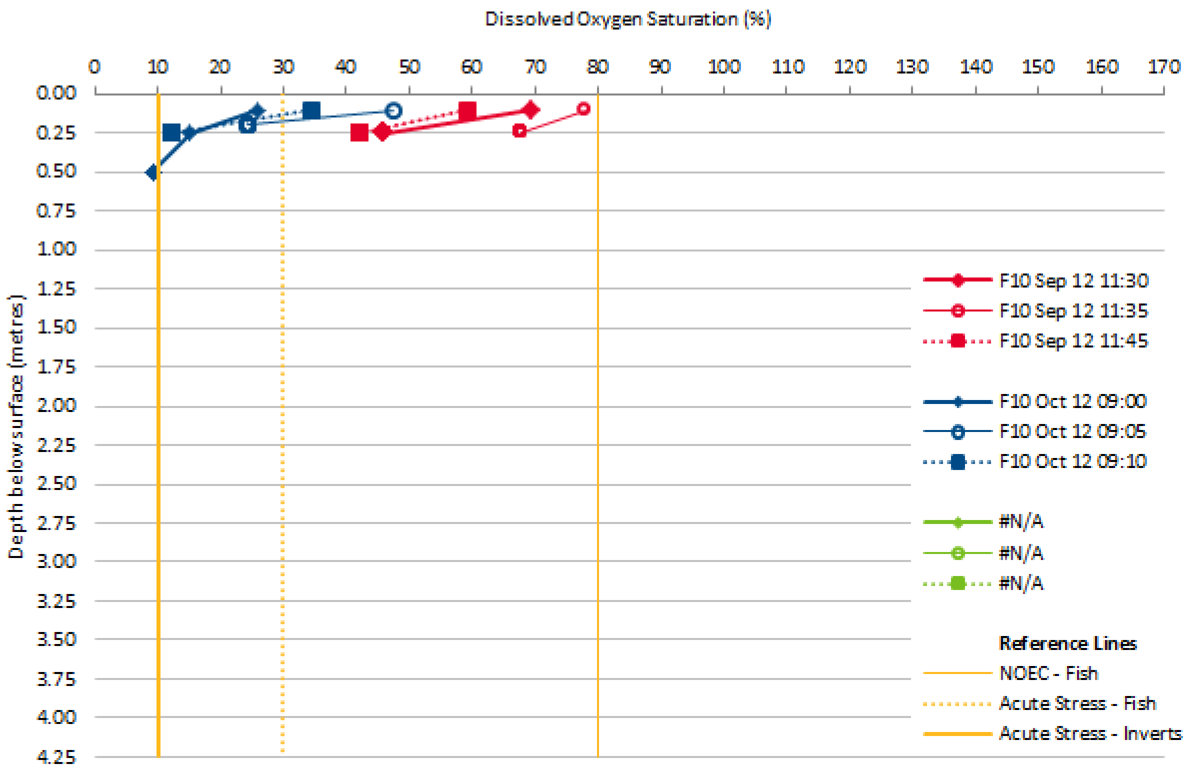


Figure 85 Dissolved oxygen saturation (%) vertical water column profiles at waterhole F10. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

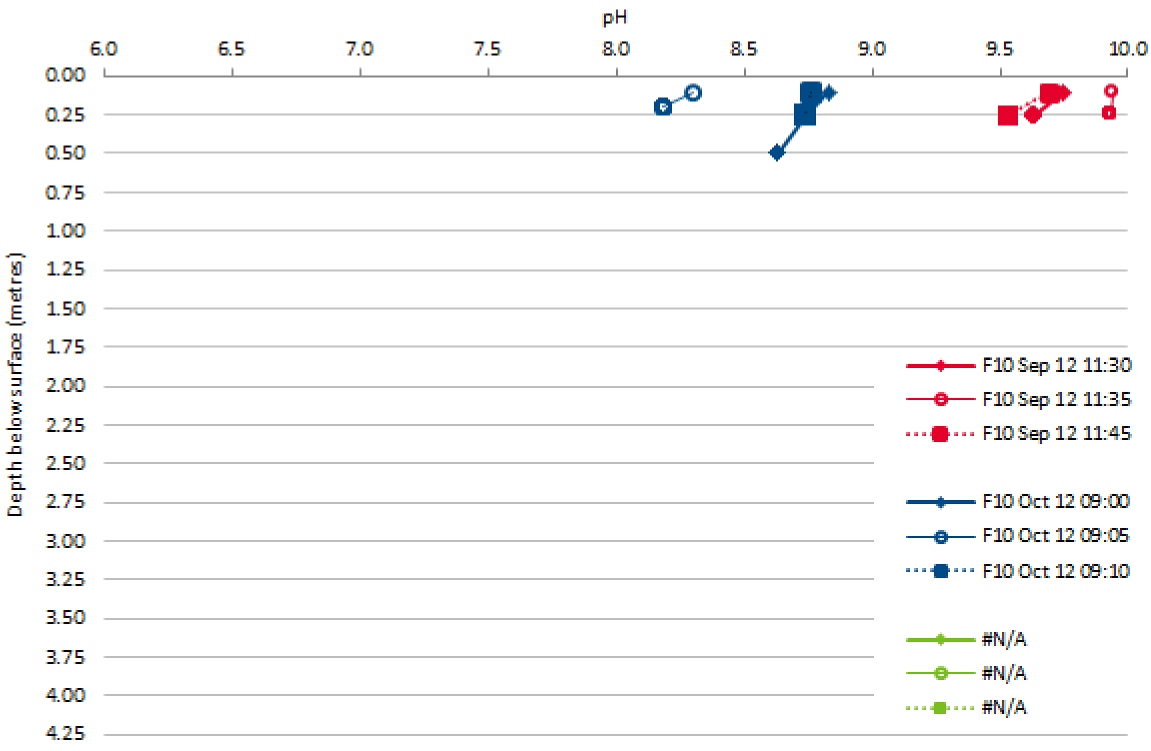


Figure 86 pH vertical water column profiles at waterhole F10. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

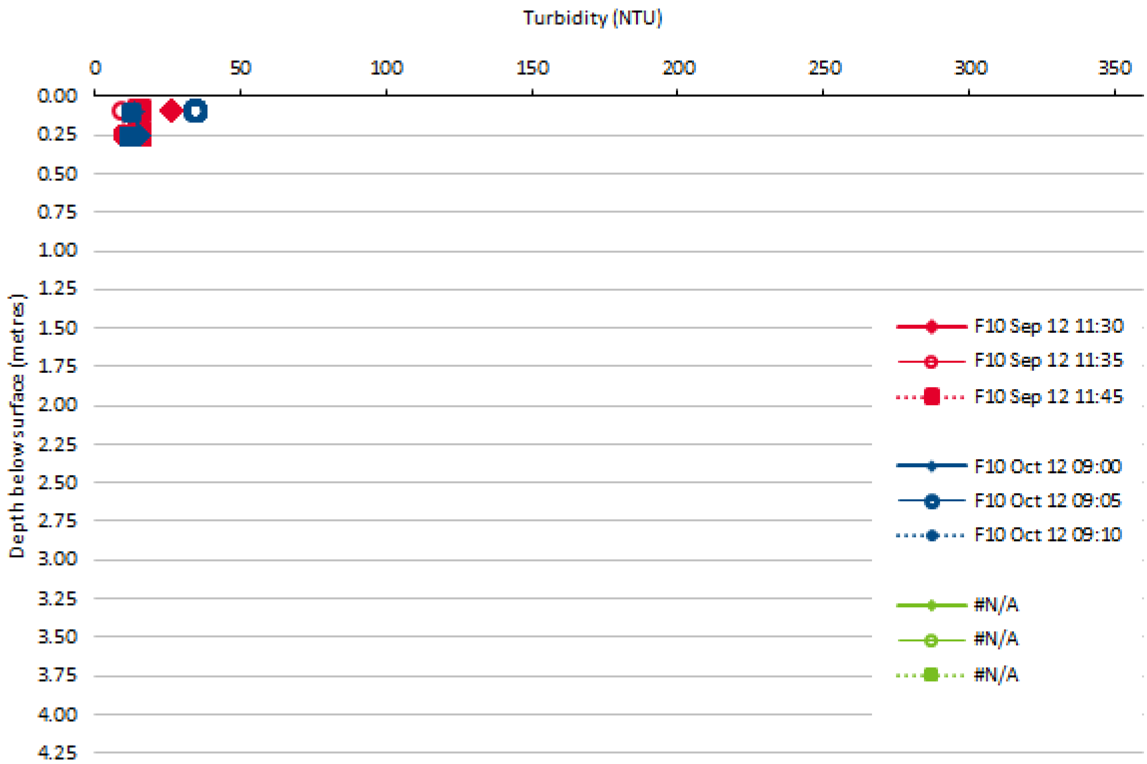
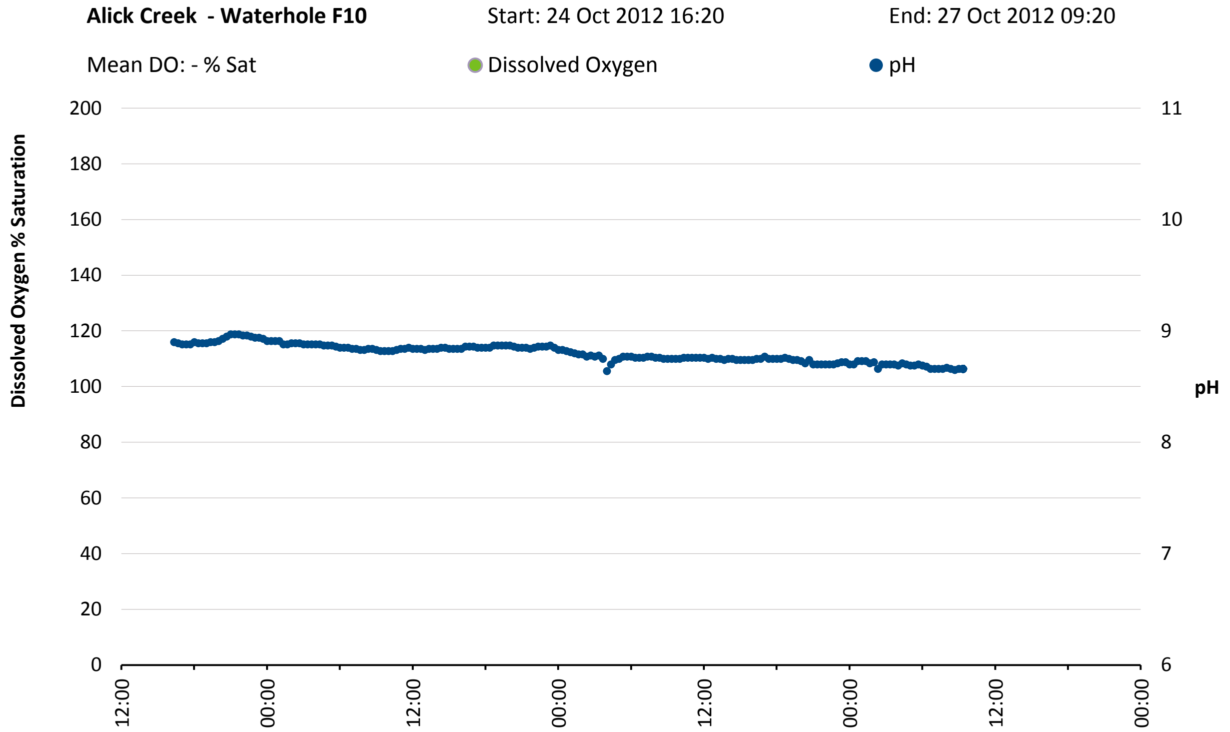


Figure 87 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole F10. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



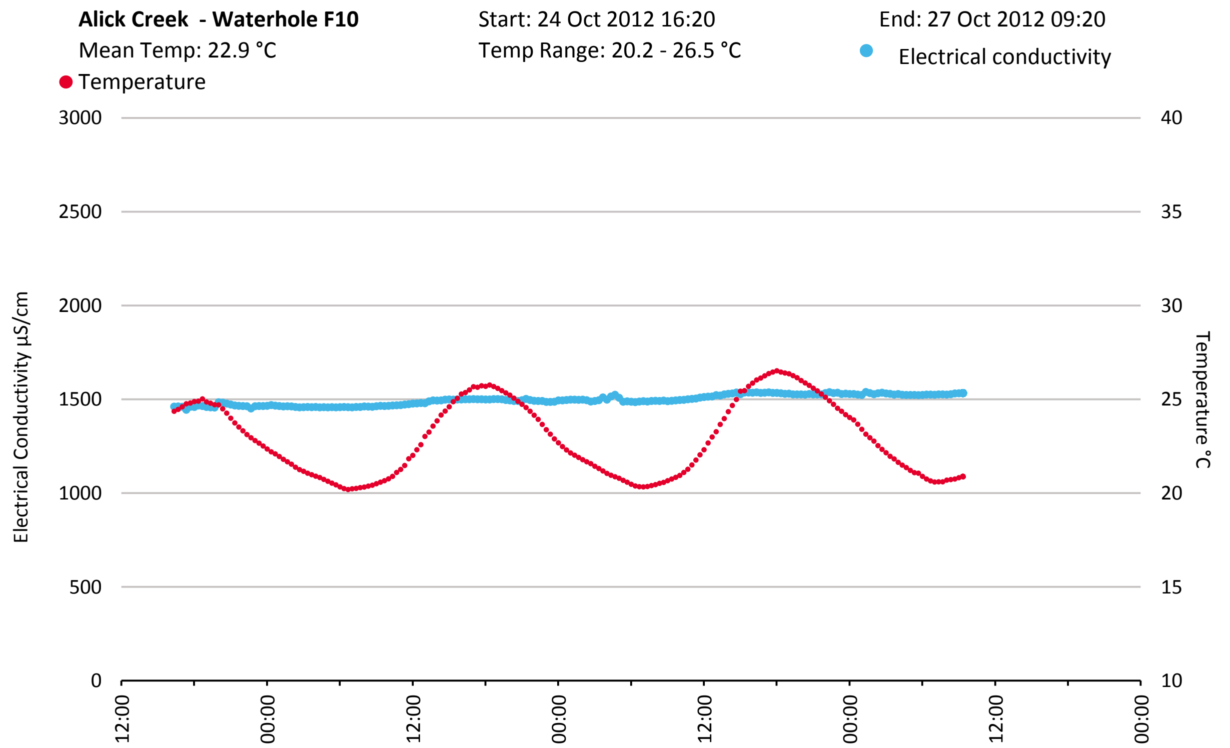


Figure 88 Diel physico chemical data for waterhole F10, Oct 2012. Note: Dissolved oxygen sensor failed during this deployment

Appendix F Gilbert River catchment waterhole habitat descriptions

WATERHOLE G01

FAMILY NAME	SPECIES NAME
Waterhole	G01
Catchment	Gilbert River
Watercourse	Bundock Creek
Waterhole location	-19.172855°, 144.441439°. This waterhole is located on the upstream side of the Gulf Development Road culvert across Bundock Creek.
Waterhole elevation	~700 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 8-Oct-12
	Survey 3: 15-Nov-12
	Survey 5: 1-Dec-12
	Survey 7: 20-Jan-12
	Survey 9: 27-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~15,500 m^2
	Waterhole volume: ~12,700 m^3
	Wetted perimeter: ~ 1480 m
	Maximum depth: 2.3 m
	Average depth: 0.8 m
	Waterhole length: 720 m
Instream habitats	This waterhole has a predominantly sandy and silty bottom habitat, with some rocky sections close to the downstream causeway. Instream there was a high biomass of aquatic macrophytes (*Myriophyllum* sp.) as well as epiphytic, epilithic and planktonic algae. Biomass appeared to increase in the downstream area adjacent to the road culvert. Further macrophyte species noted as present included *Ottelia alismoides* and *Potamogeton tricarinatus*.
Riparian zone	Riparian tree cover is fairly sparse. In the downstream areas, a number of *Casuarina cunninghamiana* trees are present; whilst further upstream riparian species include *Eucalyptus platyphylla.* Little recruitment of tree species was noted. Groundcover is dense where cattle are excluded, with grasses hanging into the waterhole along waterhole edges. Thistles are scattered throughout the riparian zone.
Waterhole depth changes	Depth remained constant at this waterhole across the Assessment period.
Other notes	Some cattle access damage was evident along the upstream waterhole edges.

a)

b)

Figure 1 a) GoogleEarth 2004 aerial view of G01. b) Left to right: 1) Left bank. 2) Road causeway and dense *Myriophyllum* sp. 3) Aquatic macrophytes, *Ottelia alismoides*. 4) Looking upstream from causeway

Figure 2 Bathymetry map of waterhole G01. Depth and waterhole perimeter data generated from data collected Oct 2012

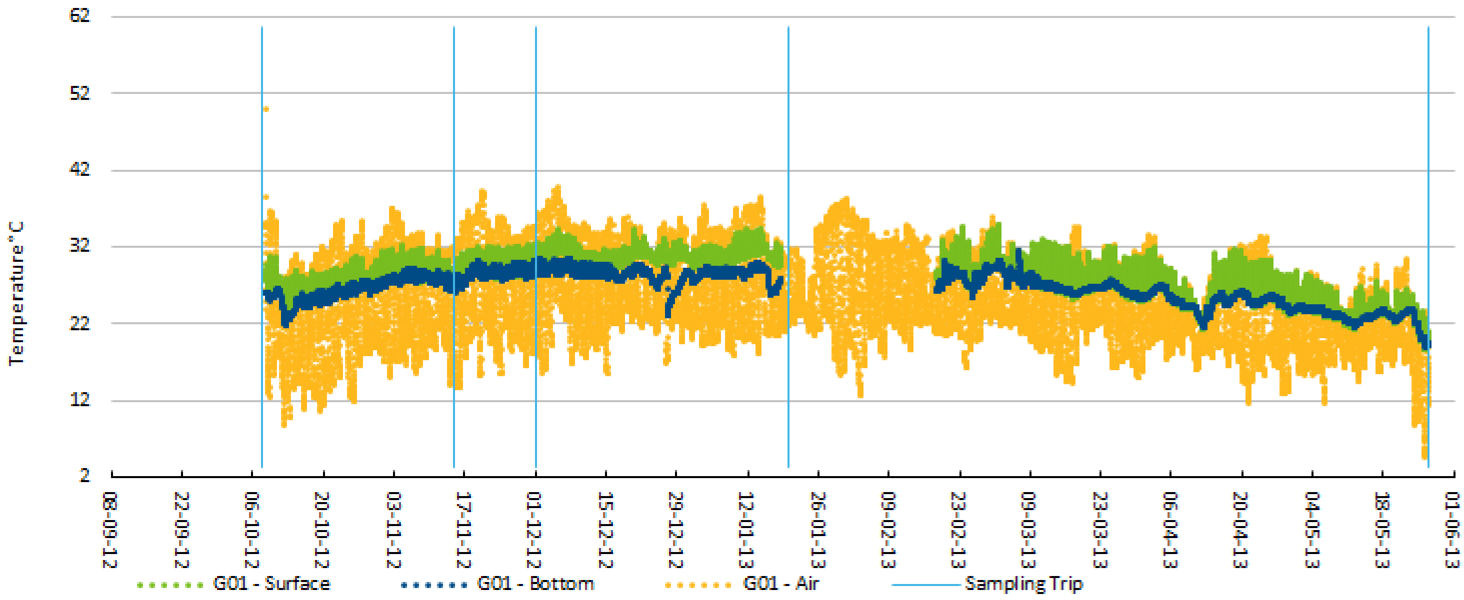
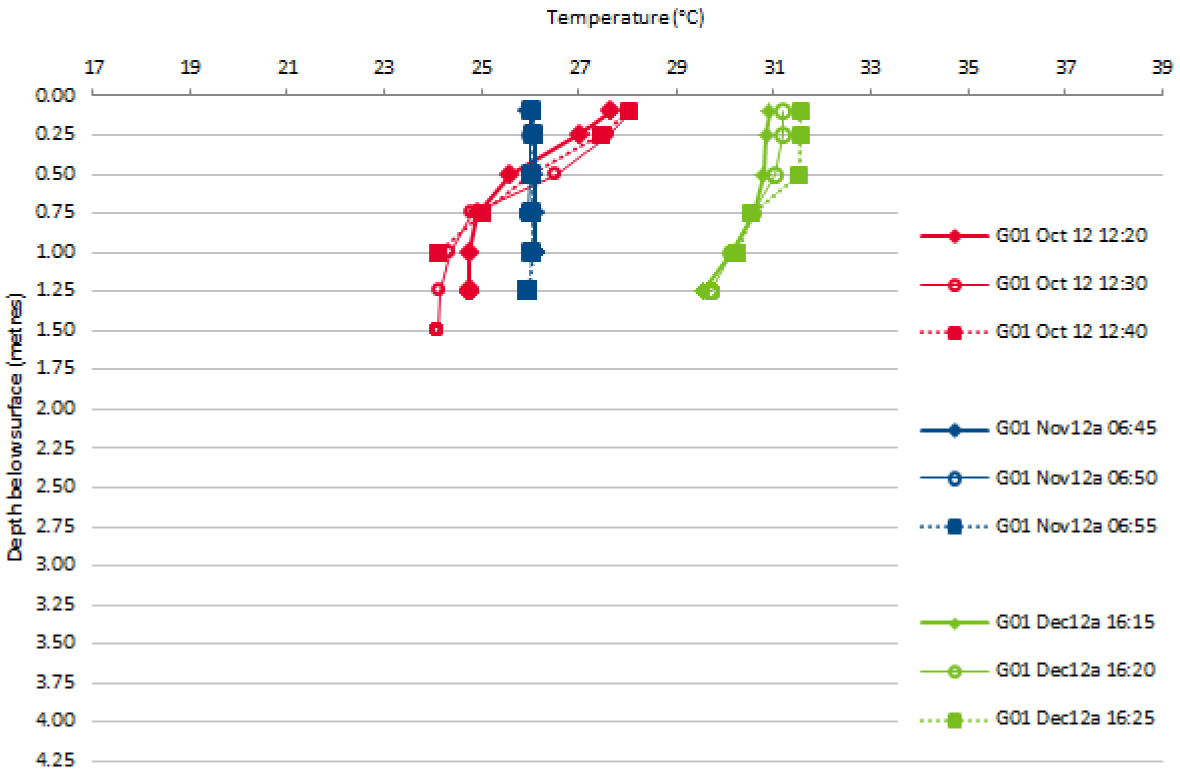


Figure 3 Long term temperature logger data for waterhole G01. Missing data due to water logger malfunction

Table 1 Continuous water and air temperature logger summary statistics for each survey at waterhole G01.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Oct 12	09-10-12 00:15	11-10-12 00:15	2	12.5	25.4	36.7	25.2	27.2	30.8	25.0	25.7	26.4	0.0	1.5	5.2	65.5	49.0	37.9
Nov12a	10-11-12 00:15	15-11-12 00:15	5	13.9	24.6	33.5	26.3	28.2	31.4	26.2	27.6	28.8	-0.1	0.6	3.0	36.3	25.5	15.2
Nov12b	25-11-12 00:15	01-12-12 00:15	6	16.5	26.6	34.7	27.8	29.6	32.3	27.8	29.1	30.1	-0.2	0.5	2.7	38.2	27.1	18.5
Jan 13	14-01-13 00:15	18-01-13 00:15	4	18.1	27.0	38.5	29.8	31.4	34.3	25.7	27.9	30.0	1.8	3.5	6.3	100.0	100.0	100.0
May 13	19-05-13 00:15	21-05-13 00:15	2	16.5	20.8	29.3	22.0	23.4	26.2	22.3	22.8	23.4	-0.4	0.5	3.7	37.9	20.7	17.9



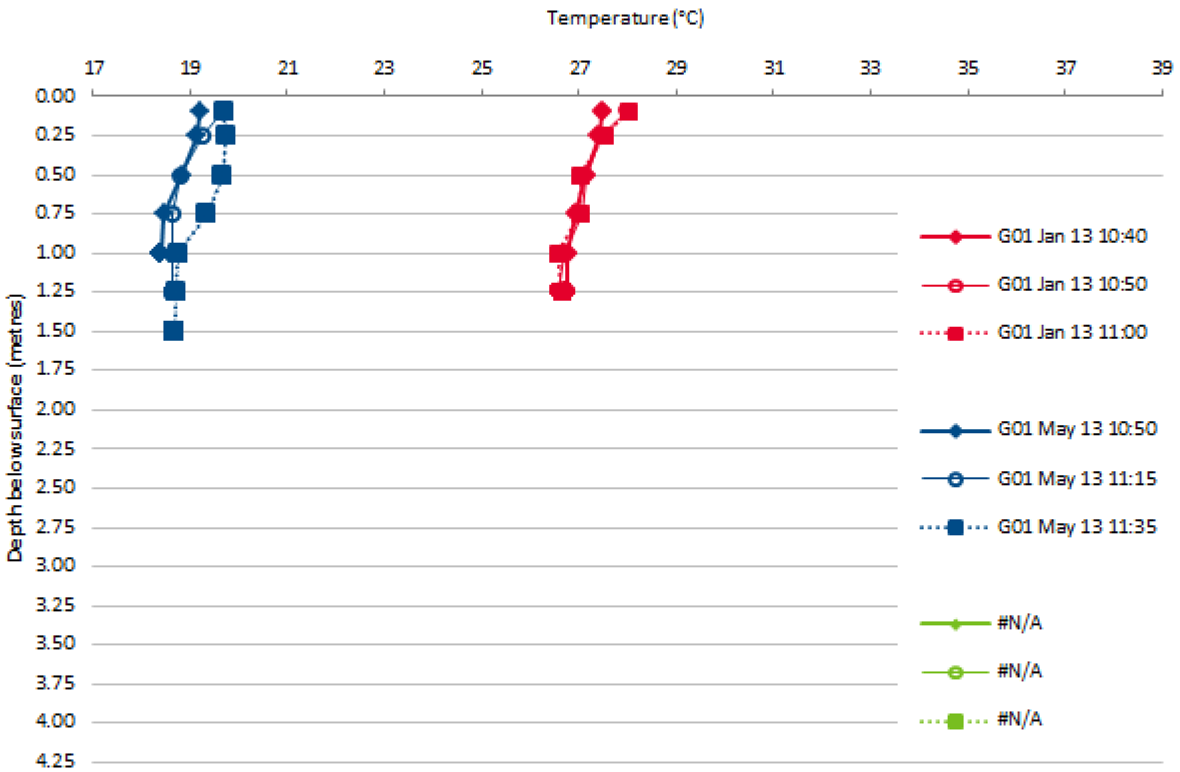
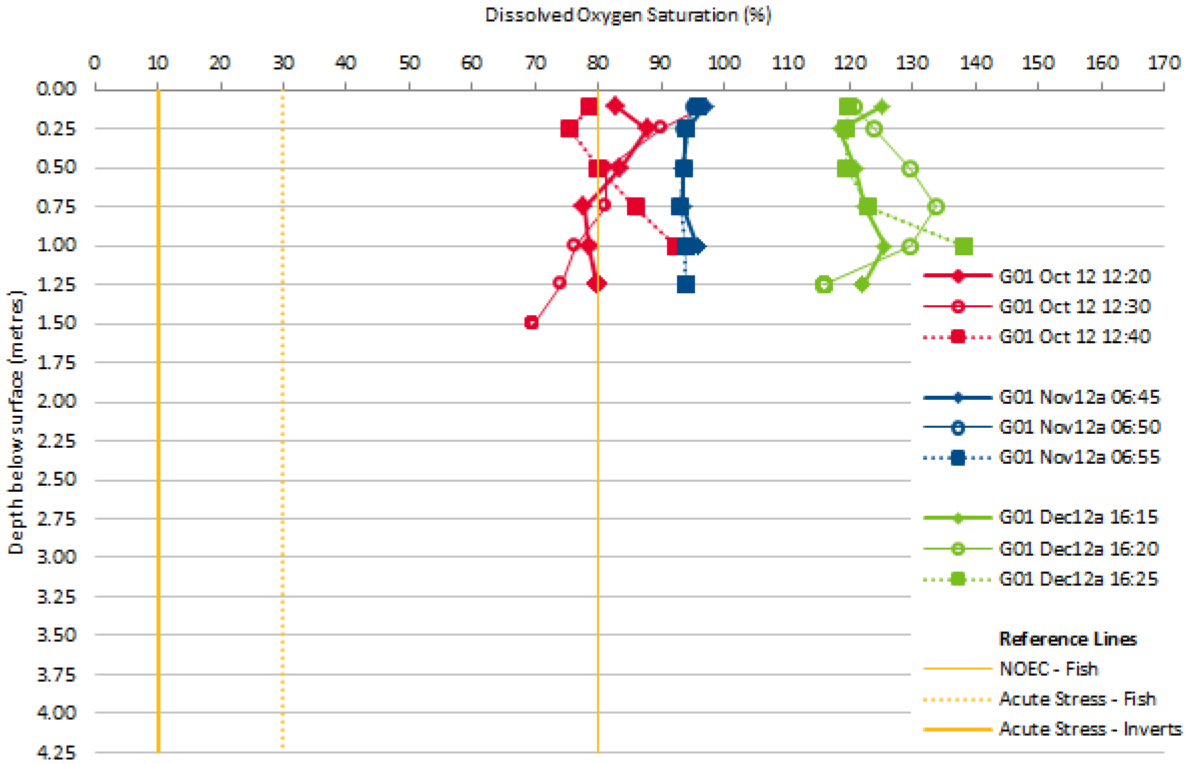


Figure 4 Temperature vertical water column profiles at waterhole G01. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



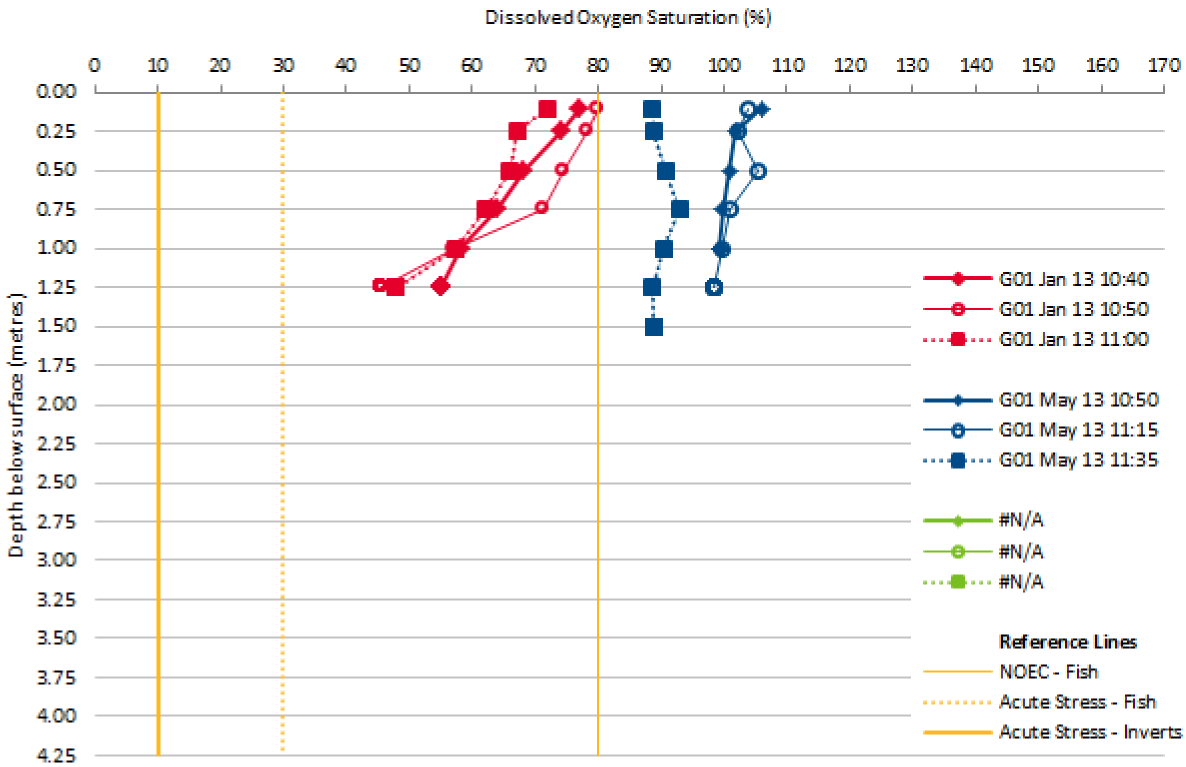
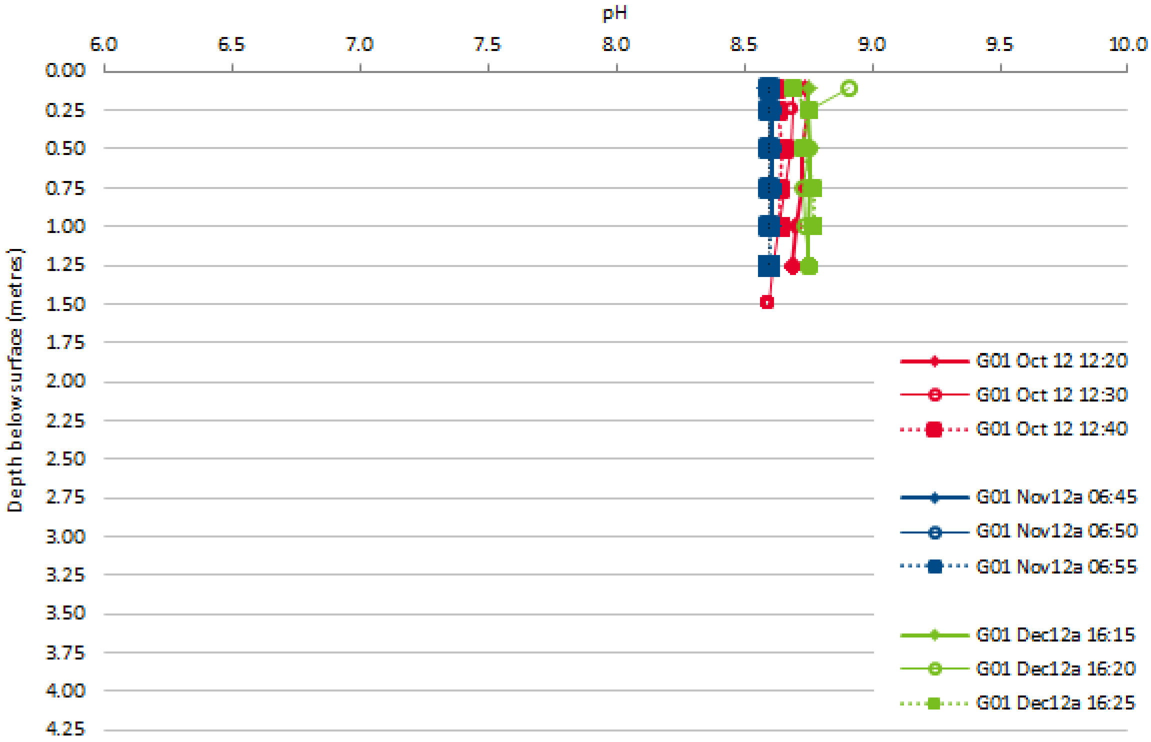


Figure 5 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G01. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



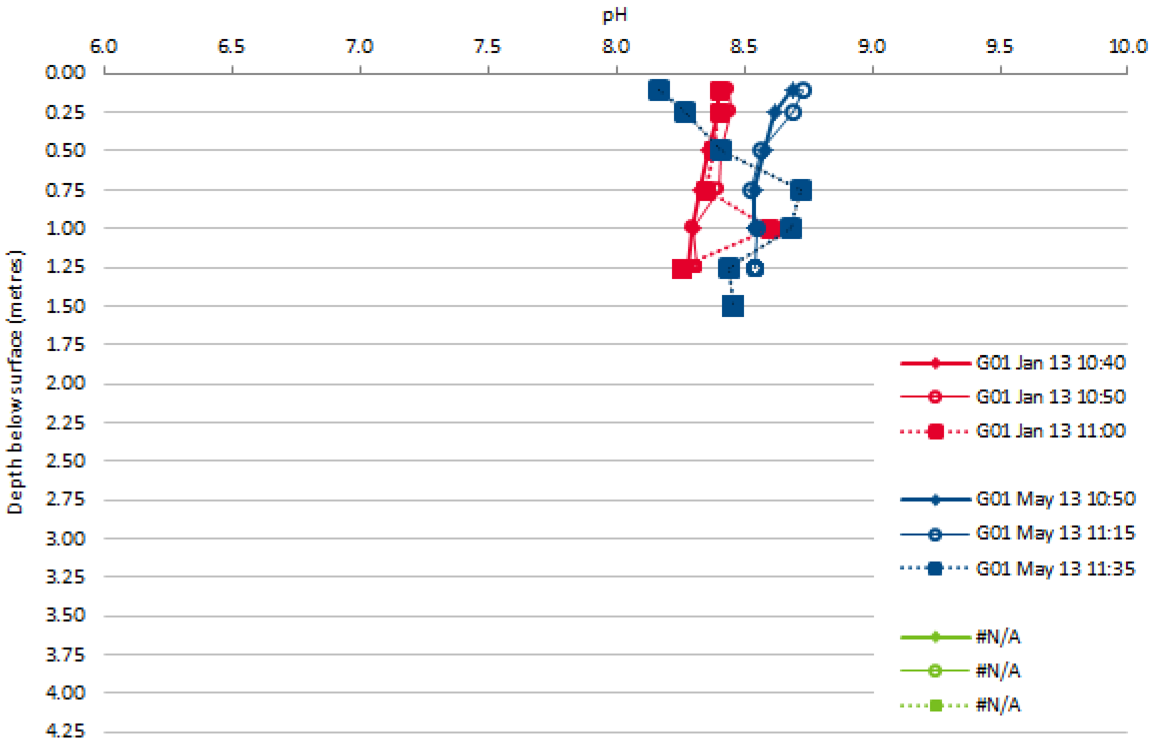
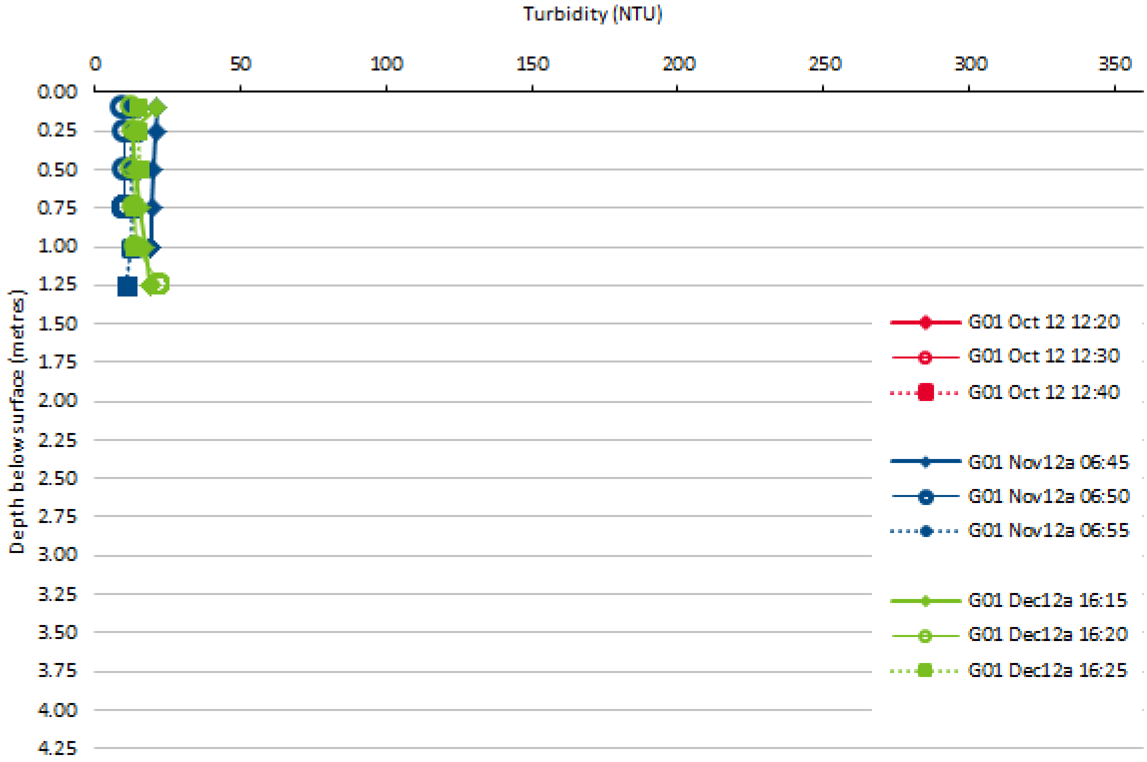


Figure 6 pH vertical water column profiles at waterhole G01. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



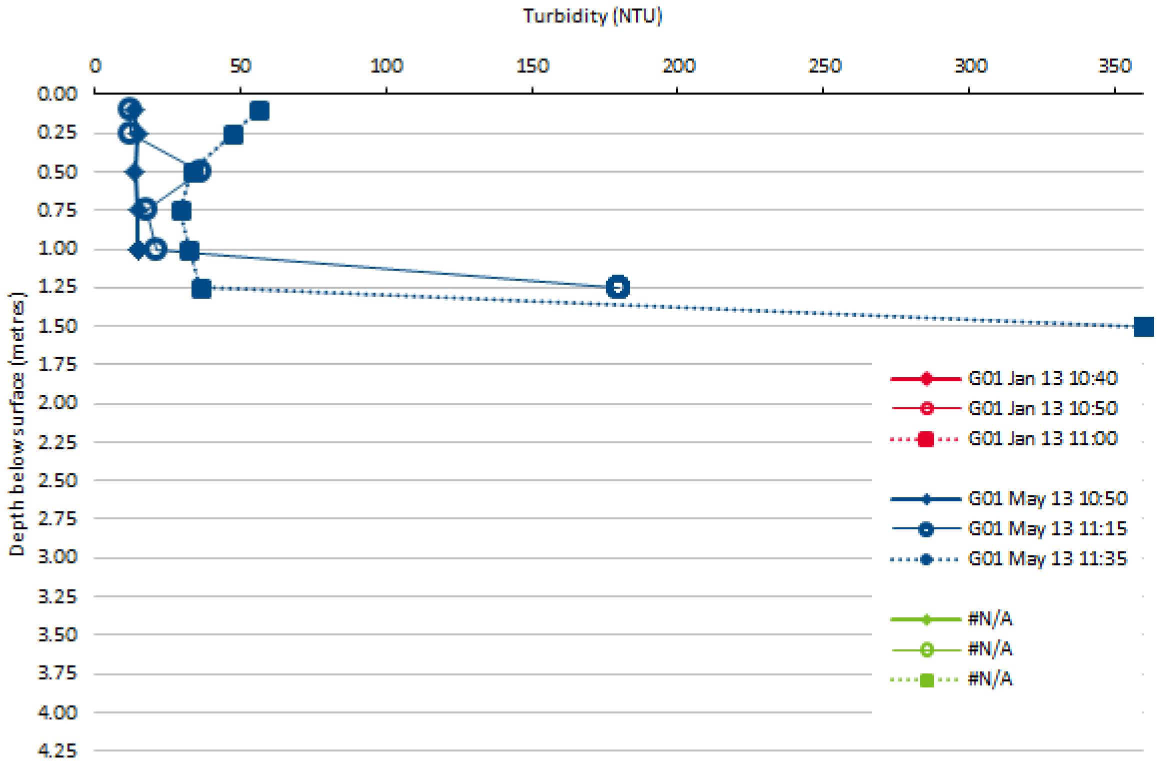
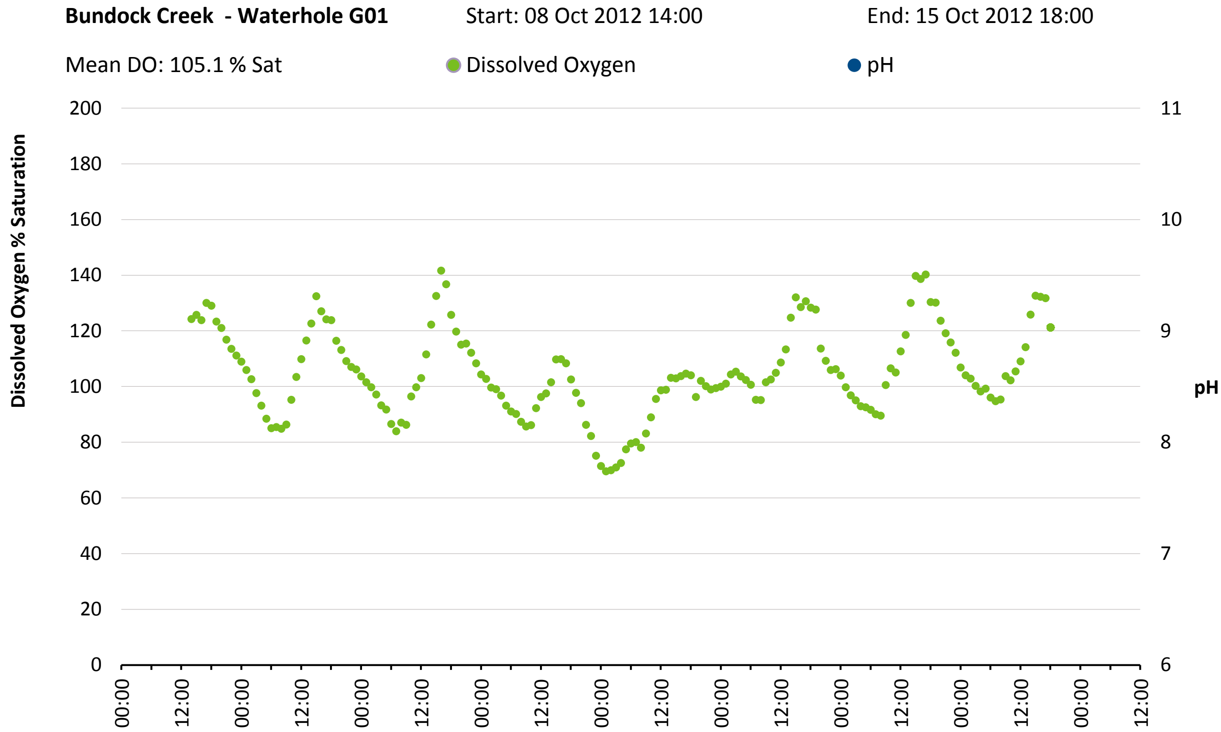


Figure 7 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G01. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



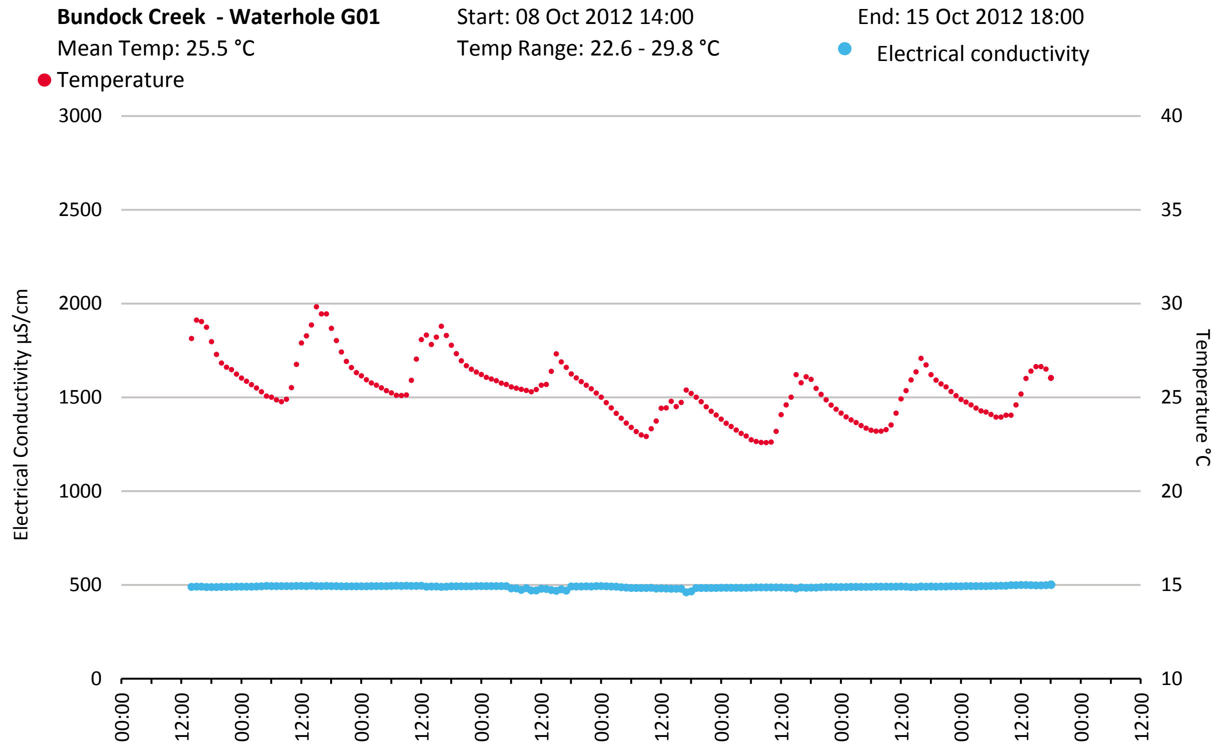
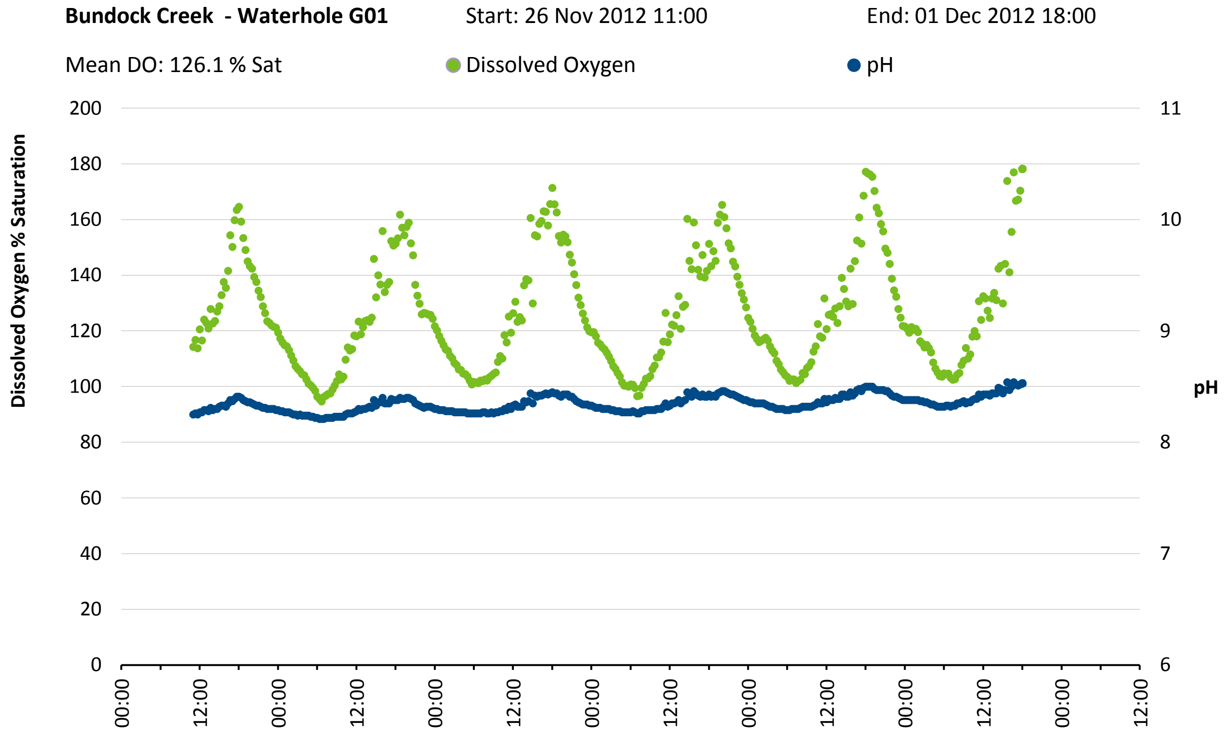


Figure 8 Diel physico-chemical data for waterhole G01, Oct 2012



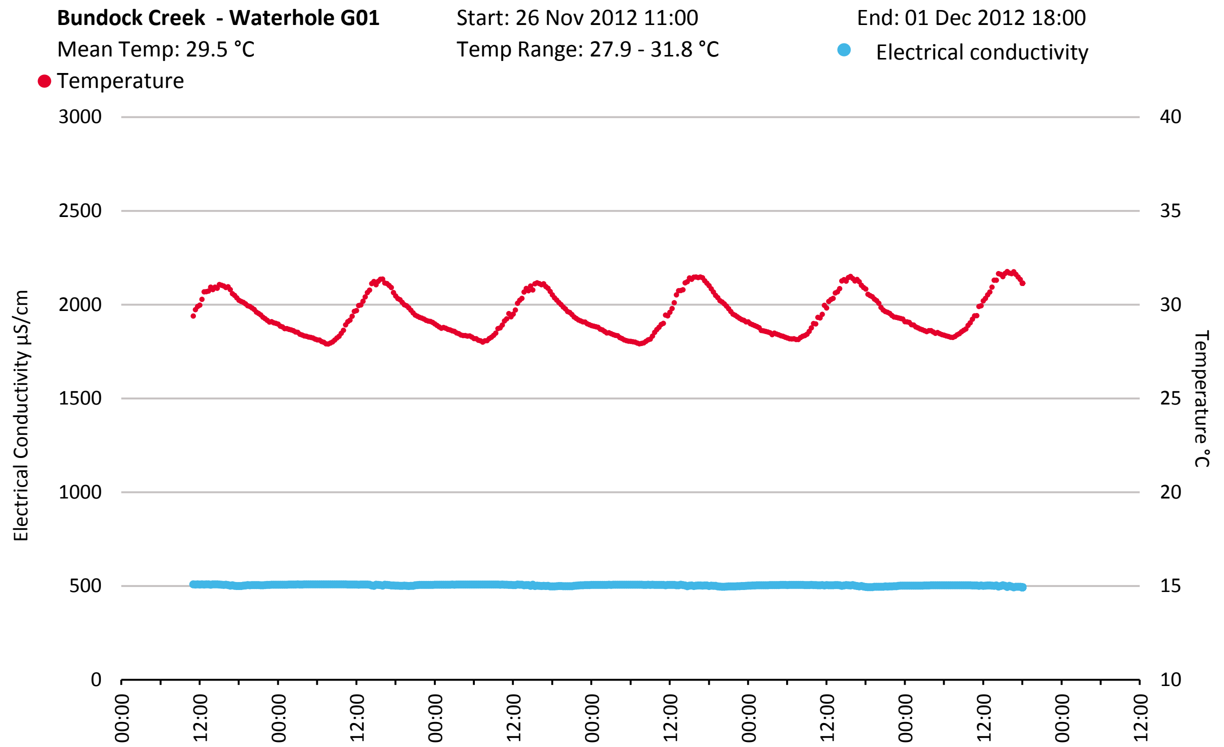


Figure 9 Diel physico-chemical data for waterhole G01, Dec 2012

WATERHOLE G02

FAMILY NAME	SPECIES NAME
Waterhole	G02
Catchment	Gilbert River
Watercourse	Mckinnons Creek
Waterhole location	-18.947426°, 144.495038°. This waterhole crosses under a bridge on the Kennedy Development Road.
Waterhole elevation	~530 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 9-Oct-12
	Survey 3: 14-Nov-12
	Survey 5: 1-Dec-12
	Survey 7: 20-Jan-12
	Survey 9: 27-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~3800 m^2
	Waterhole volume: ~4300 m^3
	Wetted perimeter: ~ 570 m
	Maximum depth: 2.3 m
	Average depth: 1.1 m
	Waterhole length: 280 m
Instream habitats	Just downstream of the bridge, a rocky area constricts flow, and it is here that the waterhole becomes disconnected at the downstream end during the dry season. A high level of detritus was evident at the downstream end of the waterhole. Aquatic macrophytes were scarce, with *Myriophyllum* sp. being the single genus identified. Biomass of epilithic algae was high. Some filamentous algae were present.
Riparian zone	The riparian condition of this waterhole is good. Cattle traffic is restricted, and grass cover along the waterhole edges is extensive. Riparian shade offered over the waterhole is moderate. The dominant riparian tree species is the River red gum (*Eucalyptus camaldulensis*).
Waterhole depth changes	Waterhole depth dropped steadily between September 2012 and late December 2012. In January 2013 the waterhole filled to a similar depth to that recorded during September 2012, then reduced towards May 2013.
Other notes	Minor cattle damage was evident at the downstream end of the waterhole.

a)

b)

Figure 10 a) GoogleEarth 2009 aerial view of G02. Yellow arrow indicates location of rock bar at the downstream end of G02 where the waterhole becomes separated during the dry season. b) Left to right 1) Downstream from lower end of the waterhole. 2) Upstream from mid-stream. 3) Looking downstream from lower end of the waterhole. 4) High flow conditions, from right bank

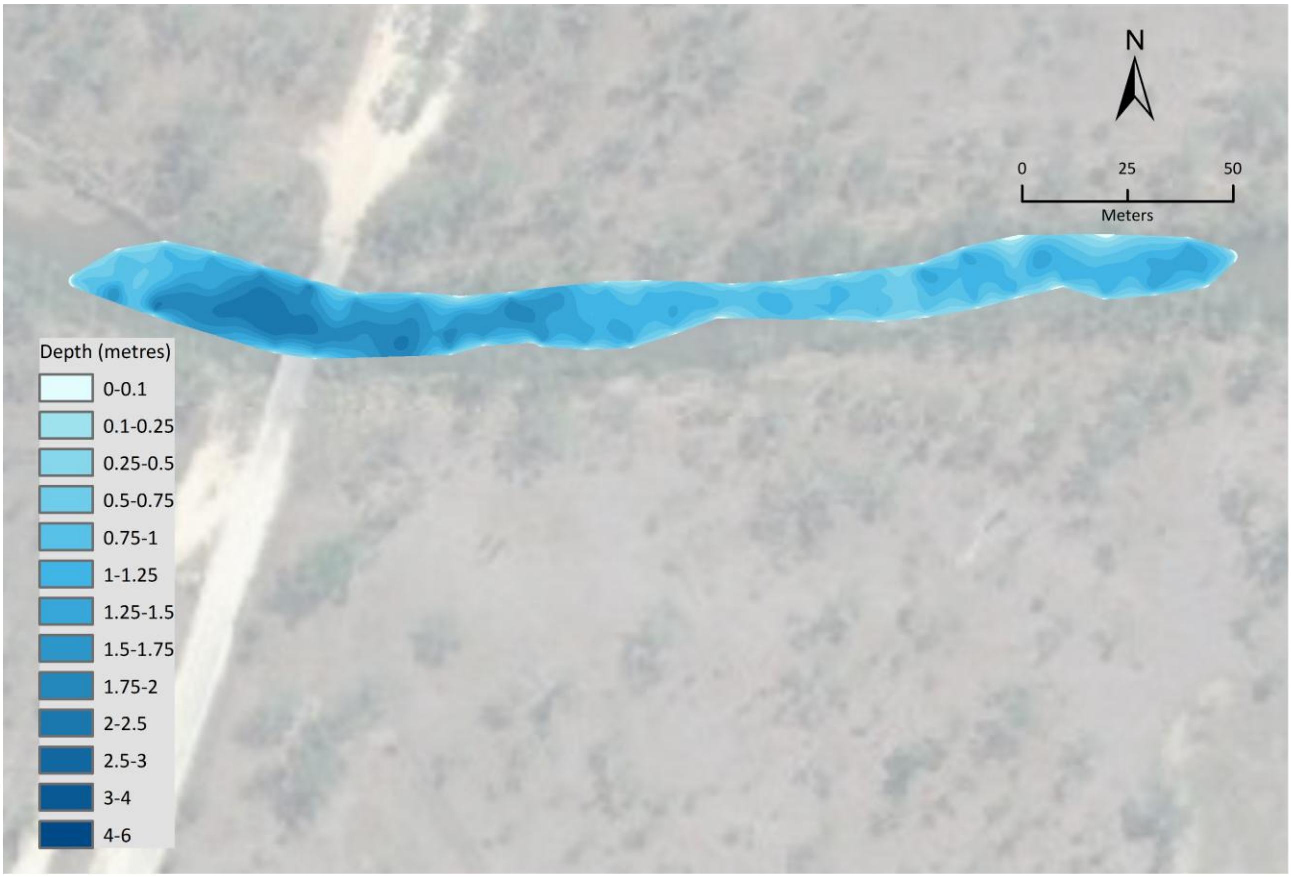


Figure 11 Bathymetry map of waterhole G02. Depth and waterhole perimeter data generated from data collected Oct 2012

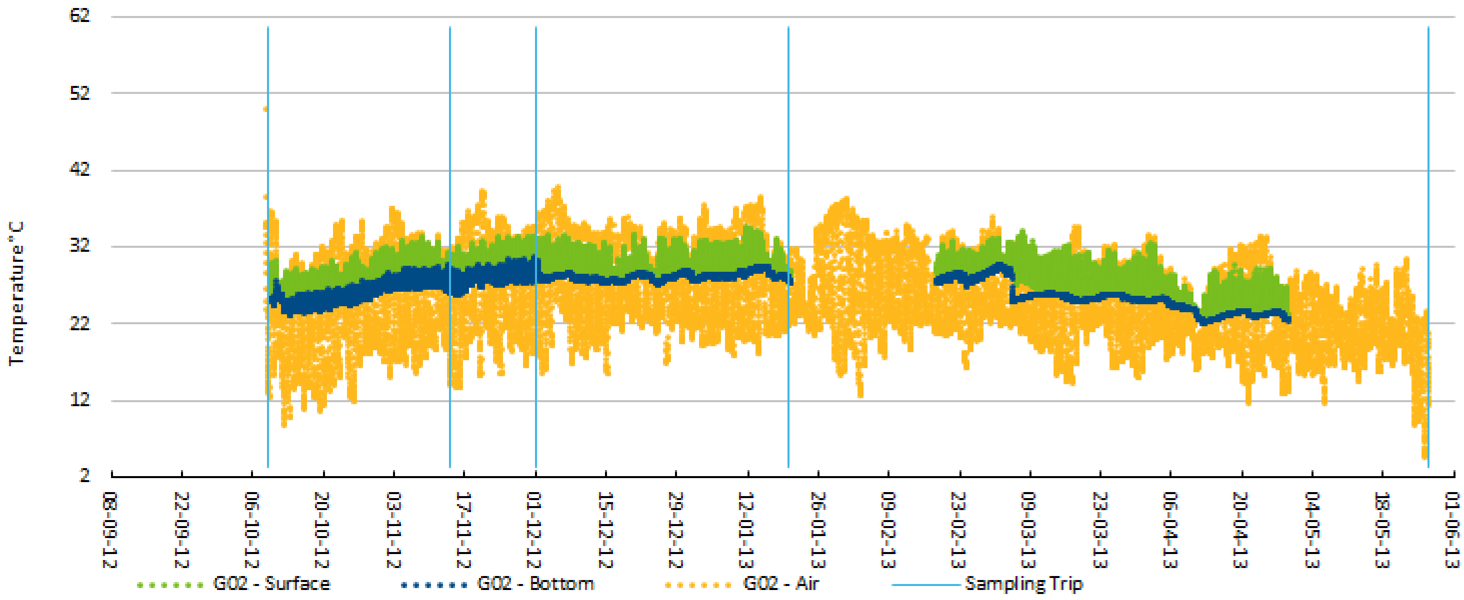
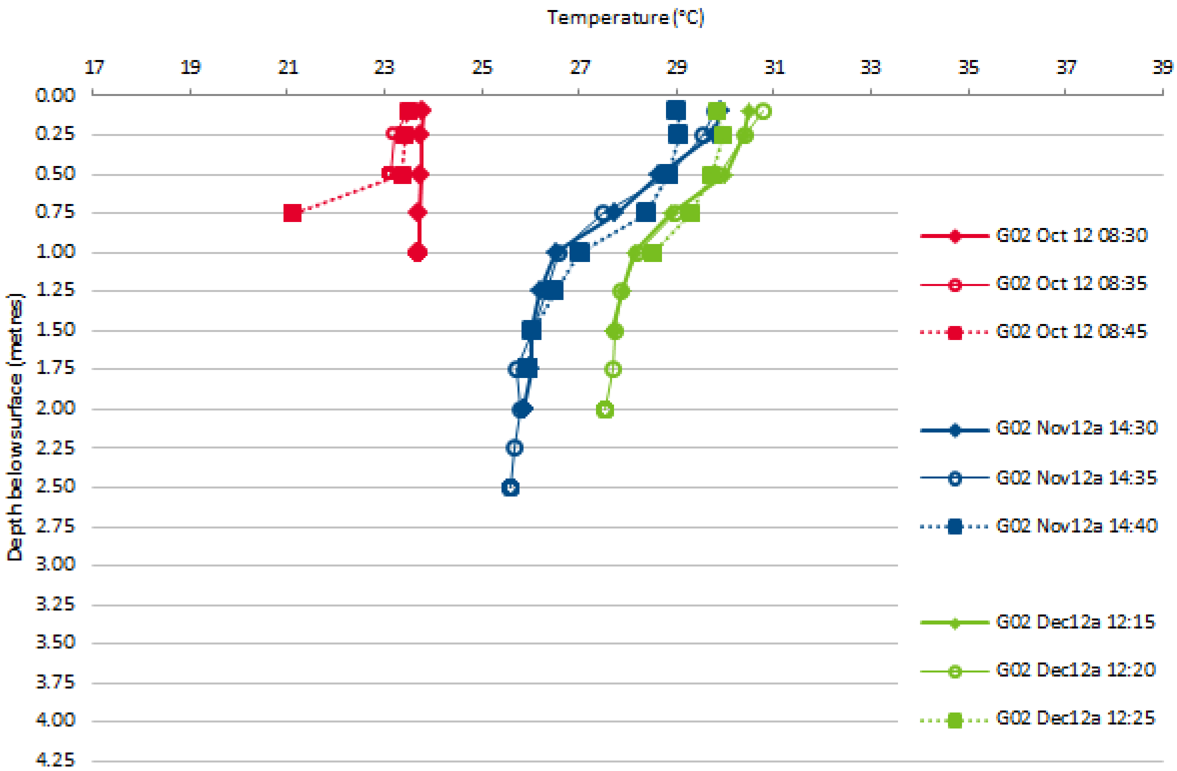


Figure 12 Long term temperature logger data for waterhole G02. Missing data corresponds to logger malfunction

Table 2 Continuous water and air temperature logger summary statistics for each survey at waterhole G02.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Oct 12	11-10-12 00:15	12-10-12 00:15	1	14.3	19.9	26.2	24.9	25.9	27.5	24.9	25.6	26.3	-0.1	0.3	1.7	28.8	9.6	2.7
Nov12a	07-11-12 00:15	13-11-12 00:15	6	15.7	25.0	33.8	26.6	28.9	33.4	26.4	27.8	29.4	-0.1	1.1	5.1	44.6	35.1	28.2
Nov12b	20-11-12 00:15	28-11-12 00:15	8	15.2	27.0	39.4	27.2	29.5	33.3	26.8	28.5	30.4	-0.1	1.0	4.3	45.5	34.4	27.3
Jan 13	19-01-13 00:15	20-01-13 00:15	1	21.1	23.8	30.7	27.9	28.5	29.5	27.9	28.0	28.4	-0.1	0.4	1.5	38.4	20.5	0.0



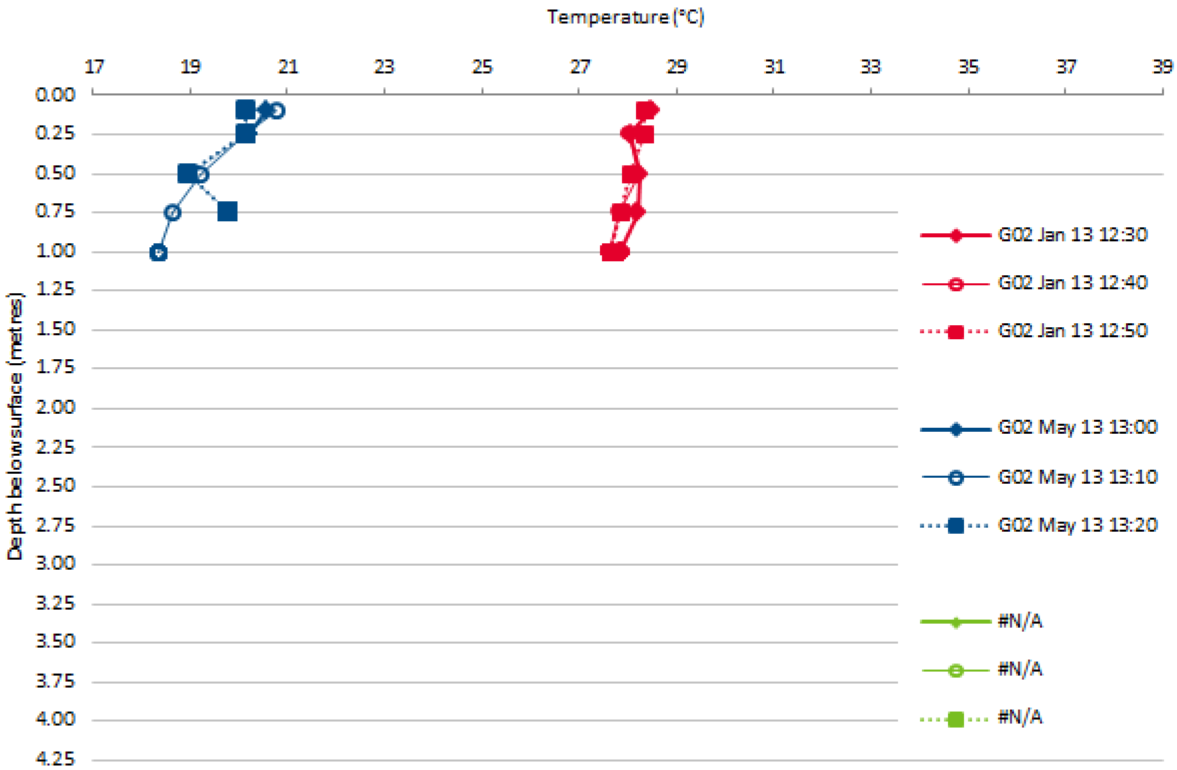
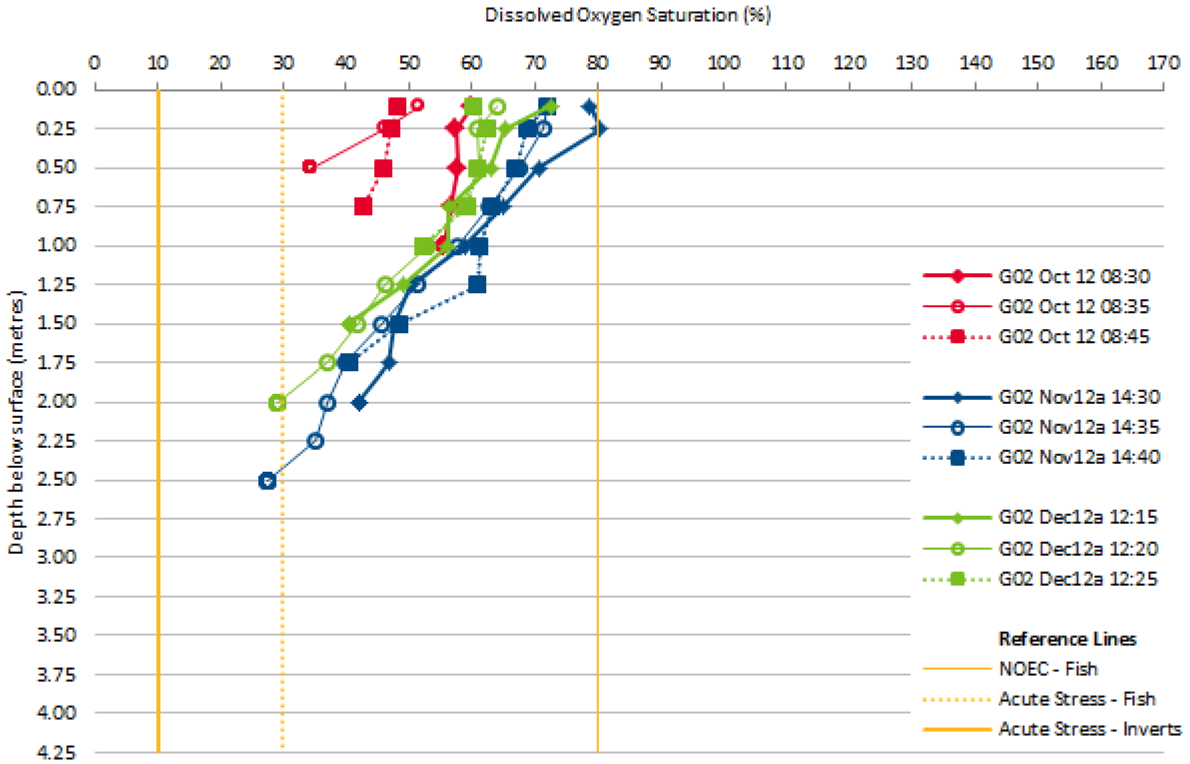


Figure 13 Temperature vertical water column profiles at waterhole G02. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



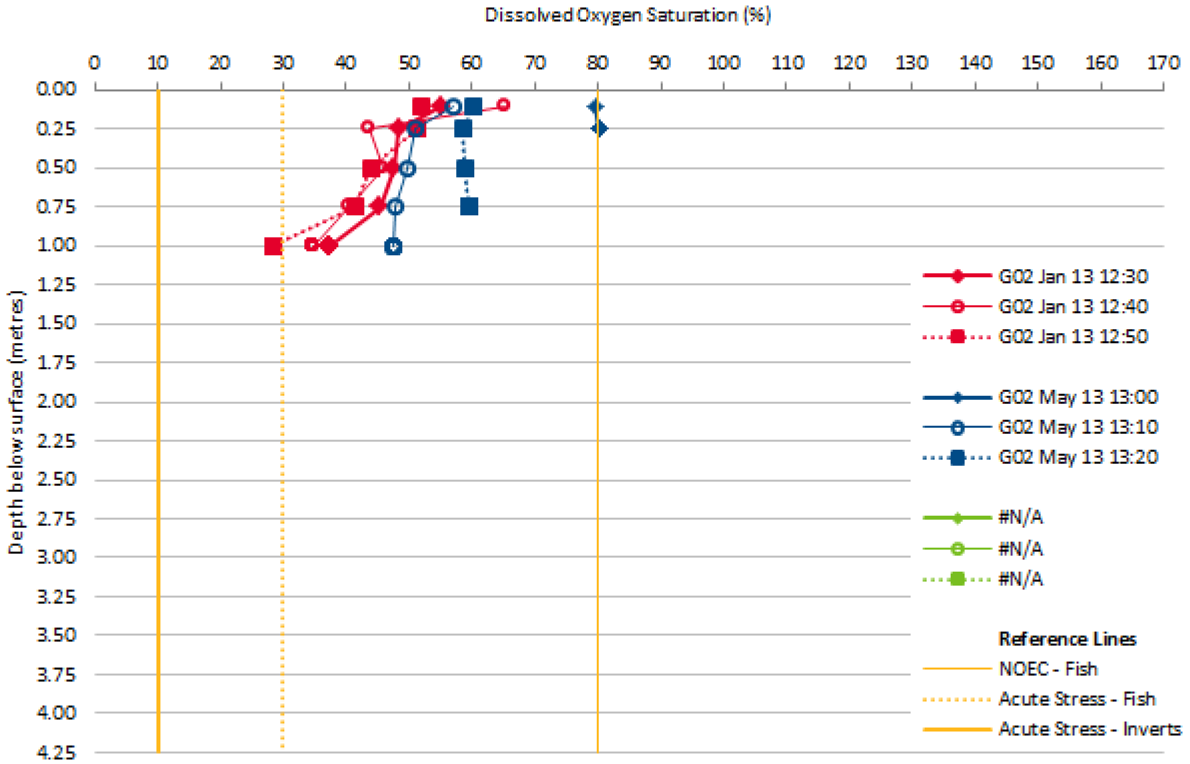
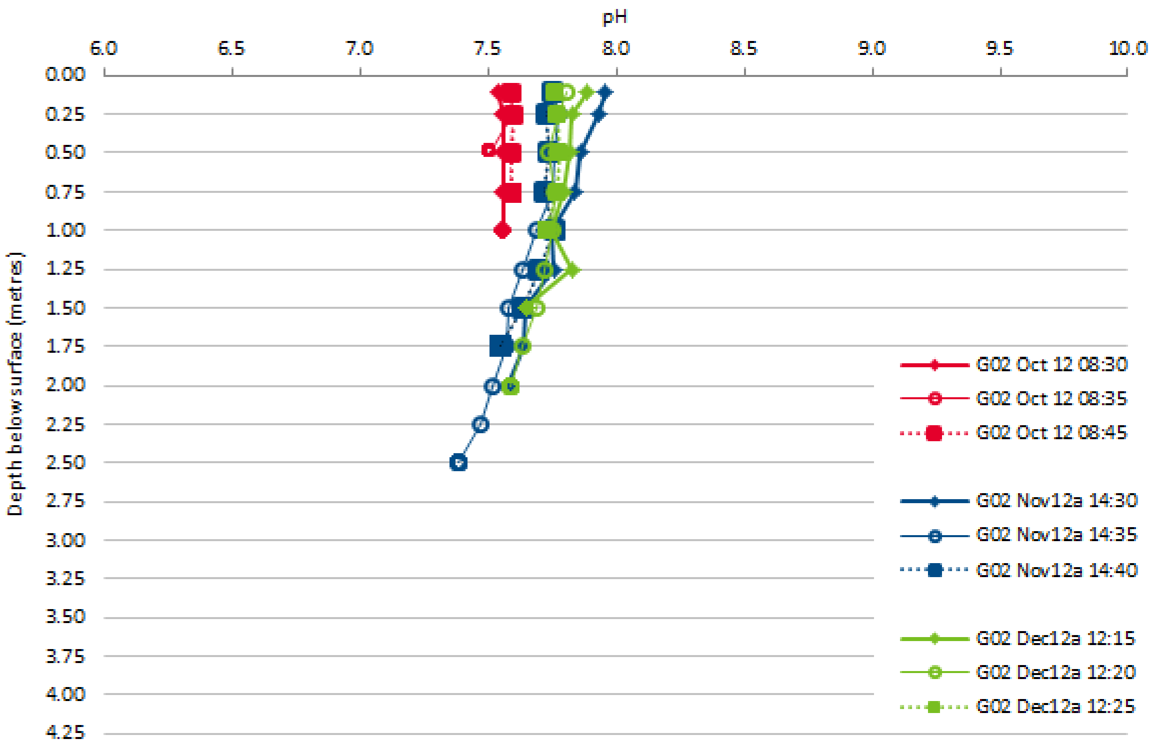


Figure 14 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G02. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



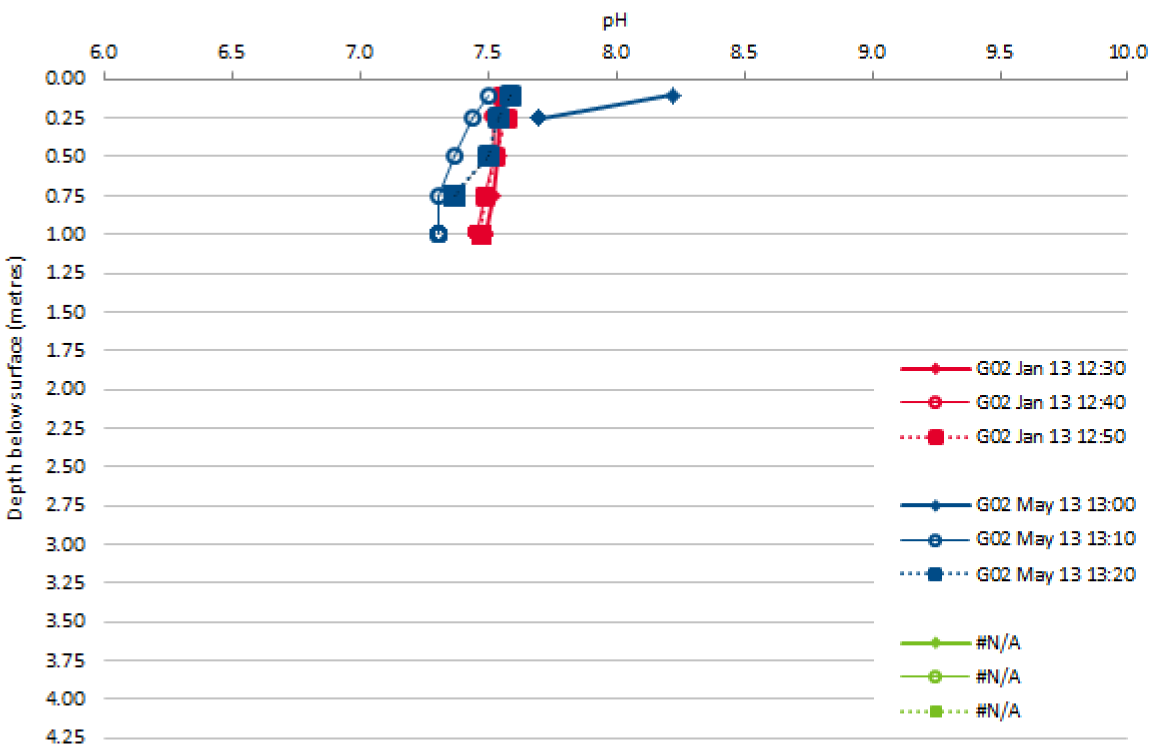
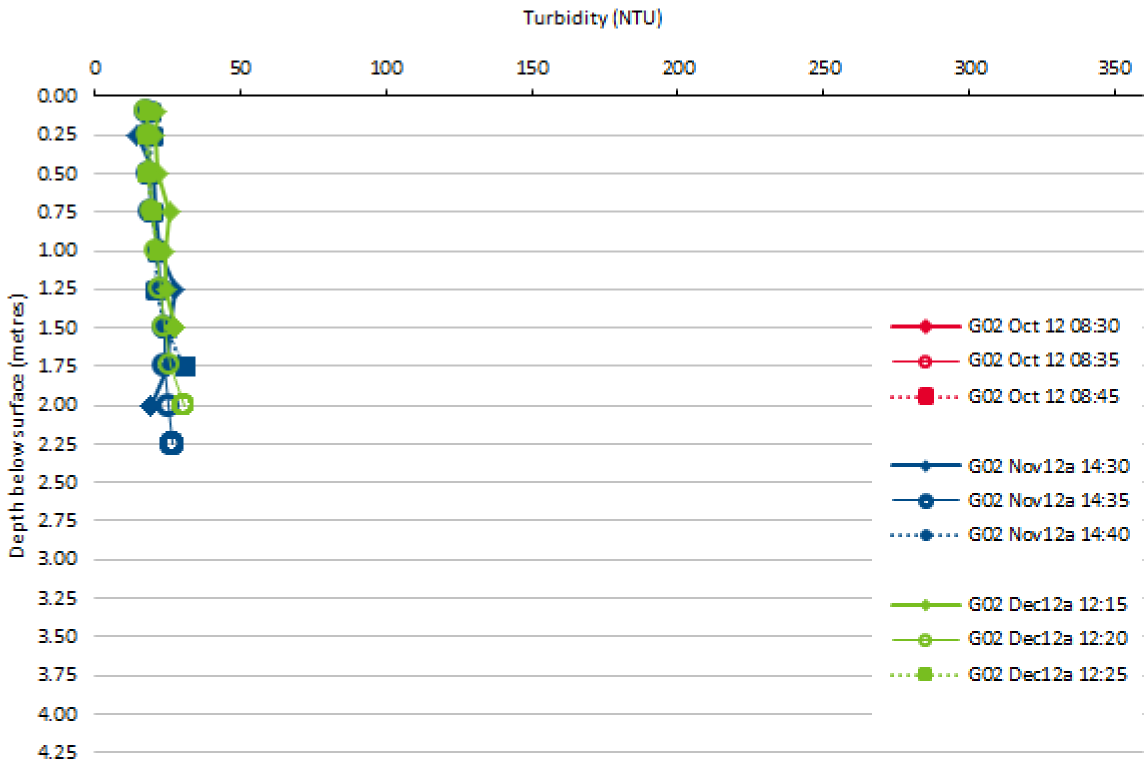


Figure 15 pH vertical water column profiles at waterhole G02. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



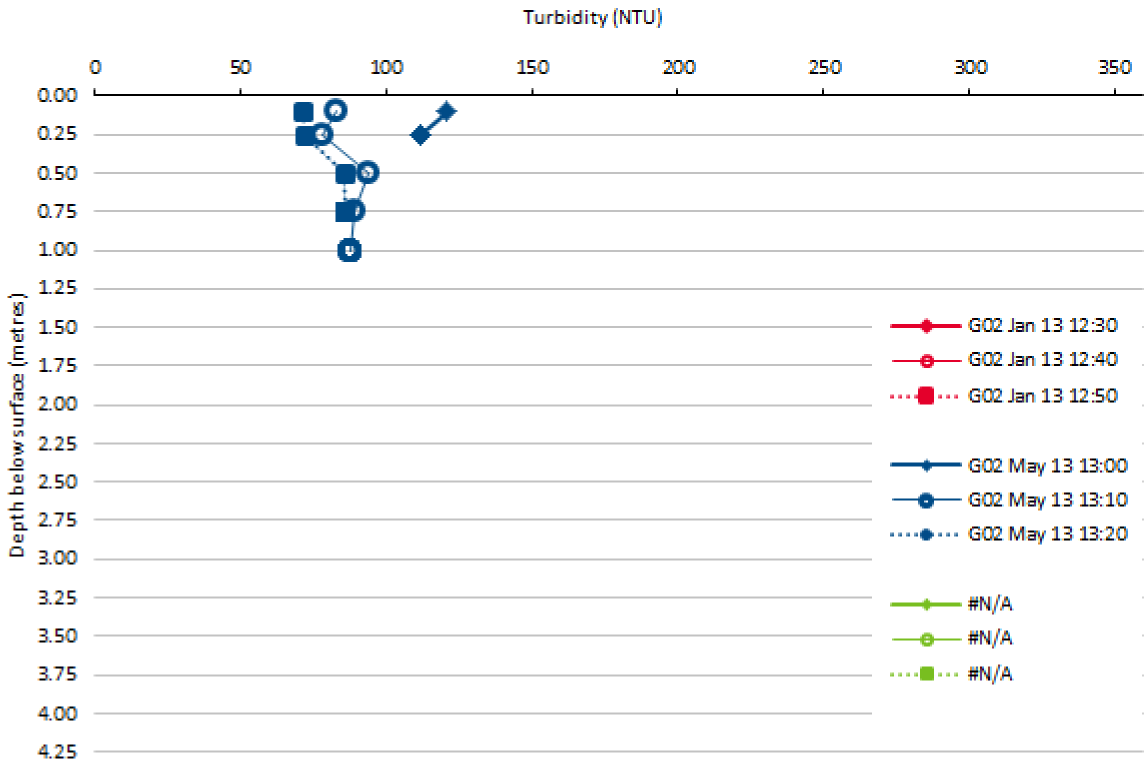
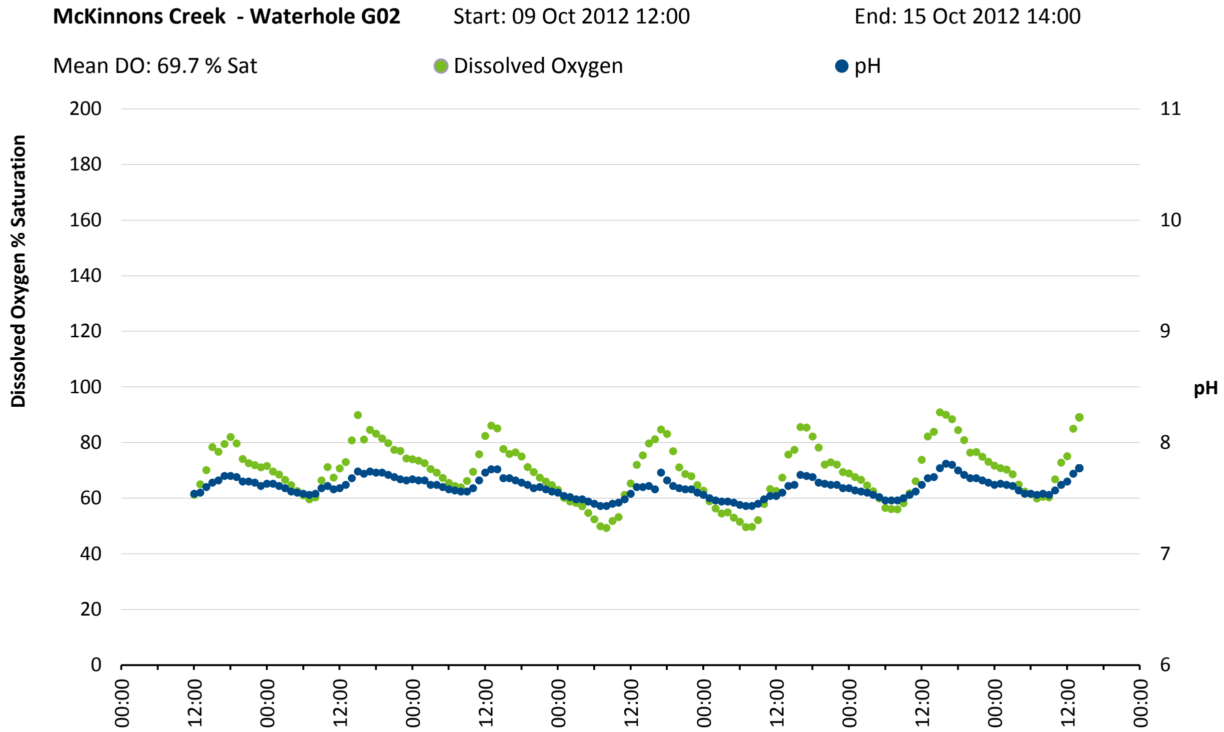


Figure 16 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G02. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



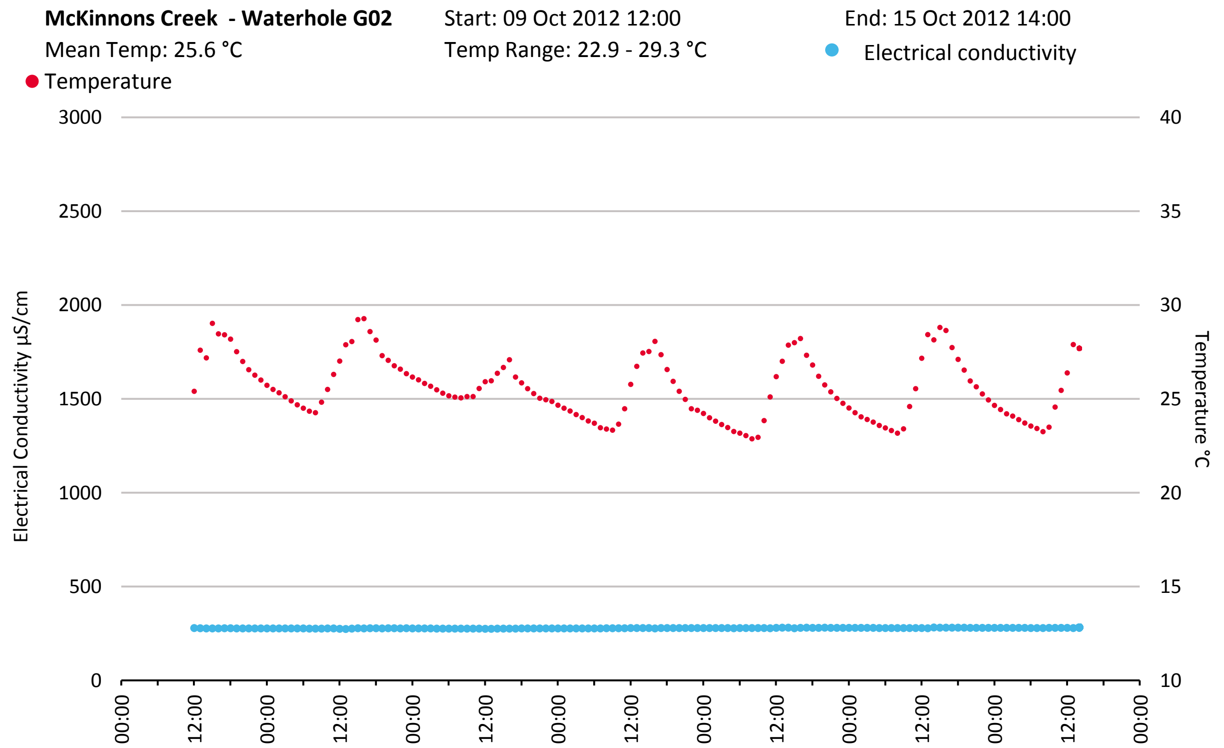
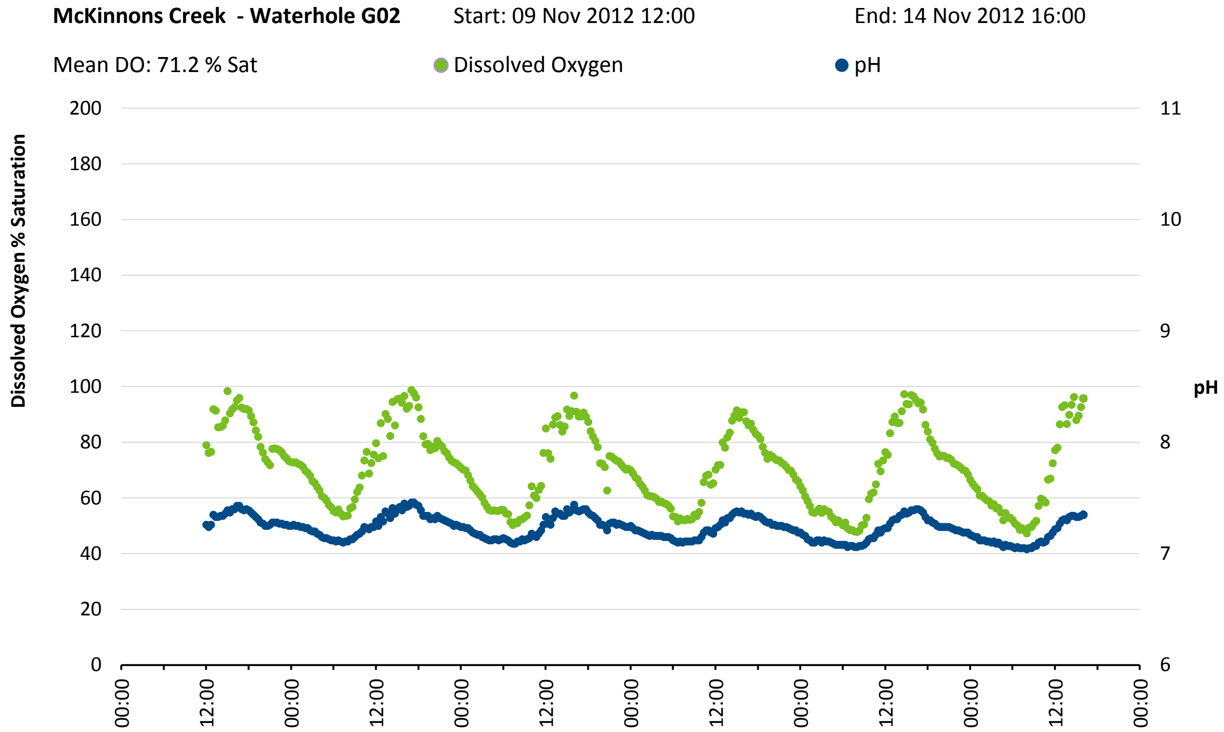


Figure 17 Diel physico-chemical data for waterhole G02, Oct 2012



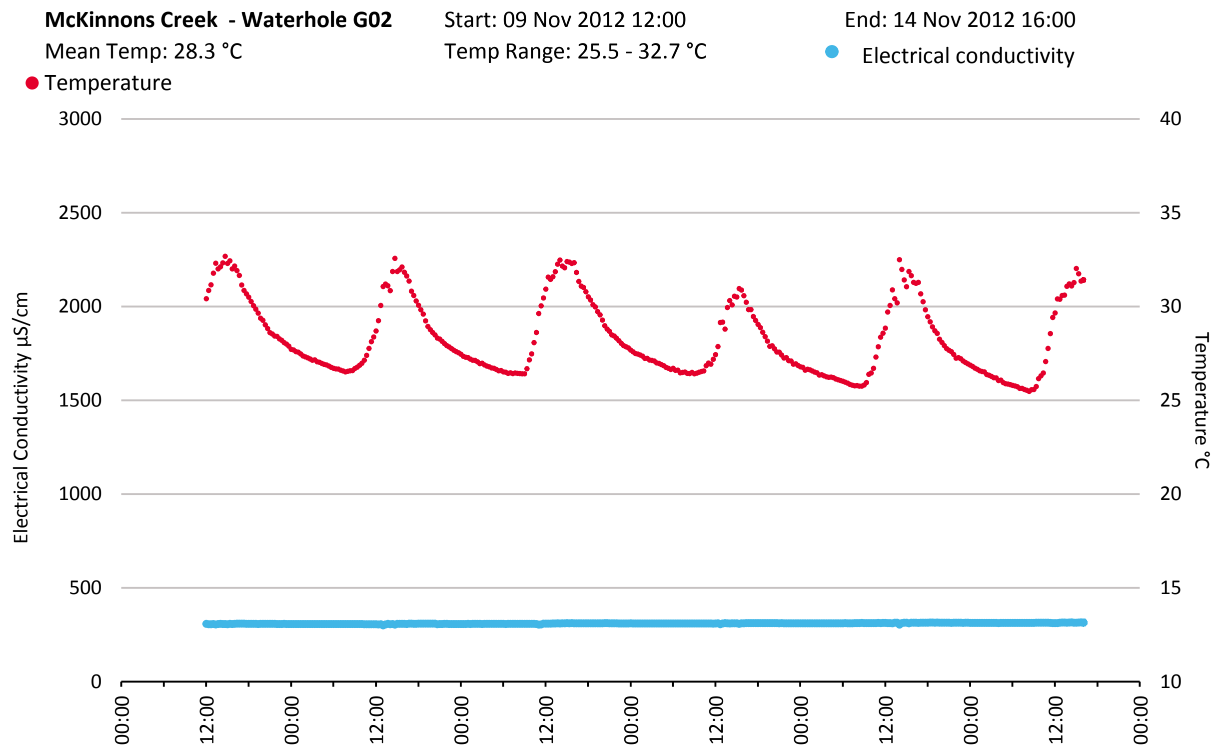
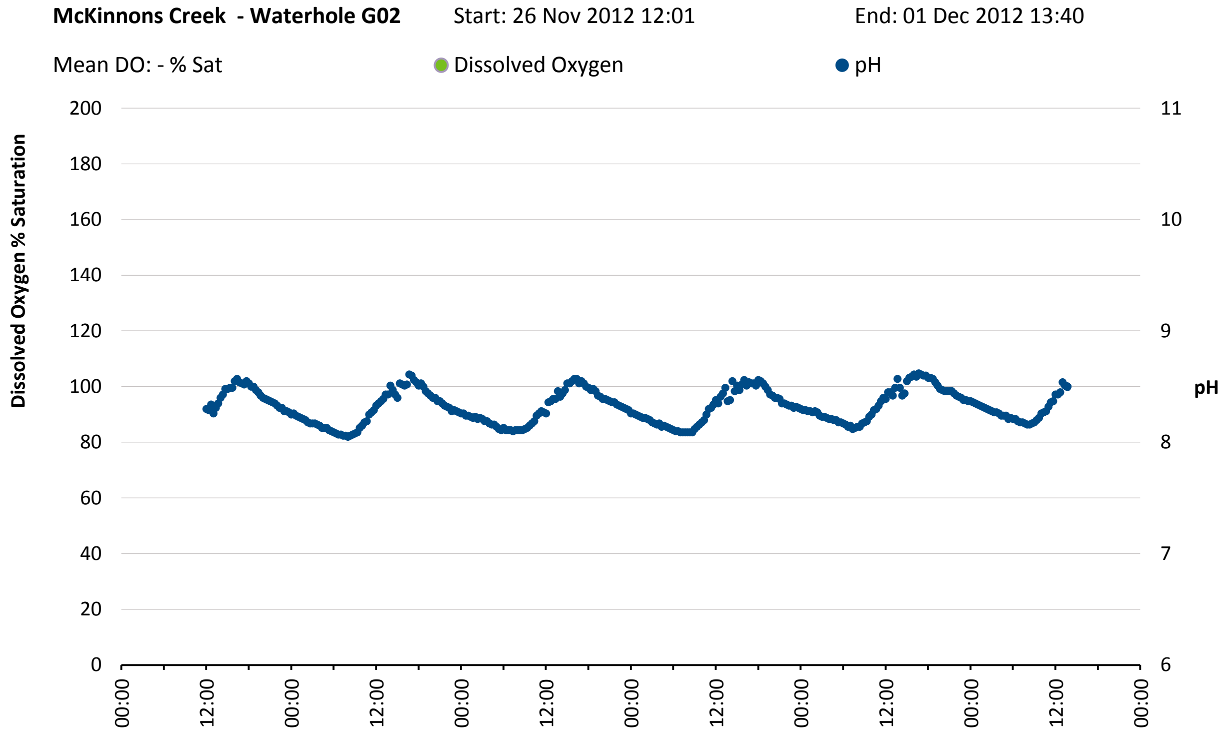


Figure 18 Diel physico-chemical data for waterhole G02, Nov 2012



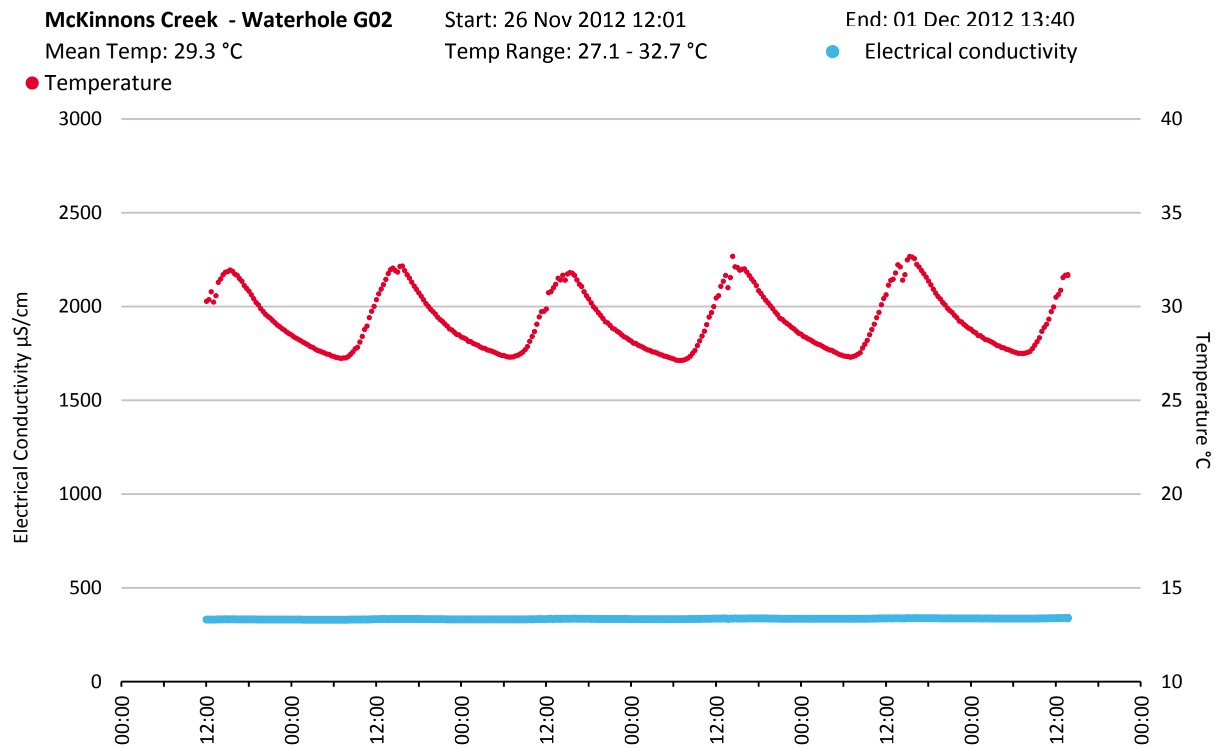


Figure 19 Diel physico-chemical data for waterhole G02, Nov-Dec 2012

WATERHOLE G03

FAMILY NAME	SPECIES NAME
Waterhole	G03
Catchment	Gilbert River
Watercourse	Einasleigh River
Waterhole location	-18.258821°, 144.061562°
Waterhole elevation	~360 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 9-Oct-12
	Survey 3: 14-Nov-12
	Survey 5: 28-Nov-12
	Survey 7: 18-Jan-13
	Survey 7: 19-Feb-13
	Survey 9: 28-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~13,100 m^2
	Waterhole volume: ~11,800 m^3
	Wetted perimeter: ~ 810 m
	Maximum depth: 1.8 m
	Average depth: 0.9 m
	Waterhole length: 350 m
Instream habitats	The waterhole was well vegetated with a range of habitats along its length. The instream habitats were dominated by rock bars and aquatic macrophyte beds. In shallower areas a range of macrophyte species were present, including *Chara* and *Blyxa* species, *Potamogeton crispus* and *Ottelia alismoides*. Deeper water hosted some areas of dense *Myriophyllum* sp.
Riparian zone	The riparian condition of this waterhole was good. Although present, cattle traffic appeared to be fairly light, and grass was present along most banks. Dominant riparian tree species are the River red gum (*Eucalyptus camaldulensis*) and *Melaleuca* species.
Waterhole depth changes	Waterhole depth dropped steadily between September 2012 and late December 2012. In January 2013 the waterhole filled to a similar depth to that recorded during September 2012, then reduced again until May 2013.
Other notes	Minor cattle damage was evident along the waterhole banks. A small tributary feeds into the waterhole on midway along its length.

a)

b)

Figure 20 a) GoogleEarth 2011 aerial view of G03. b) Left to right: 1) Upstream from right bank. 2) *Myriophyllum* sp. aquatic macrophyte bed. 3) Example of high habitat complexity, rock bars, woody debris and multiple macrophyte species.4) Looking towards right bank

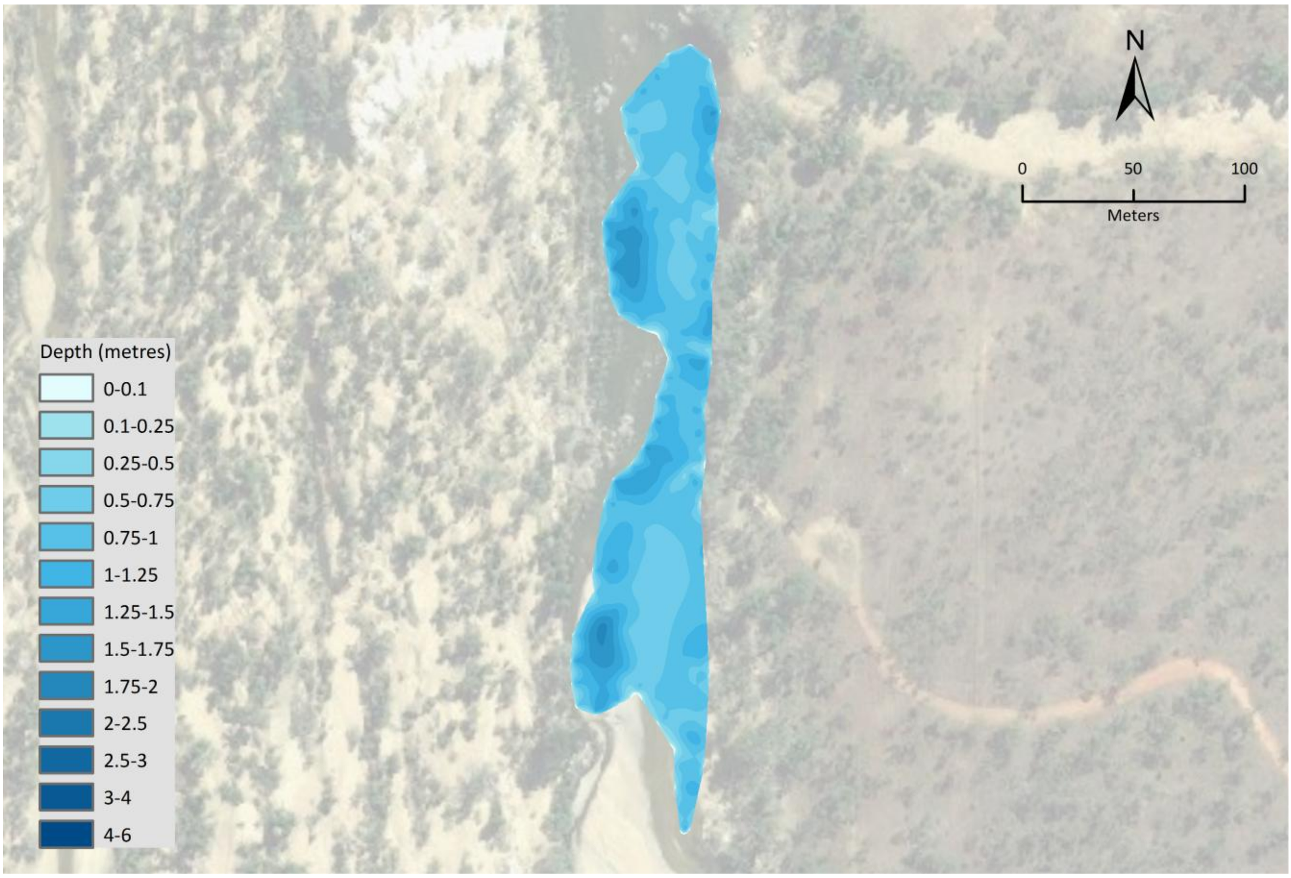


Figure 21 Bathymetry map of waterhole G03. Depth and waterhole perimeter data generated from data collected Oct 2012

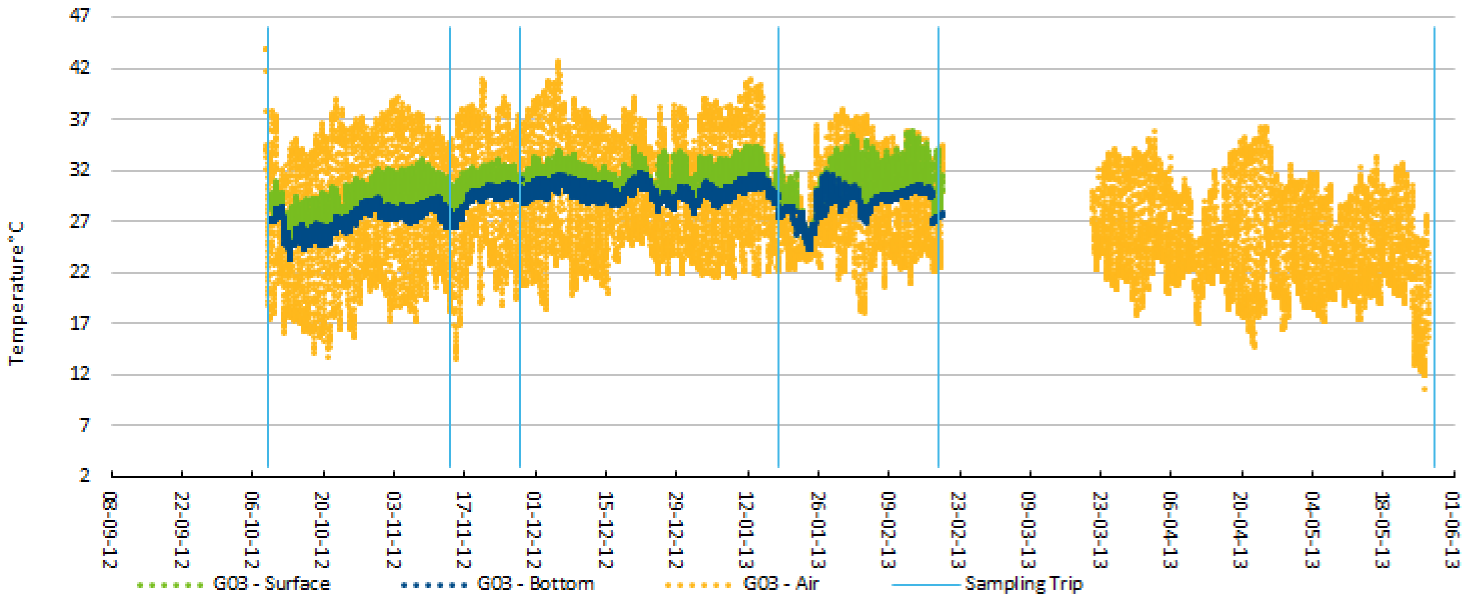
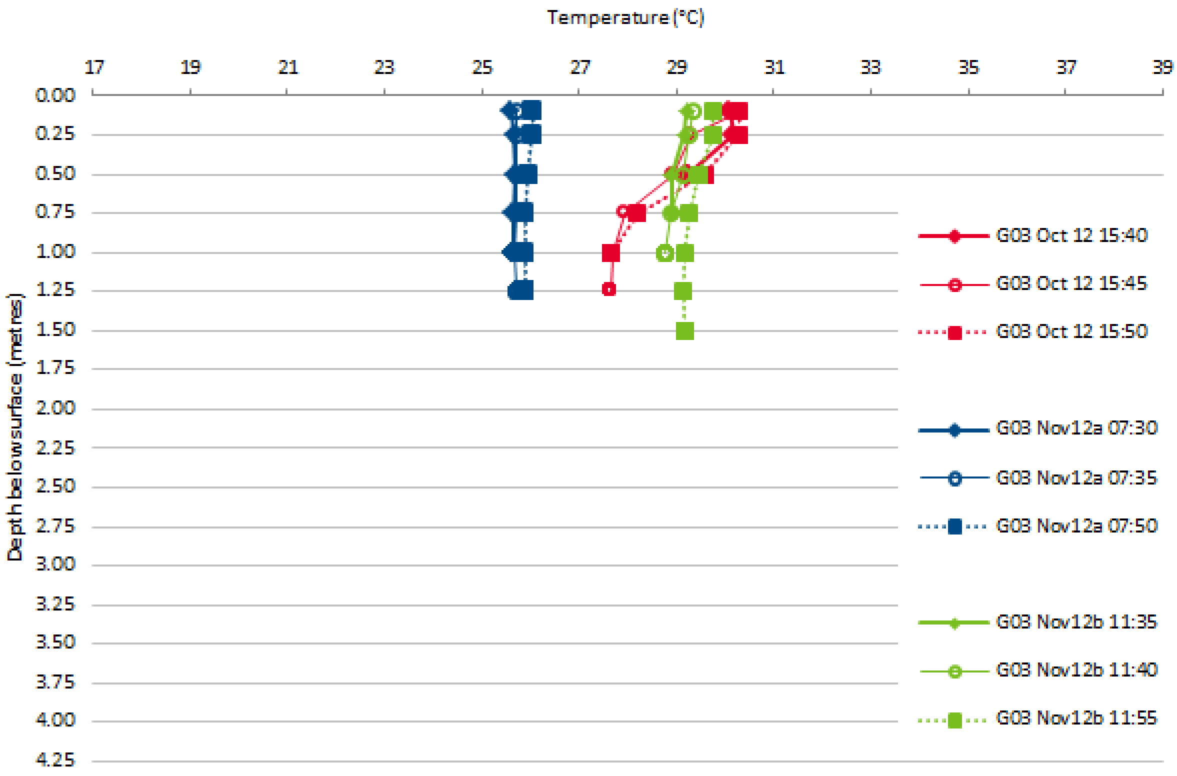


Figure 22 Long term temperature logger data for waterhole G03. Missing data corresponds to logger malfunction

Table 3 Continuous water and air temperature logger summary statistics for each survey at waterhole G03.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Oct 12	11-10-12 00:15	13-10-12 00:15	2	16.0	24.8	32.6	25.3	27.4	29.9	24.7	26.9	28.4	0.0	0.6	2.1	54.5	14.5	4.1
Nov12a	10-11-12 00:15	14-11-12 00:15	4	20.2	27.9	37.1	27.3	29.7	32.2	26.5	28.4	29.4	0.1	1.3	3.4	80.6	50.5	35.3
Nov12b	22-11-12 00:15	25-11-12 00:15	3	18.9	28.3	39.2	29.2	30.8	33.0	29.2	30.0	30.7	0.0	0.8	2.7	58.5	32.3	21.7
Jan 13	15-01-13 00:15	18-01-13 00:15	3	22.1	28.1	35.5	28.9	30.4	32.2	28.8	30.0	31.5	-0.1	0.4	2.3	29.5	12.9	6.9
Feb 13	14-02-13 00:15	18-02-13 00:15	4	22.4	27.7	35.6	28.5	31.3	35.3	26.9	29.9	30.6	0.1	1.5	4.8	72.7	55.4	41.2



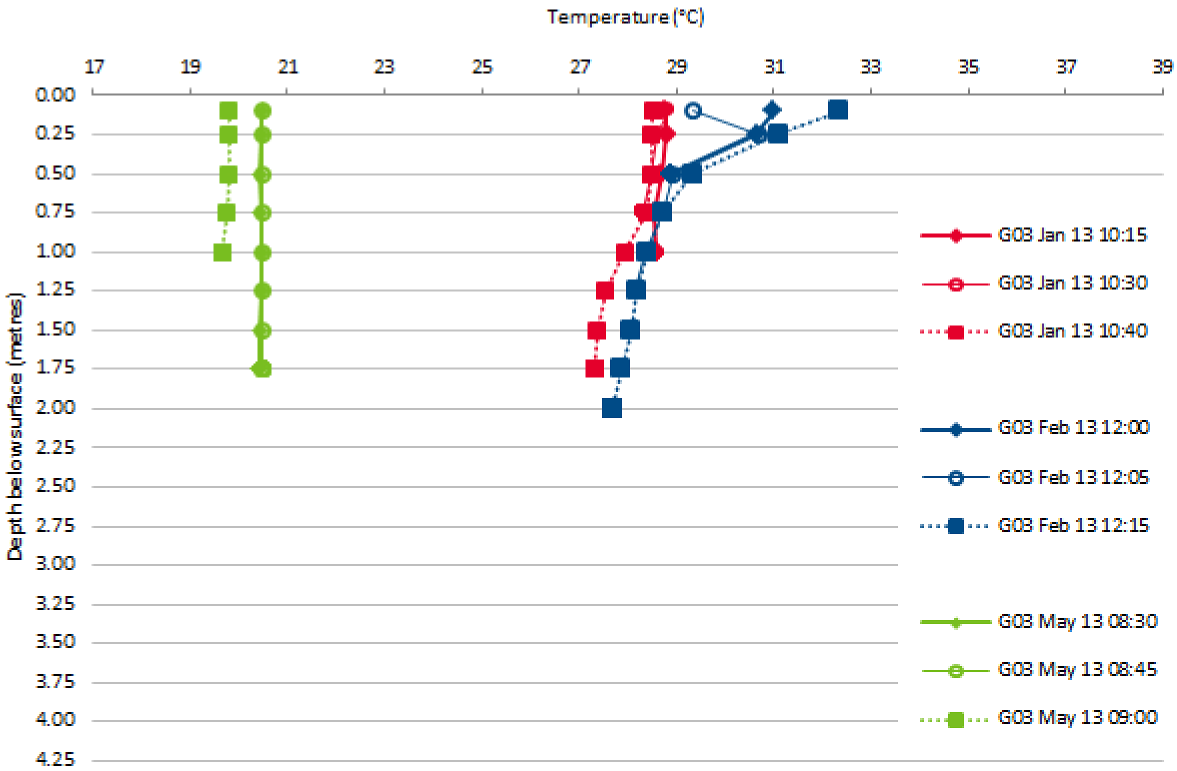
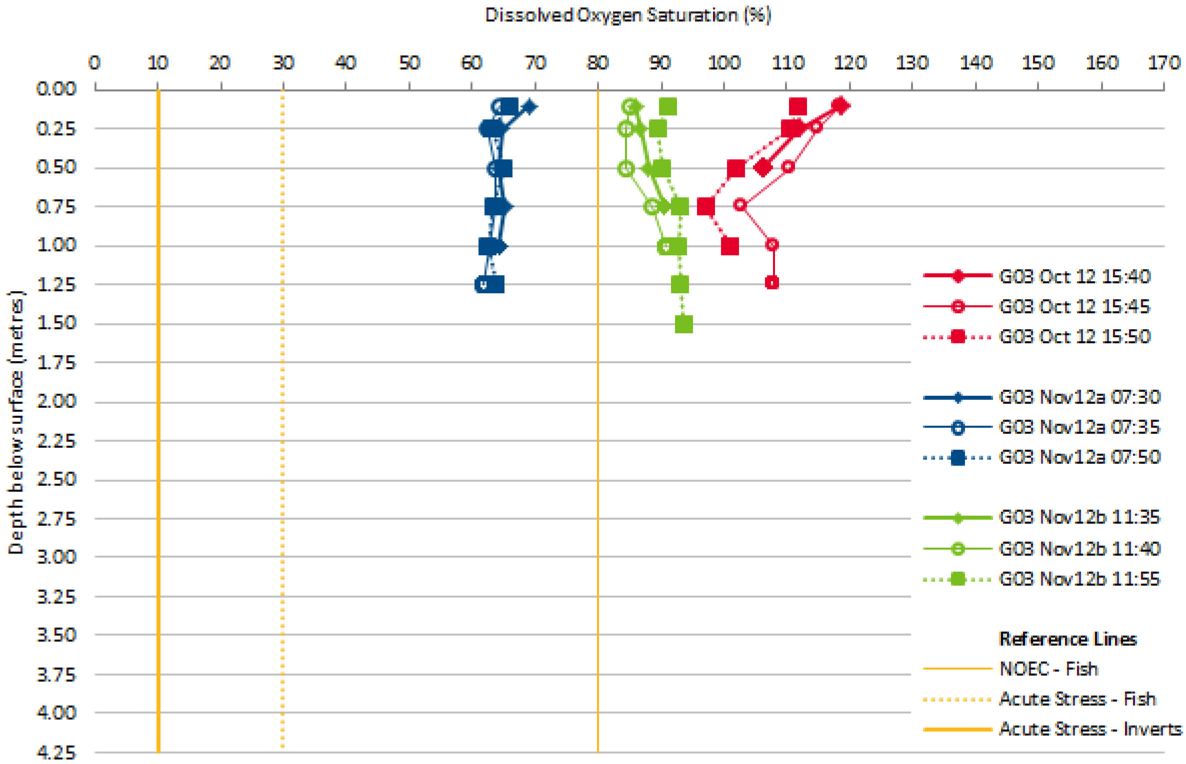


Figure 23 Temperature vertical water column profiles at waterhole G03. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



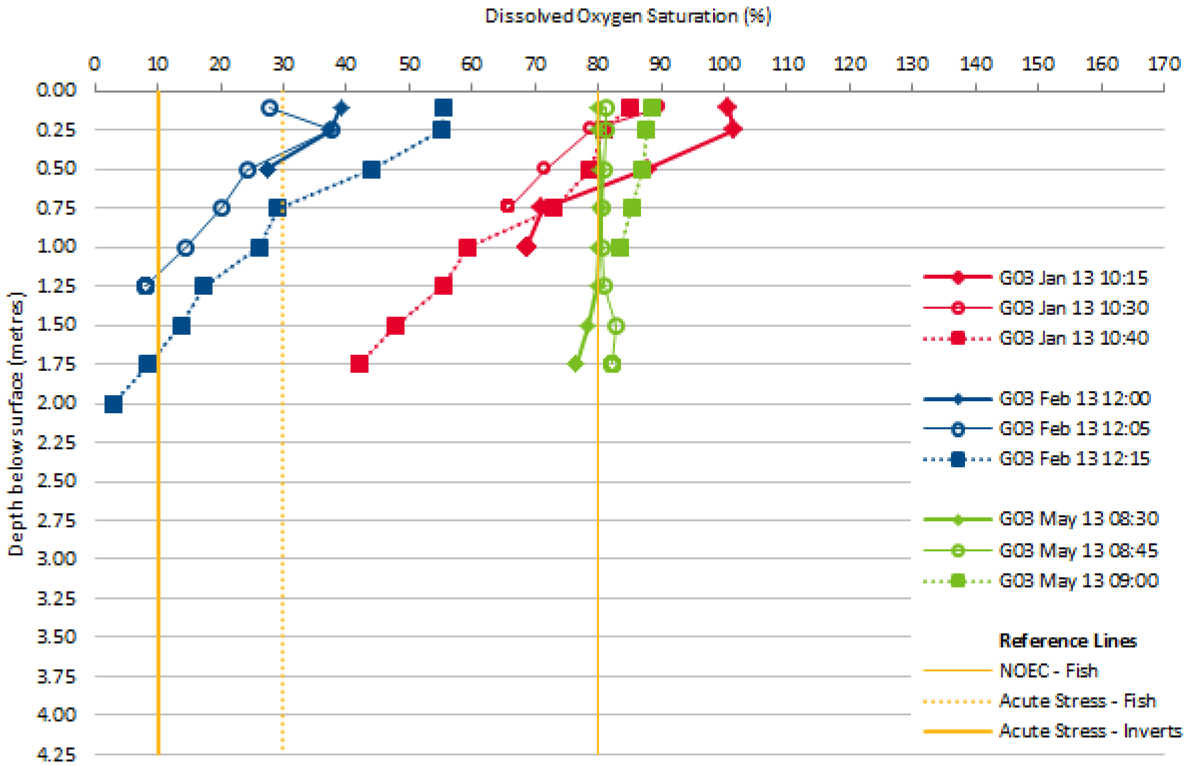
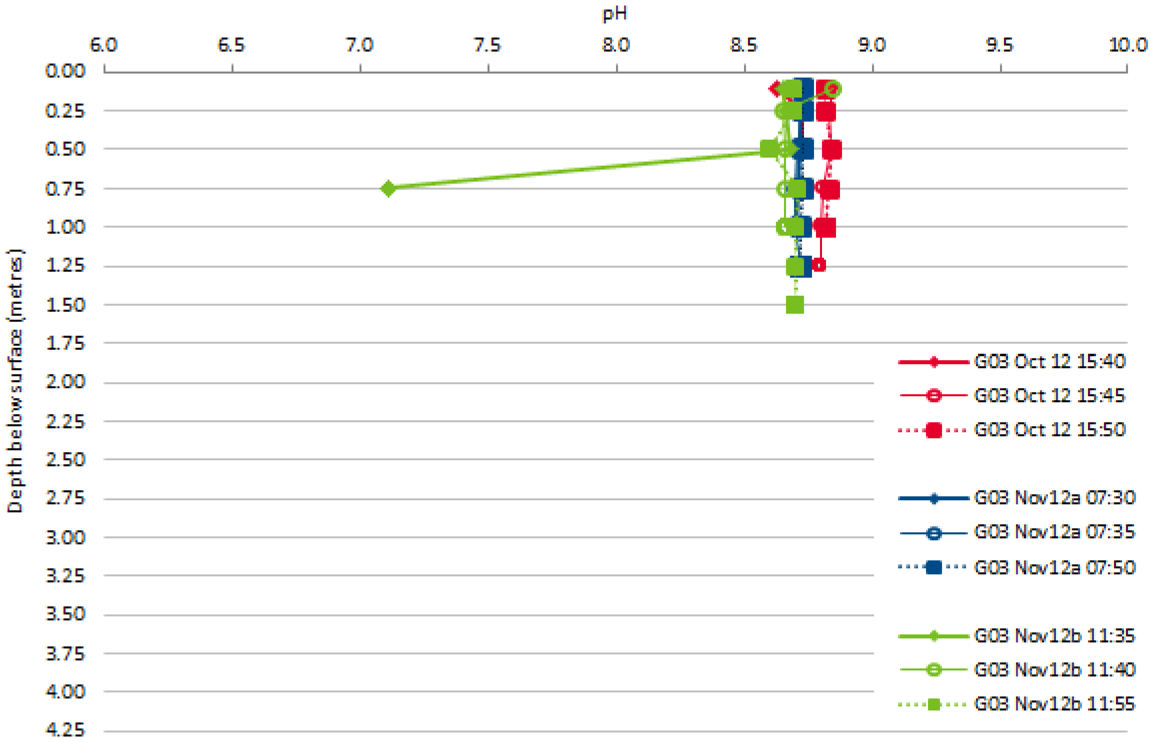


Figure 24 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G03. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



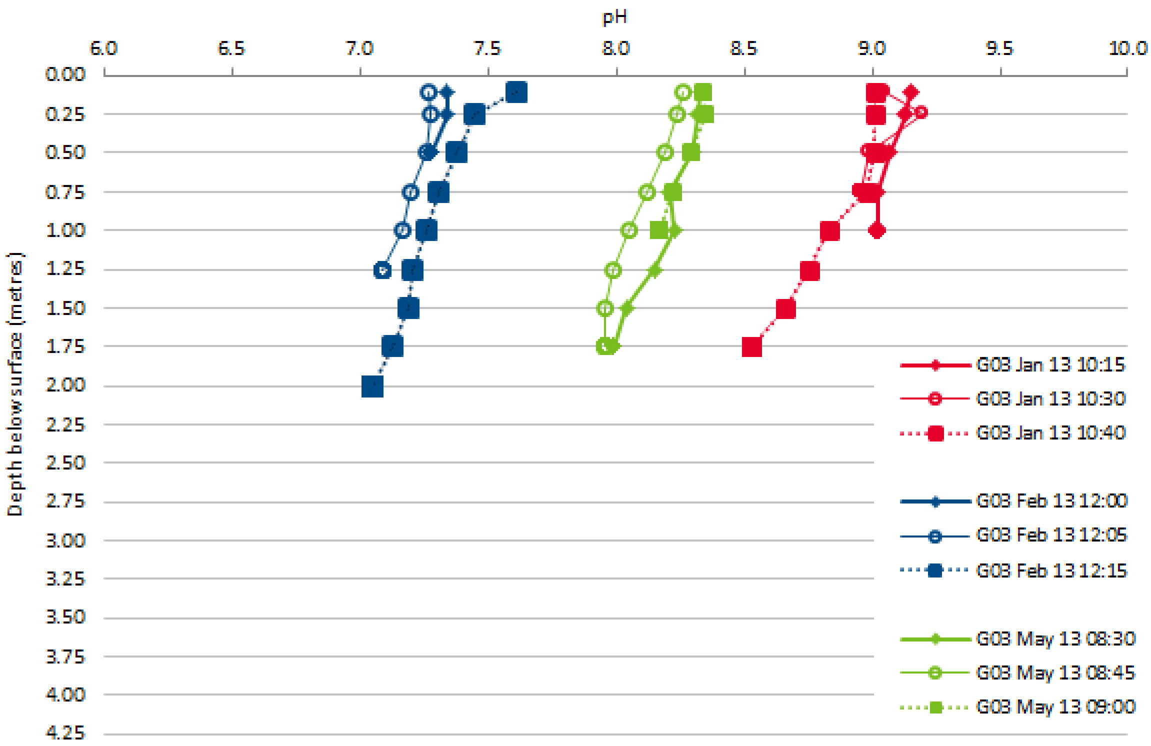
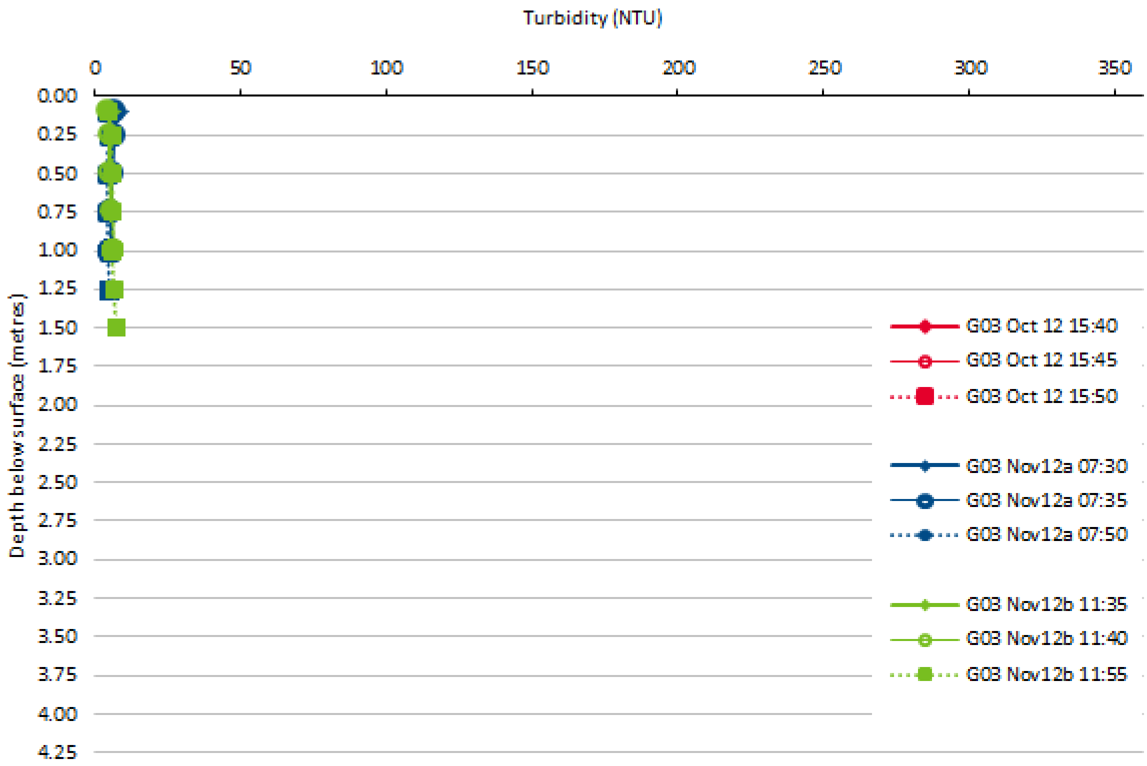


Figure 25 pH vertical water column profiles at waterhole G03. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



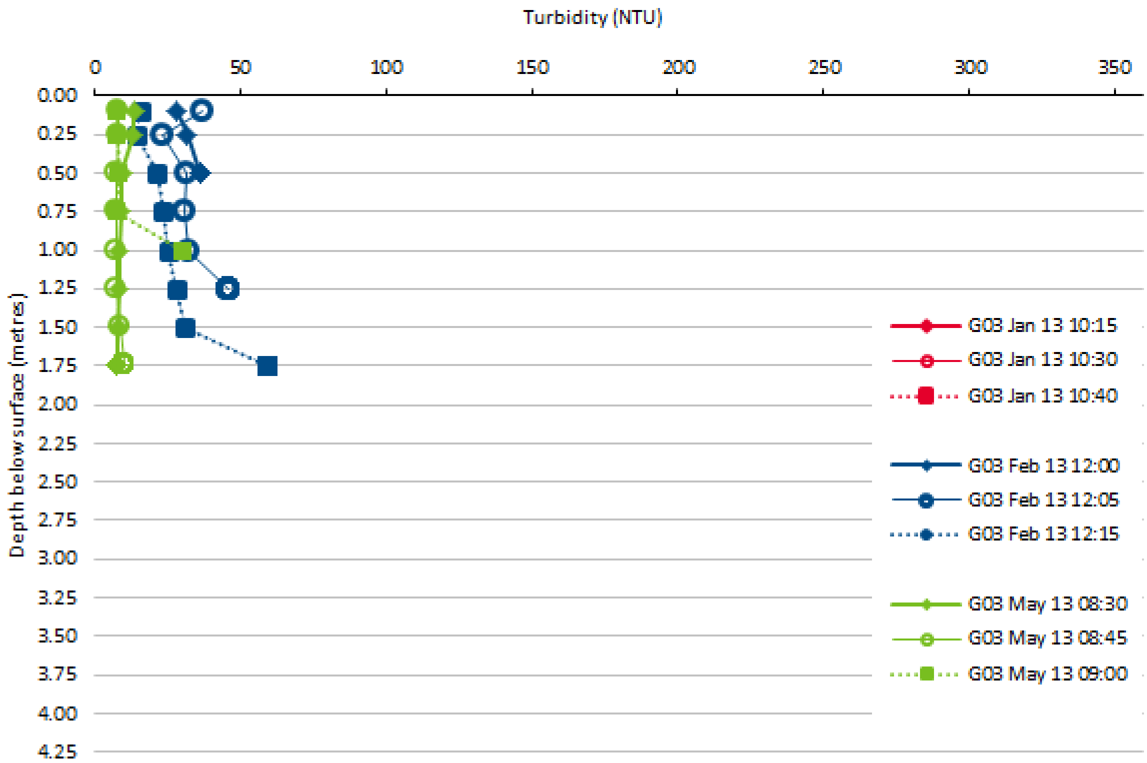
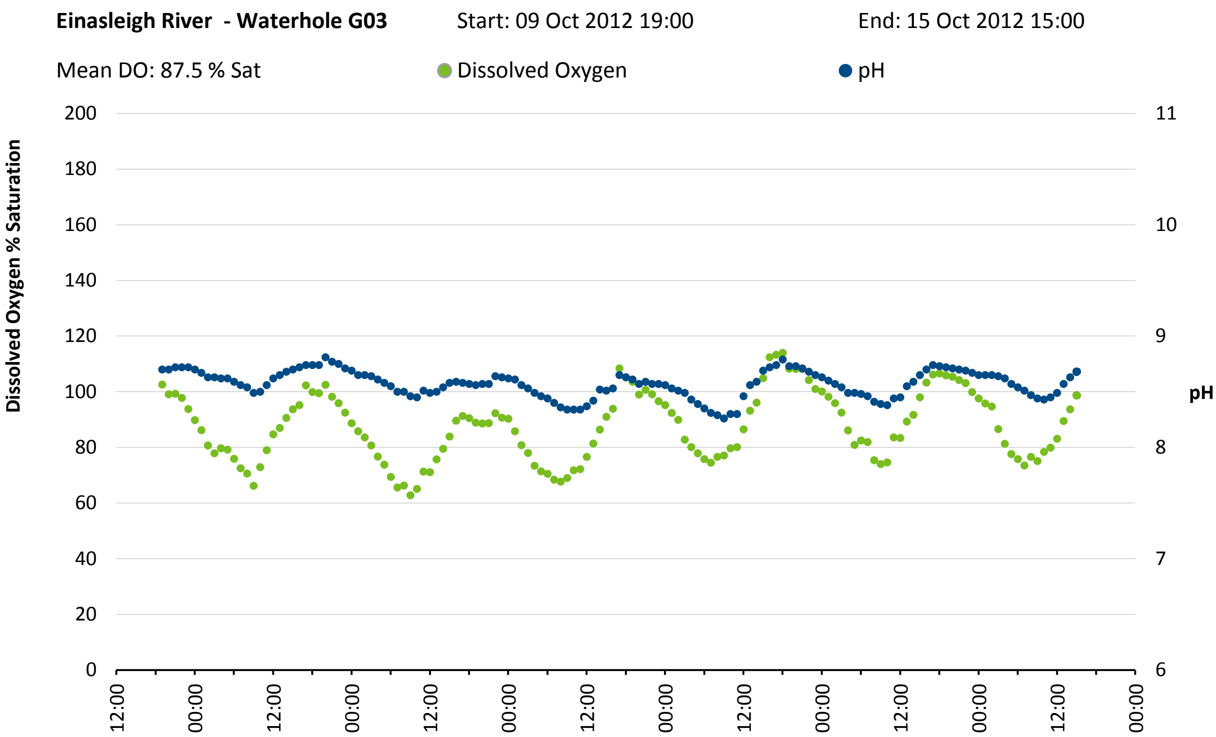


Figure 26 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G03. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



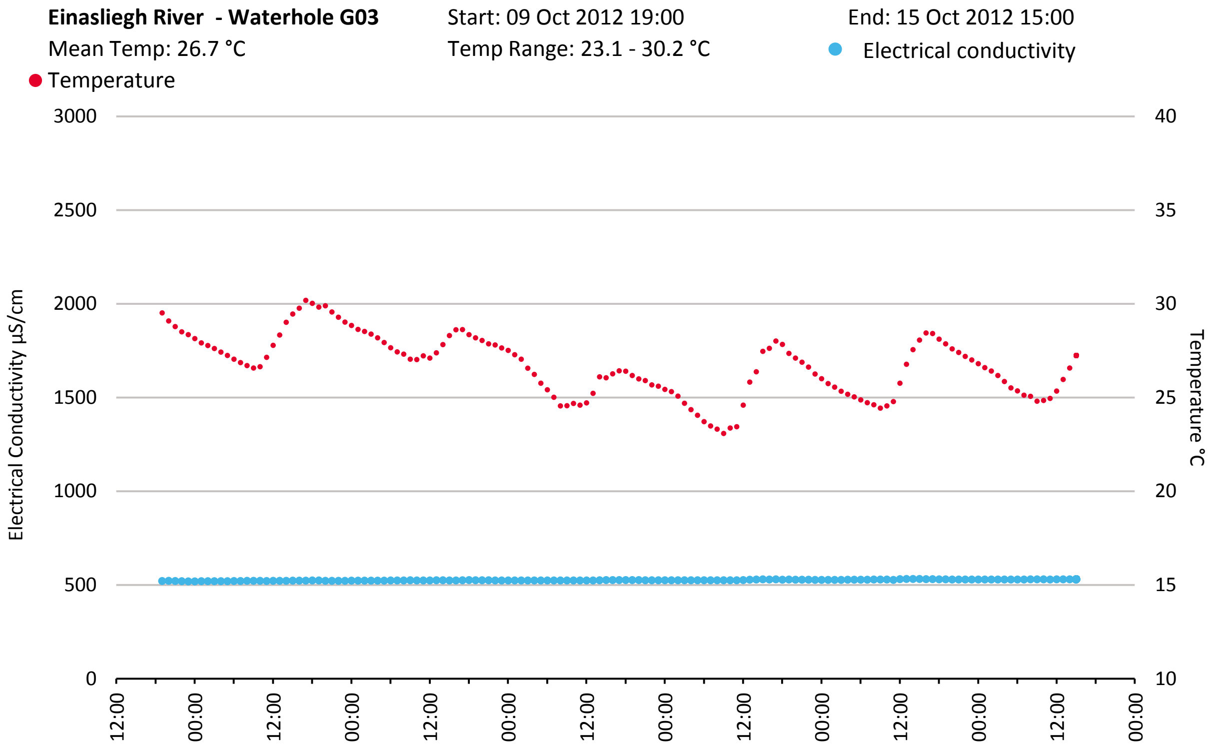
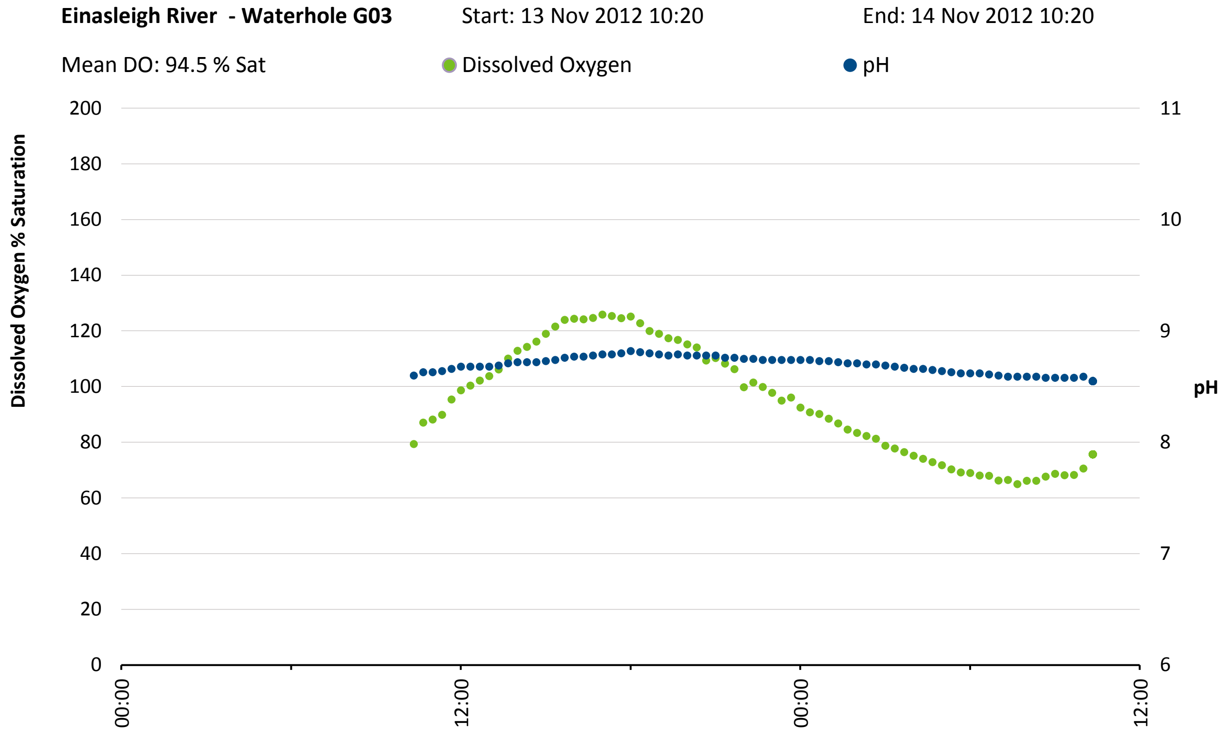


Figure 27 Diel physico-chemical data for waterhole G03, Oct 2012



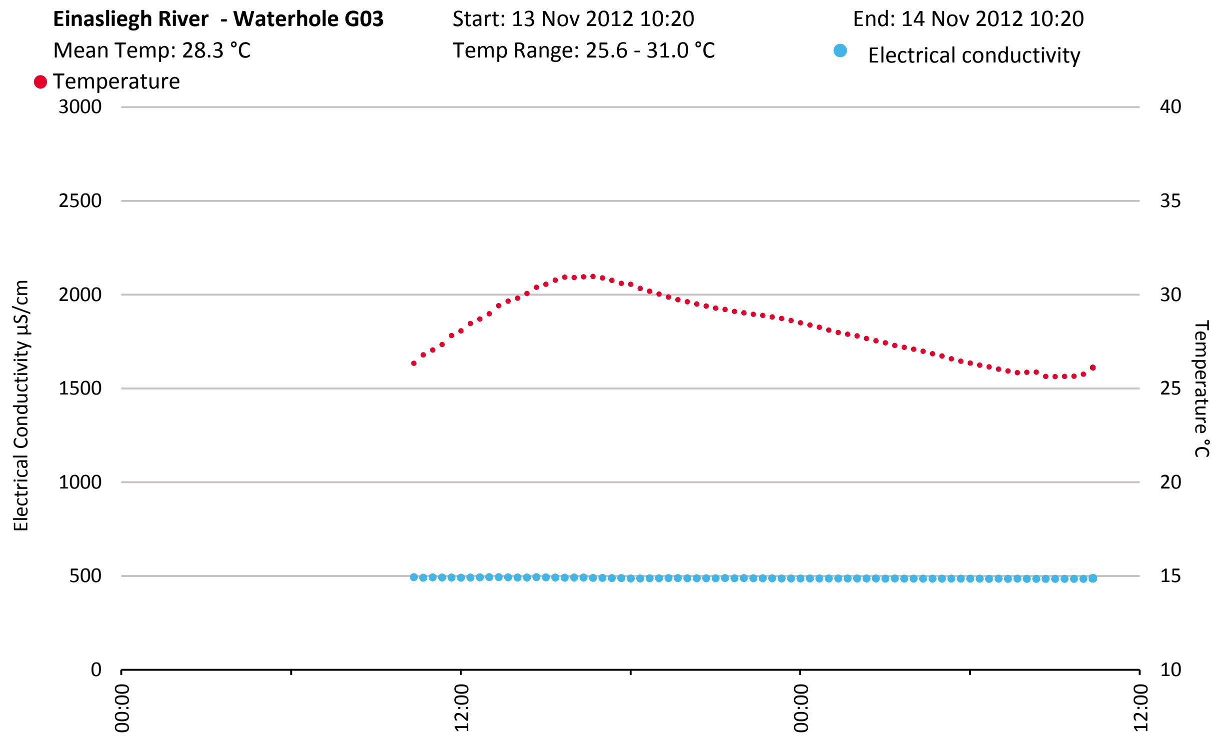
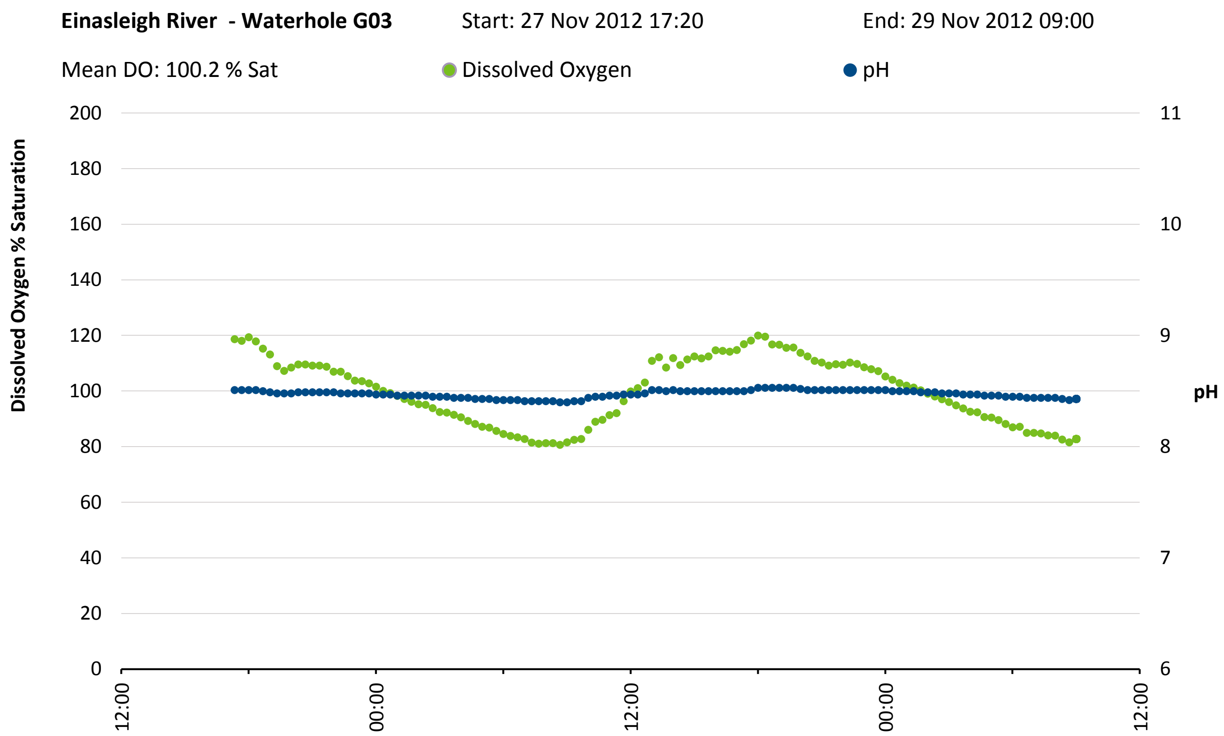


Figure 28 Diel physico-chemical data for waterhole G03, Nov 2012



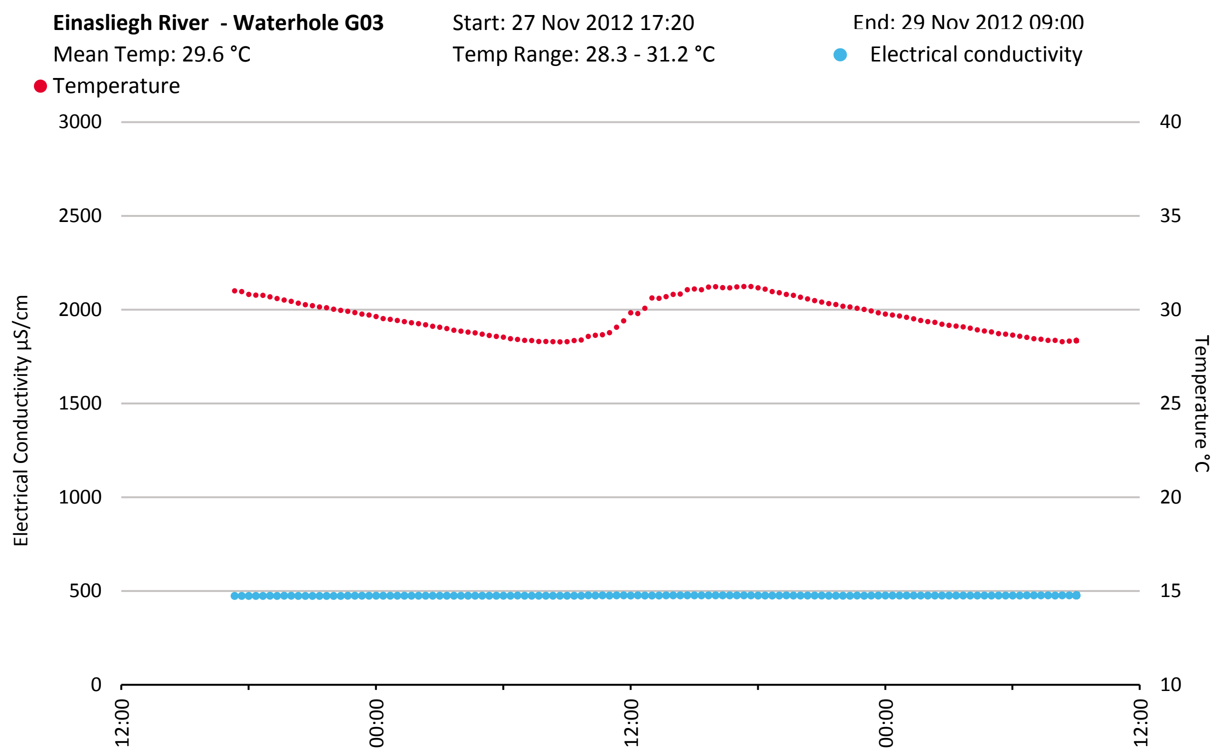


Figure 29 Diel physico-chemical data for waterhole G03, Nov 2012

WATERHOLE G04

FAMILY NAME	SPECIES NAME
Waterhole	G04
Catchment	Gilbert River
Watercourse	Einasleigh River
Waterhole location	-18.221634°, 144.036359°
Waterhole elevation	~350 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 10-Oct-12
	Survey 3: 13-Nov-12
	Survey 5: 28-Nov-12
	Survey 7: 18-Jan-13
	Survey 9: 28-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~4900 m^2
	Waterhole volume: ~3000 m^3
	Wetted perimeter: ~ 370 m
	Maximum depth: 1.4 m
	Average depth: 0.6 m
	Waterhole length: 160 m
Instream habitats	The waterhole was well vegetated with a range of habitats including rock bars at the southern and northern ends of the waterhole. Aquatic macrophyte (*Myriophyllum* sp.) beds were present, along with with *Potamogeton crispus* and *Ottelia alismoides*.
Riparian zone	Rubber vine (*Cryptostegia grandiflora*), was fairly dense in the riparian zone, and thistles were also present in lesser numbers. Cattle traffic has removed most groundcover, although some *Sporobolus* grasses remain on poor margins. *Melaleuca* spp. fringe the waterhole. On the higher banks River red gums (*Eucalyptus camaldulensis*) are common. Overall riparian vegetation offers very limited shade across the waterhole (<10%).
Waterhole depth changes	Waterhole depth remained relatively constant across the Assessment period, dropping slightly between September 2012 and late December 2012. In January 2013 depth increased to a similar level to September 2012 then dropped slightly to May 2013.
Other notes	Extensive cattle damage was evident throughout the riparian zone.

a)

b)

Figure 30 a) GoogleEarth 2011 aerial view of G04. b) Left to right: 1) Downstream from central channel. 2) From right bank, with aquatic macrophytes in the foreground 3) Looking towards left bank. Epilithic algal growth in the foreground, rubbervine in the riparian zone. 4) Upstream from central channel

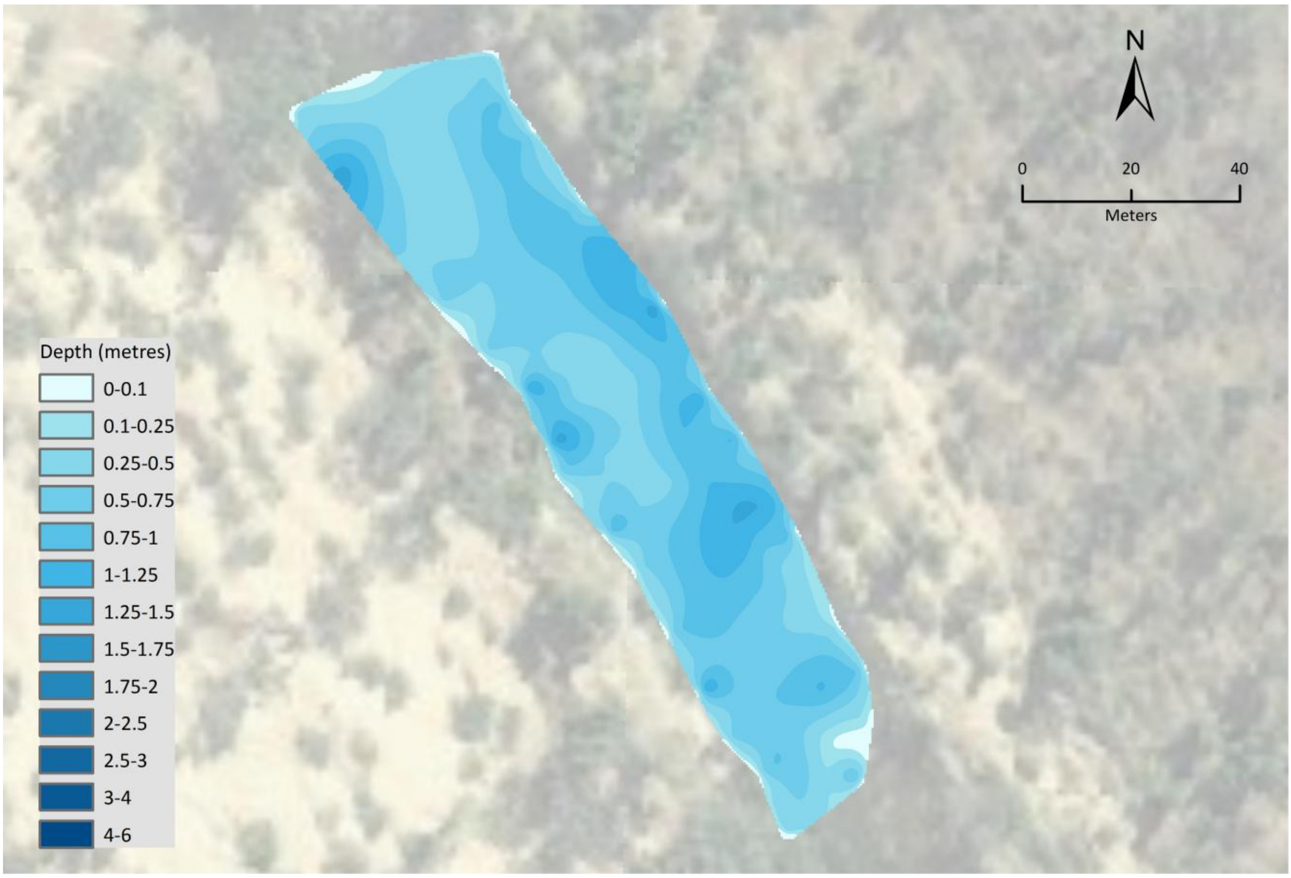


Figure 31 Bathymetry map of waterhole G04. Depth and waterhole perimeter data generated from data collected Oct 2012

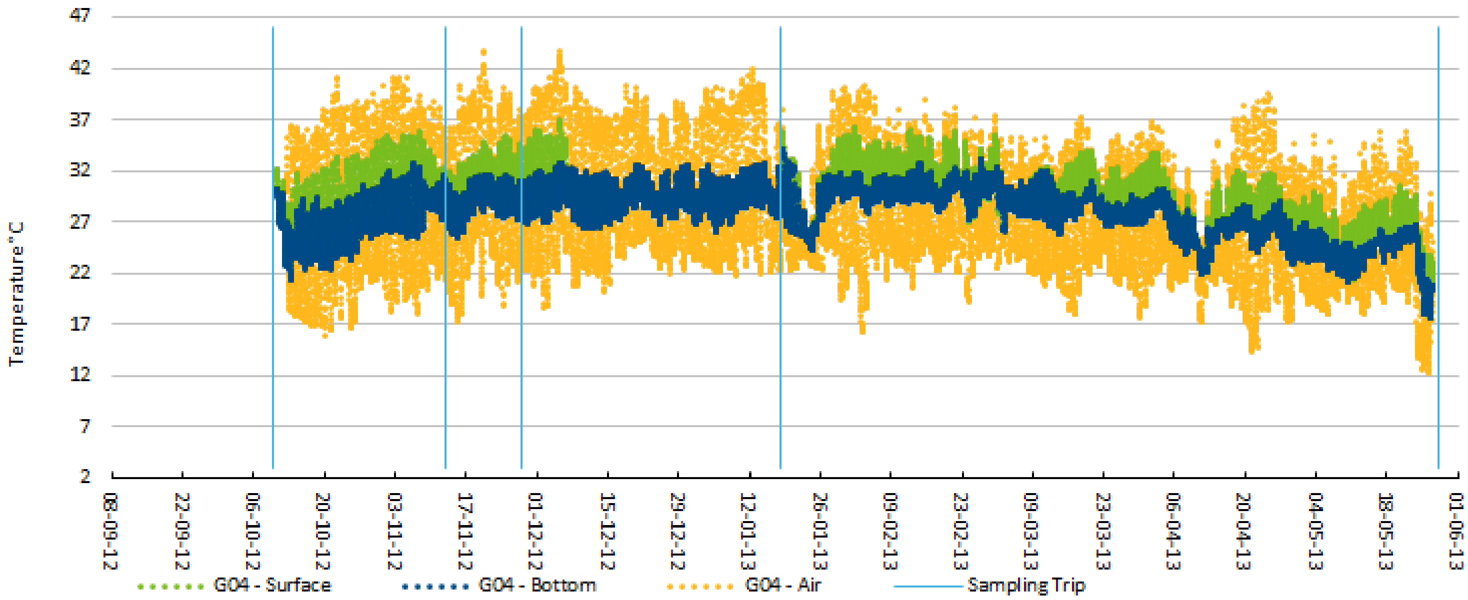
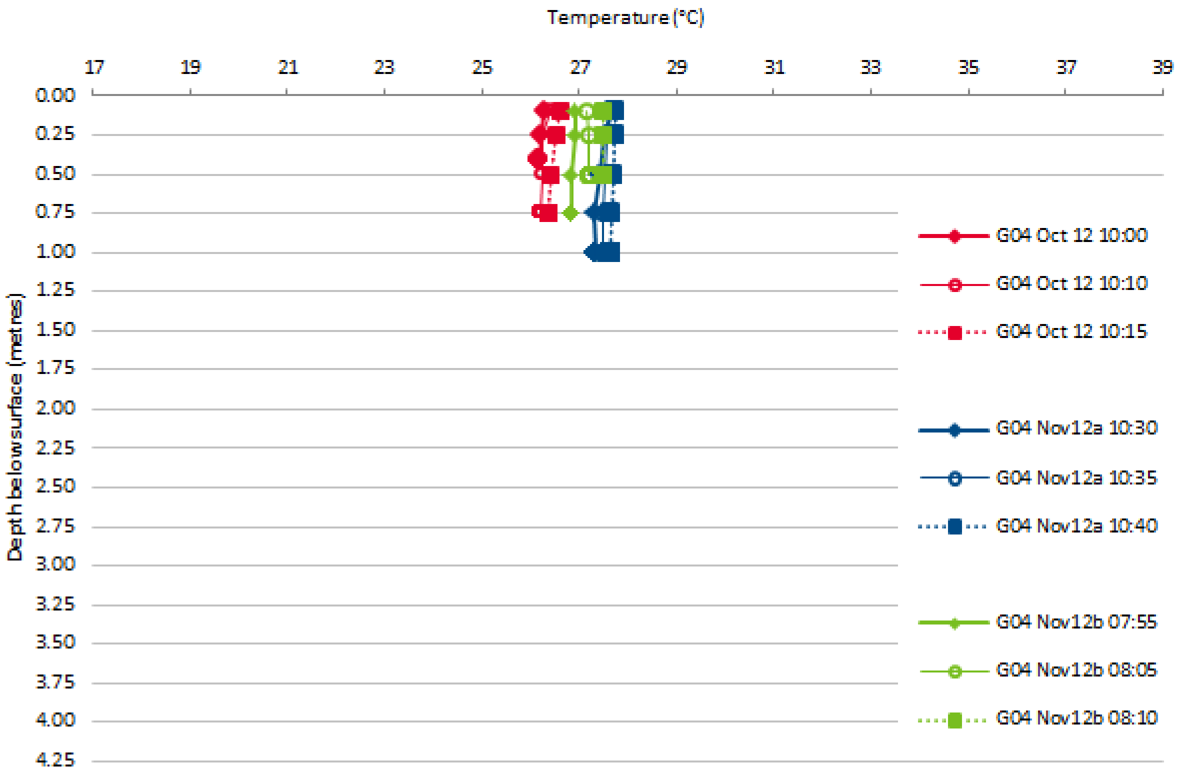


Figure 32 Long term temperature logger data for waterhole G04

Table 4 Continuous water and air temperature logger summary statistics for each survey at waterhole G04.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Oct 12	11-10-12 00:15	13-10-12 00:15	2	20.8	27.8	35.3	23.2	27.1	31.0	22.8	26.6	29.8	0.0	0.5	2.0	35.9	11.0	5.5
Nov12a	08-11-12 00:15	15-11-12 00:15	7	19.0	28.3	38.7	26.1	29.8	34.9	25.9	29.0	31.5	0.0	0.8	4.2	48.1	29.5	18.4
Nov12b	23-11-12 00:15	29-11-12 00:15	6	18.8	29.7	40.2	27.3	30.6	35.4	27.0	29.4	31.5	0.0	1.2	4.0	59.5	42.1	34.5
Jan 13	18-01-13 10:40	20-01-13 10:40	2	22.3	27.0	38.0	26.1	29.6	35.8	26.1	29.3	34.2	-0.1	0.3	2.4	16.0	8.3	5.6
May 13	21-05-13 00:15	26-05-13 00:15	5	12.5	22.4	35.9	18.0	25.1	30.1	18.0	24.2	26.6	-0.2	0.9	3.6	49.0	34.9	26.6



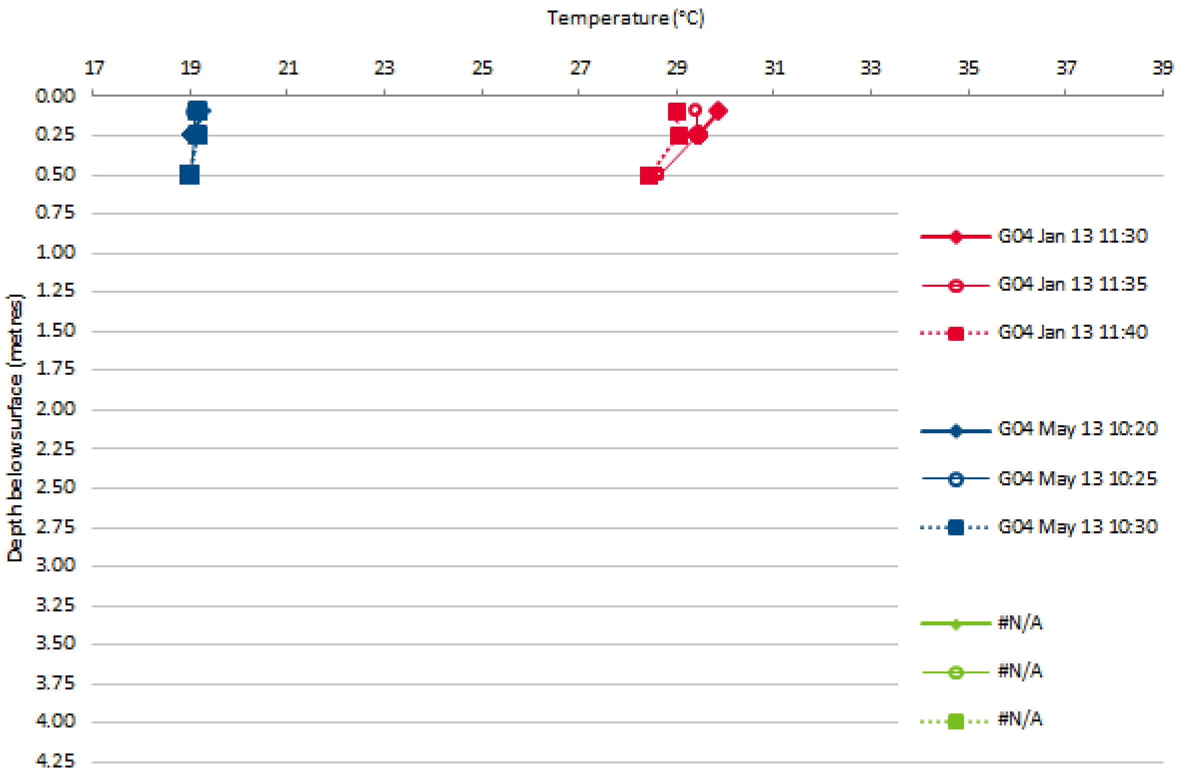
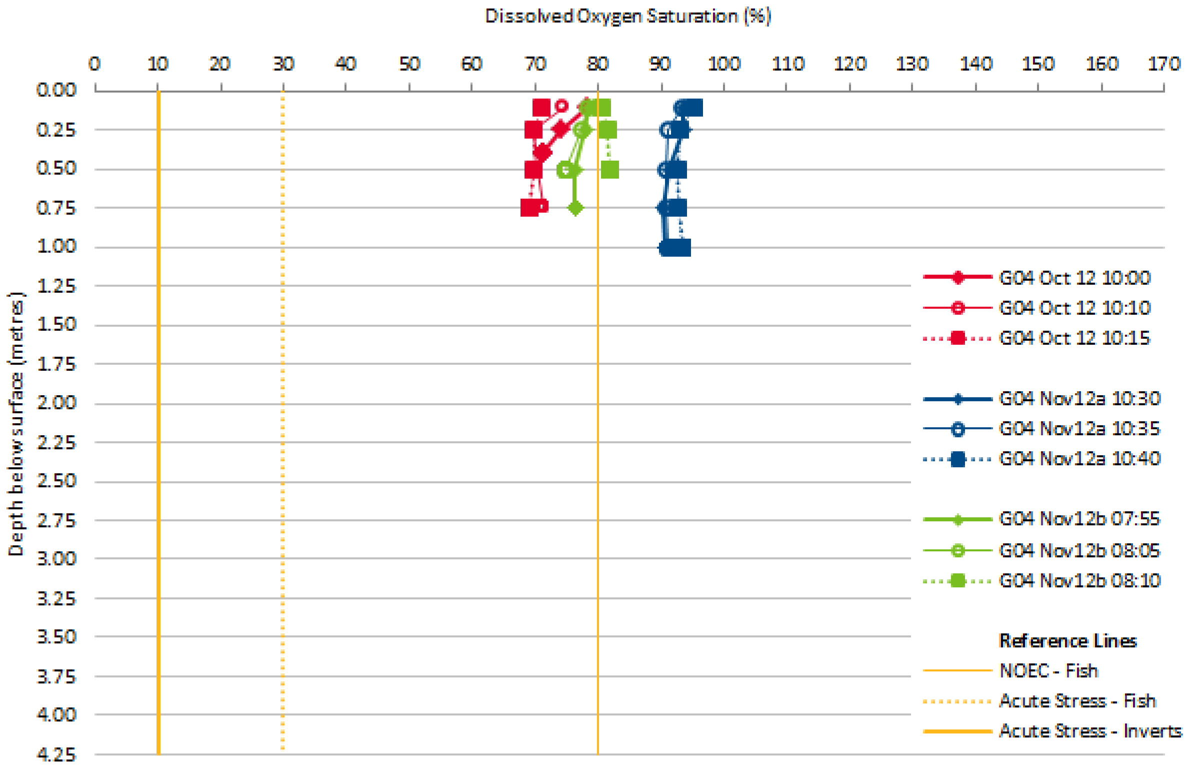


Figure 33 Temperature vertical water column profiles at waterhole G04. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



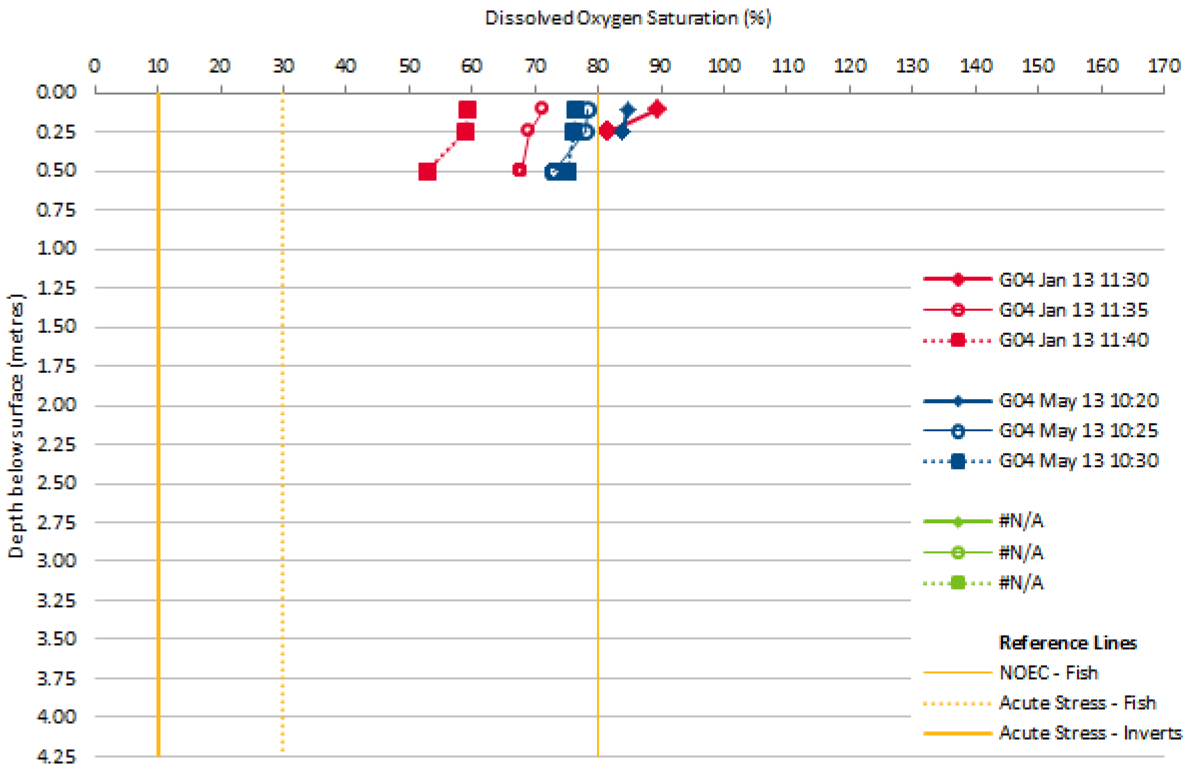
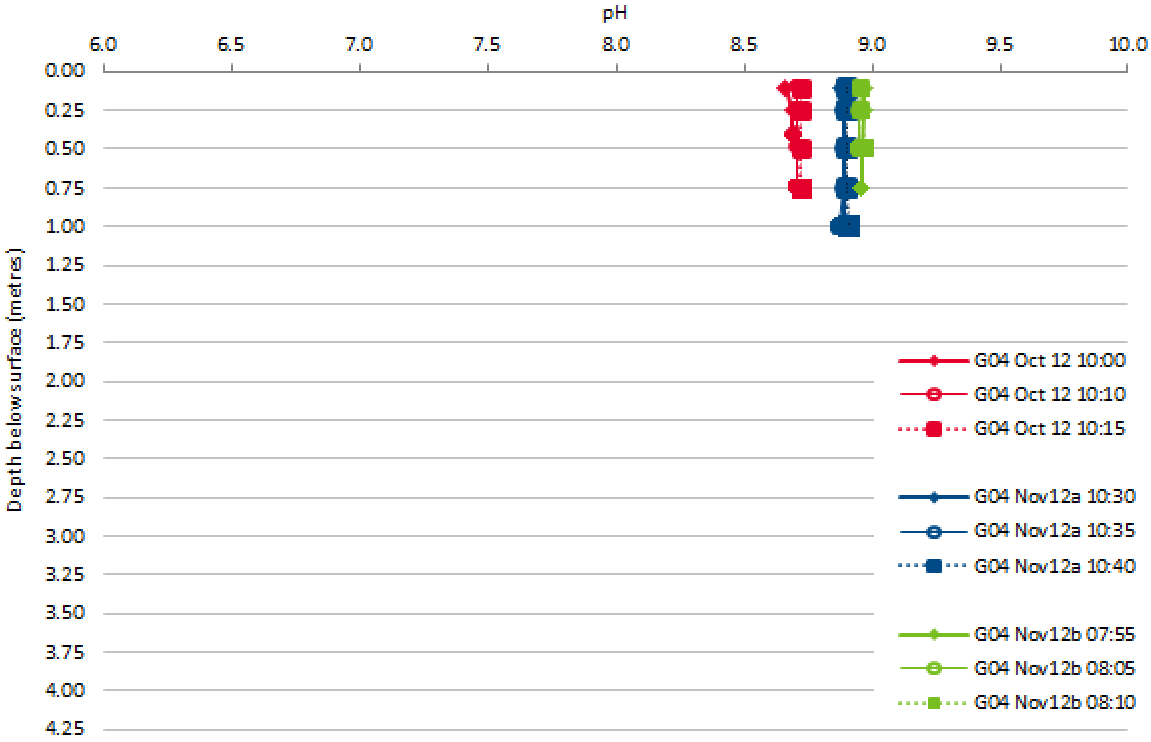


Figure 34 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G04. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



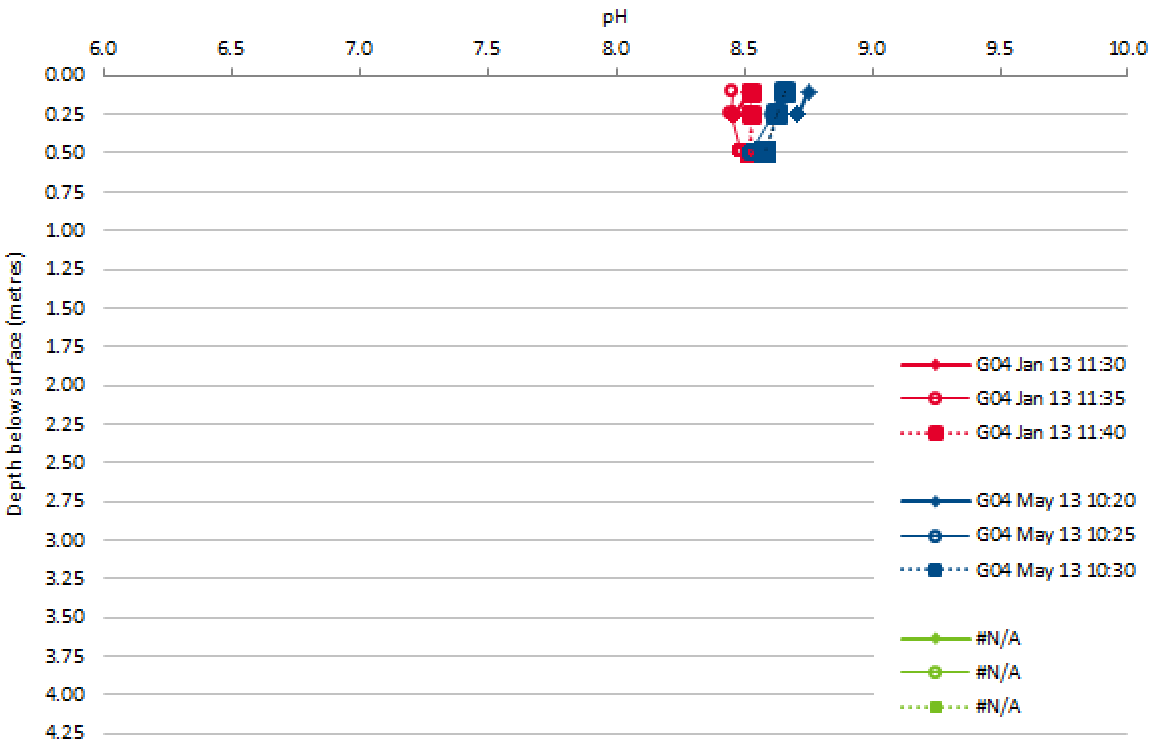
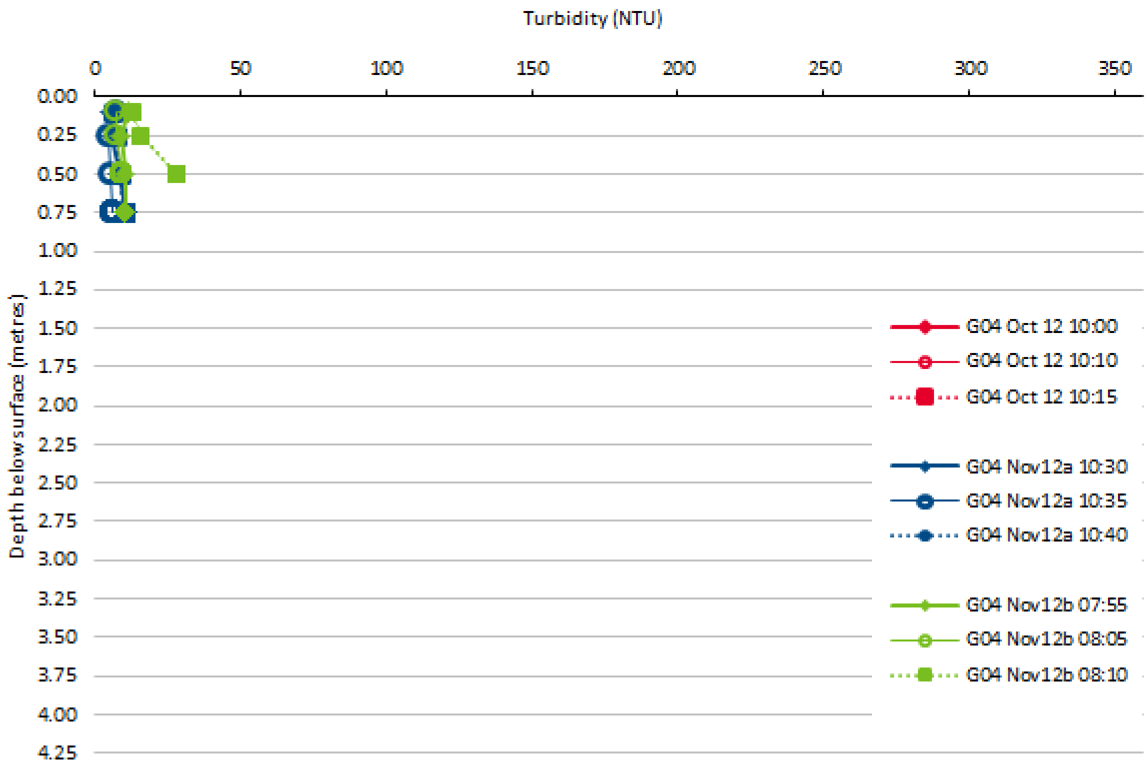


Figure 35 pH vertical water column profiles at waterhole G04. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



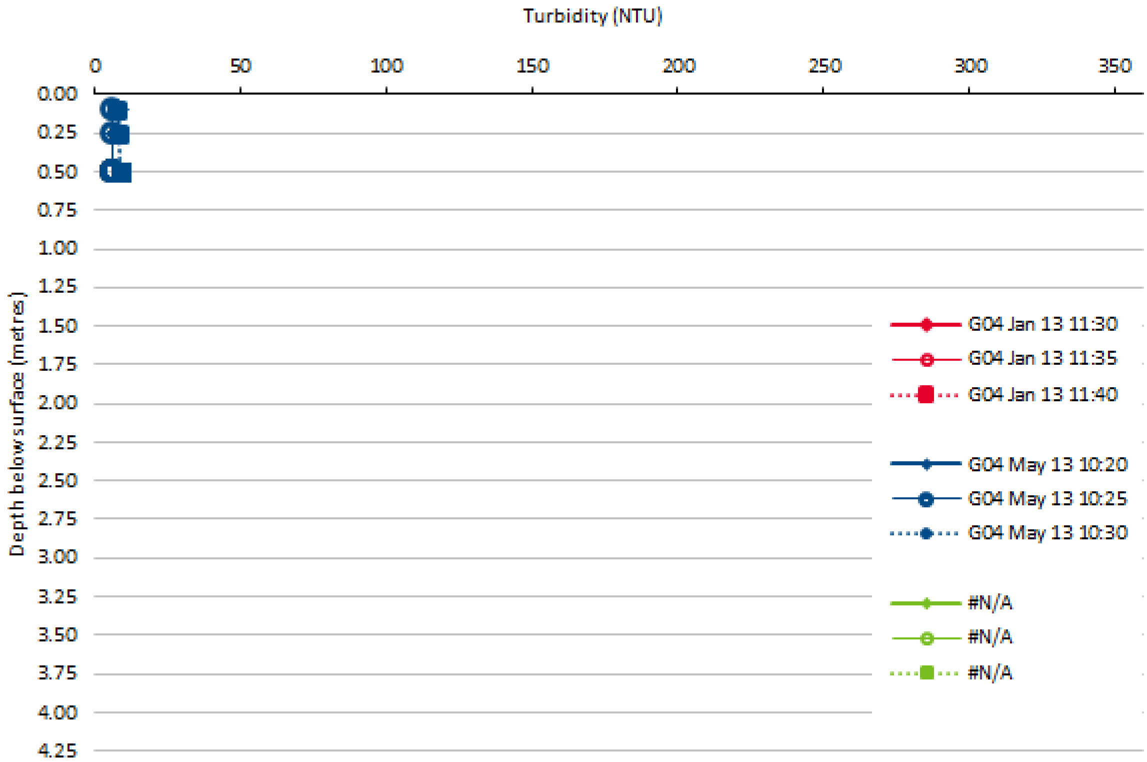
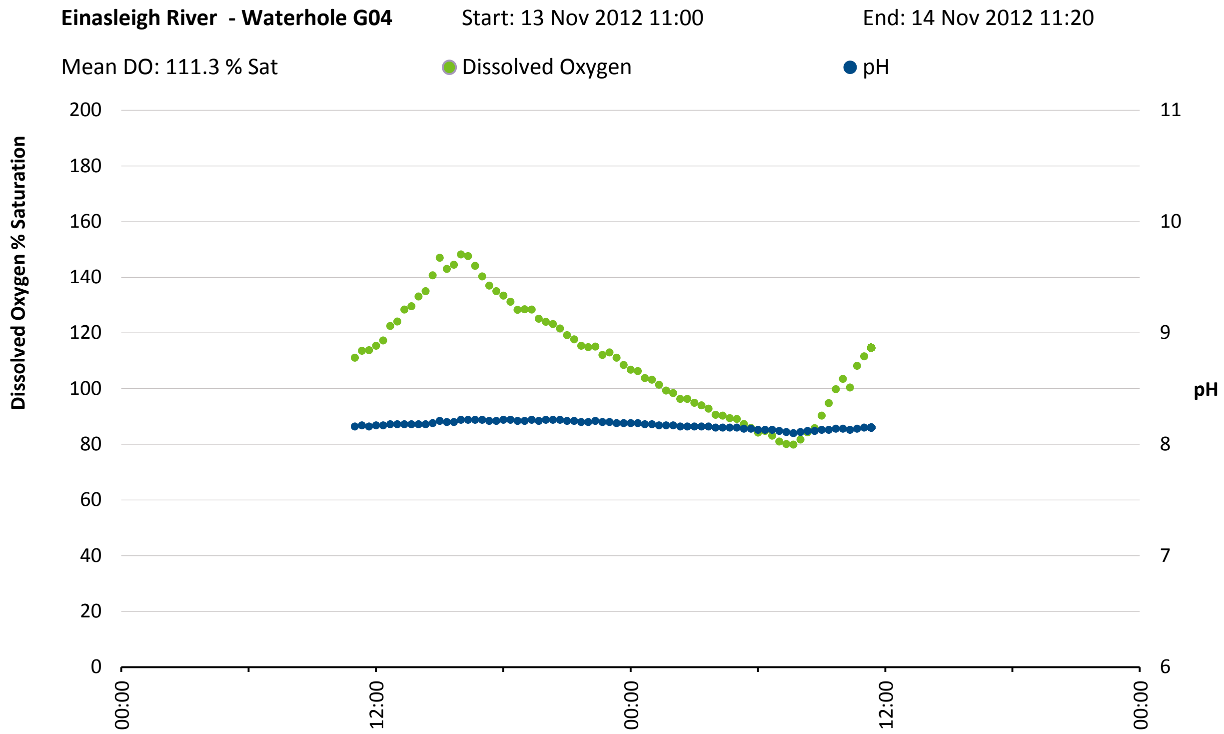


Figure 36 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G04. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



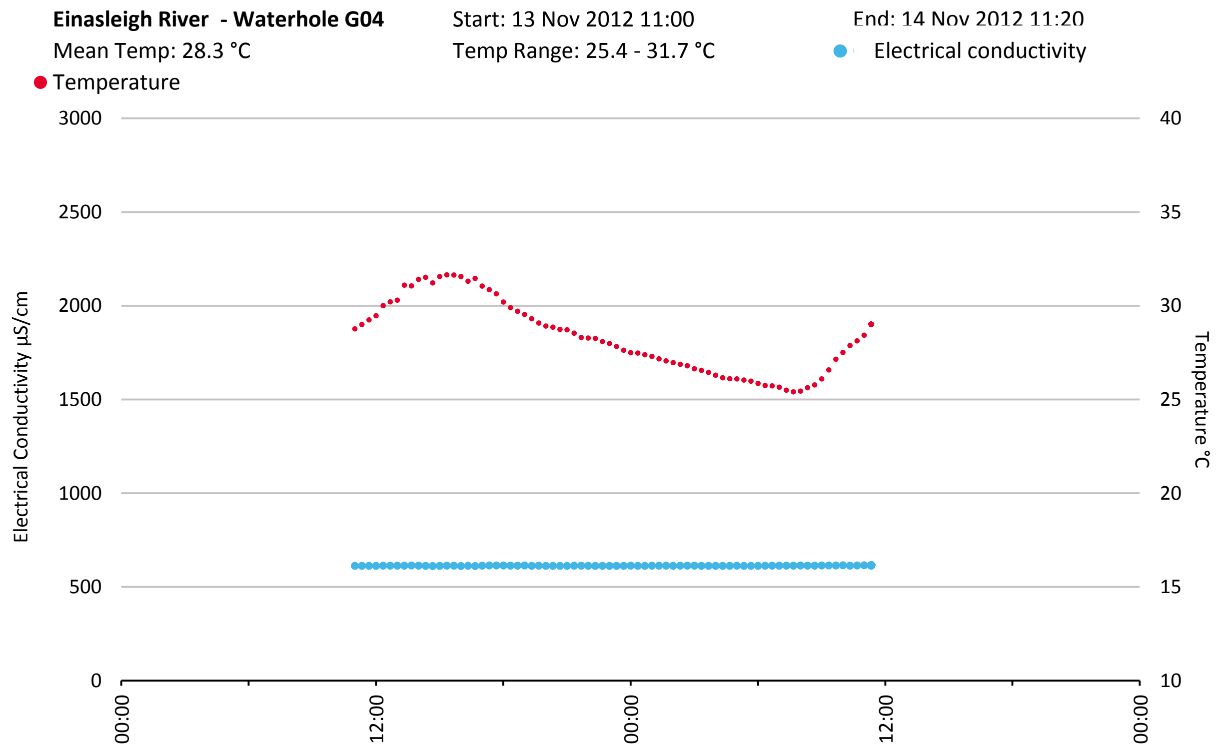
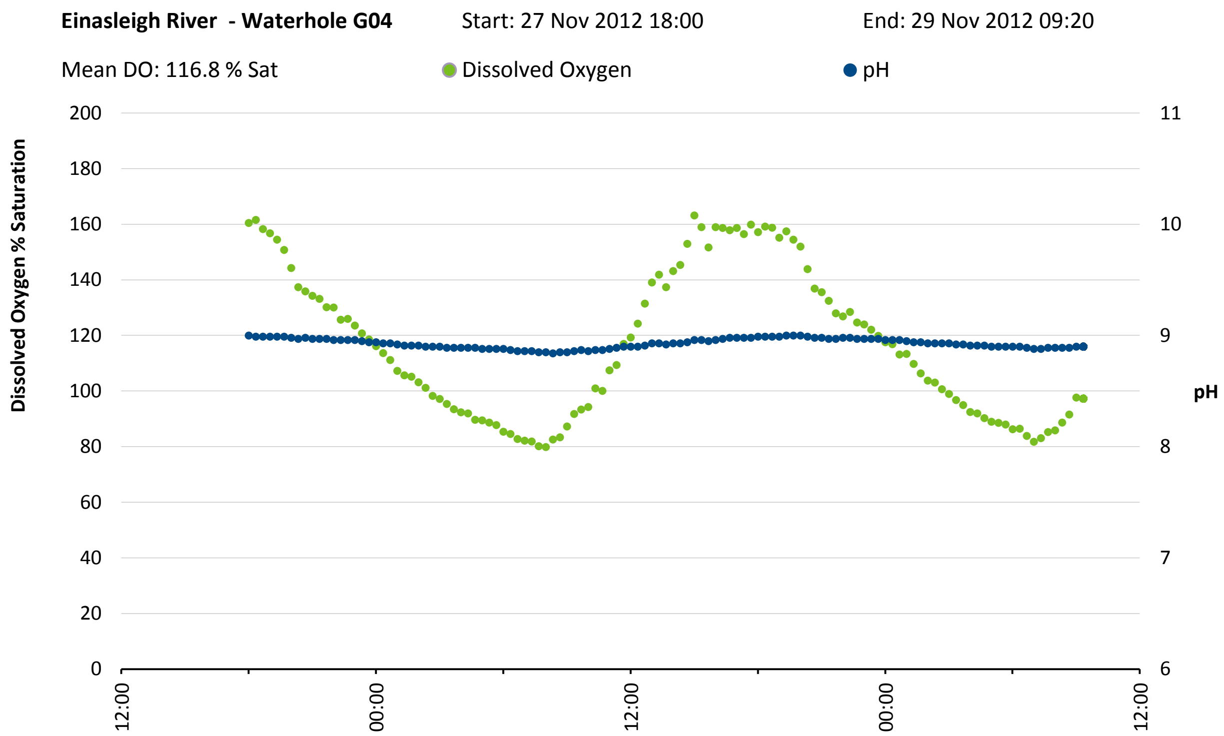


Figure 37 Diel physico-chemical data for waterhole G04, Nov 2012



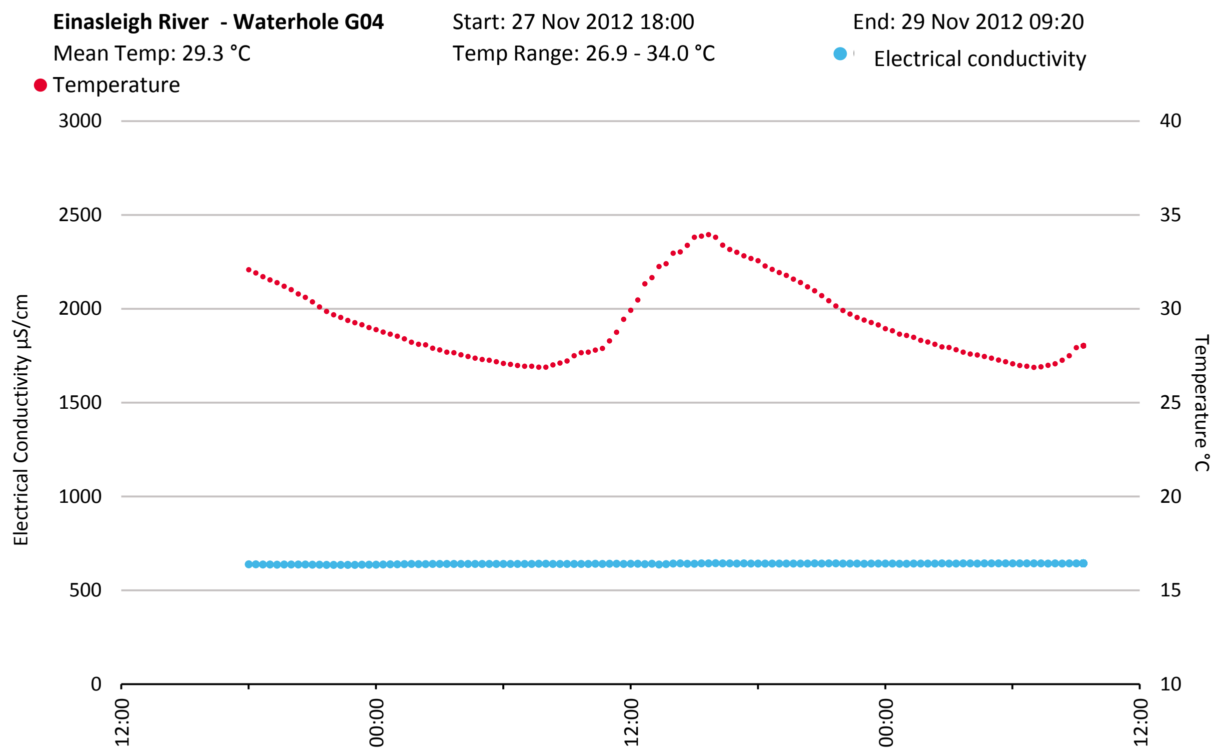
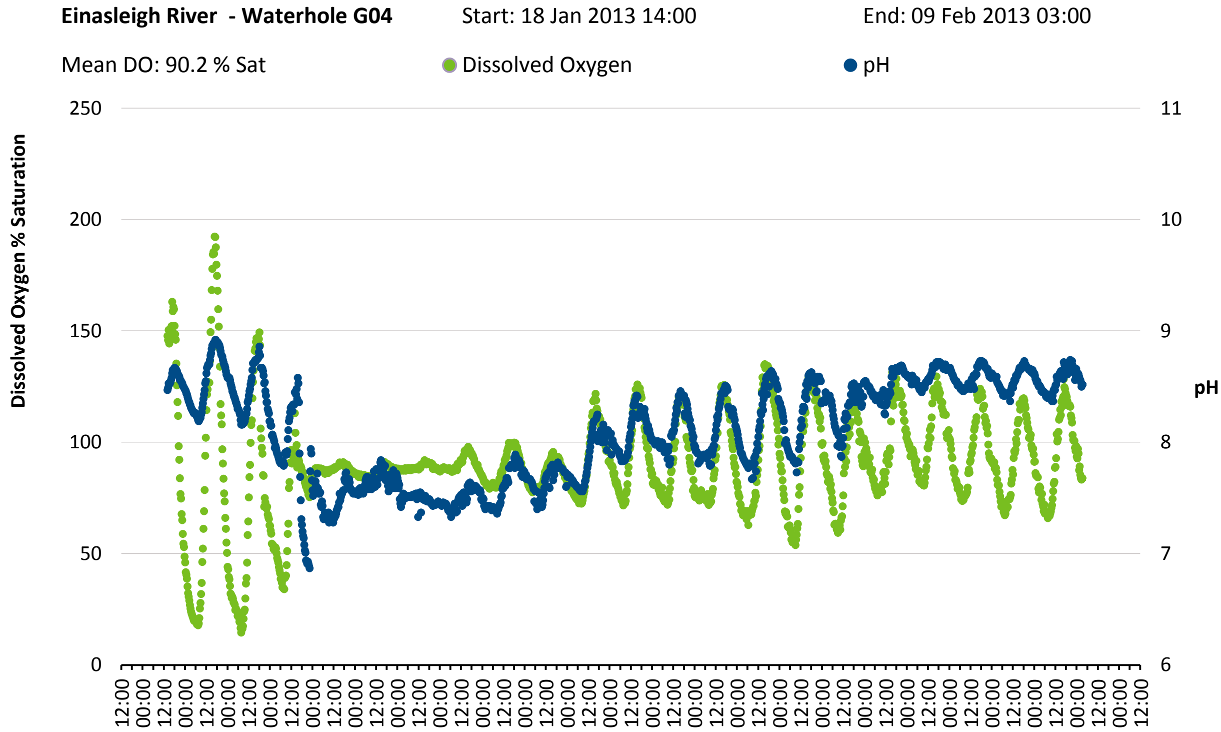


Figure 38 Diel physico-chemical data for waterhole G04, Nov 2012



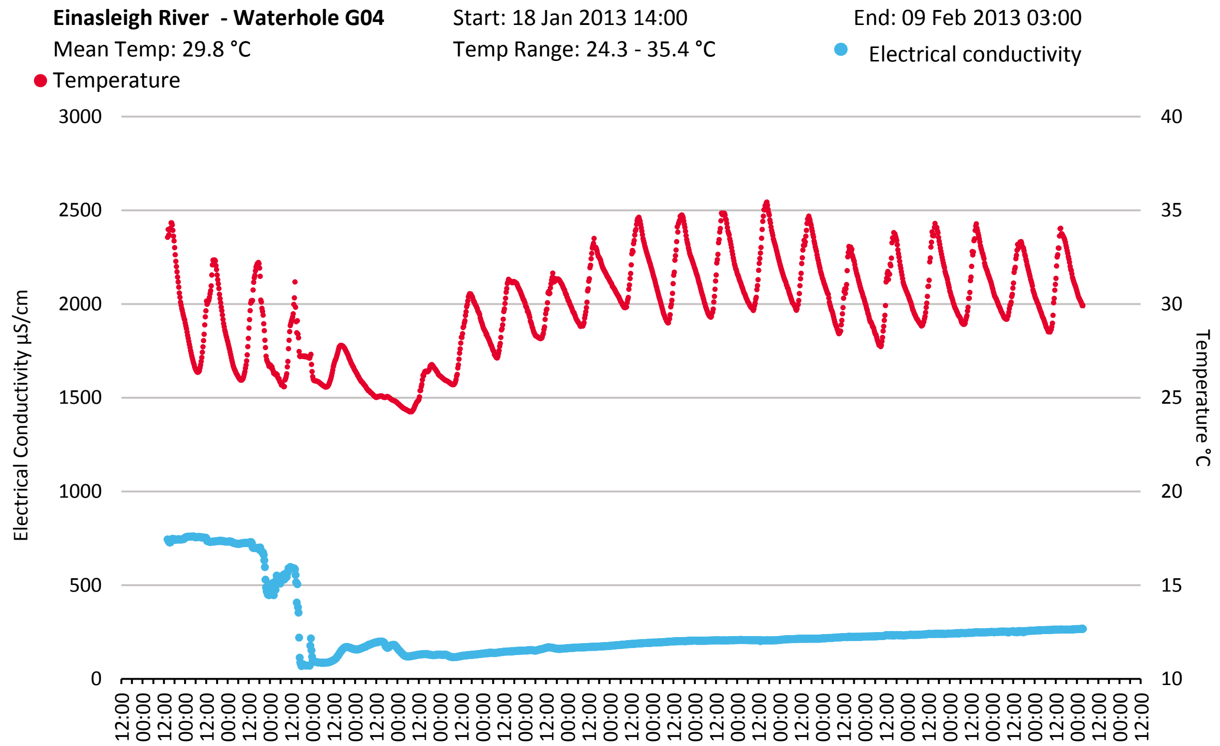


Figure 39 Diel physico-chemical data for waterhole G04, Jan-Feb 2013. Logger deployed for a longer period of time in an attempt to capture a flow event

WATERHOLE G05

FAMILY NAME	SPECIES NAME
Waterhole	G05
Catchment	Gilbert River
Watercourse	Einasleigh River
Waterhole location	-18.192245°, 144.014344°, immediately upstream of the Gulf Development Road
Waterhole elevation	~350 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 10-Oct-12
	Survey 3: 13-Nov-12
	Survey 5: 28-Nov-12
	Survey 7: 18-Jan-13
	Survey 9: 28-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~19600 m^2
	Waterhole volume: ~33700 m^3
	Wetted perimeter: ~ 800 m
	Maximum depth: 3.4 m
	Average depth: 1.7 m
	Waterhole length: 350 m
Instream habitats	A sheltered backwater on the left side of the waterhole hosts a number of large snags. The main waterhole is relatively snag free, with rock bars and some aquatic macrophytes in shallower areas. Macrophyte species included *Myriophyllm* sp., *Potamogeton crispus*, *P. pectinatus* and *Otellia alismoides*.
Riparian zone	This waterhole is used for recreational camping and fishing, as well as being subject to high cattle traffic. Understory vegetation is sparse. Thistles are also present in low numbers. Cattle traffic removed most groundcover during the dry season, although some couch grasses remained on poor margins. *Melaleuca* trees fringe the waterhole, while on the higher banks River red gums (*Eucalyptus camaldulensis*) are common. Overall riparian vegetation offers very limited shade across the waterhole due to the width of the waterhole (<10%).
Waterhole depth changes	Waterhole depth remained relatively constant across the Assessment period.
Other notes	A moderate level of cattle damage is evident. Water access points are obvious. Water extraction for road work activities along the Gulf Development Road is ongoing, with trucks regularly pumping from the waterhole.

a)

b)

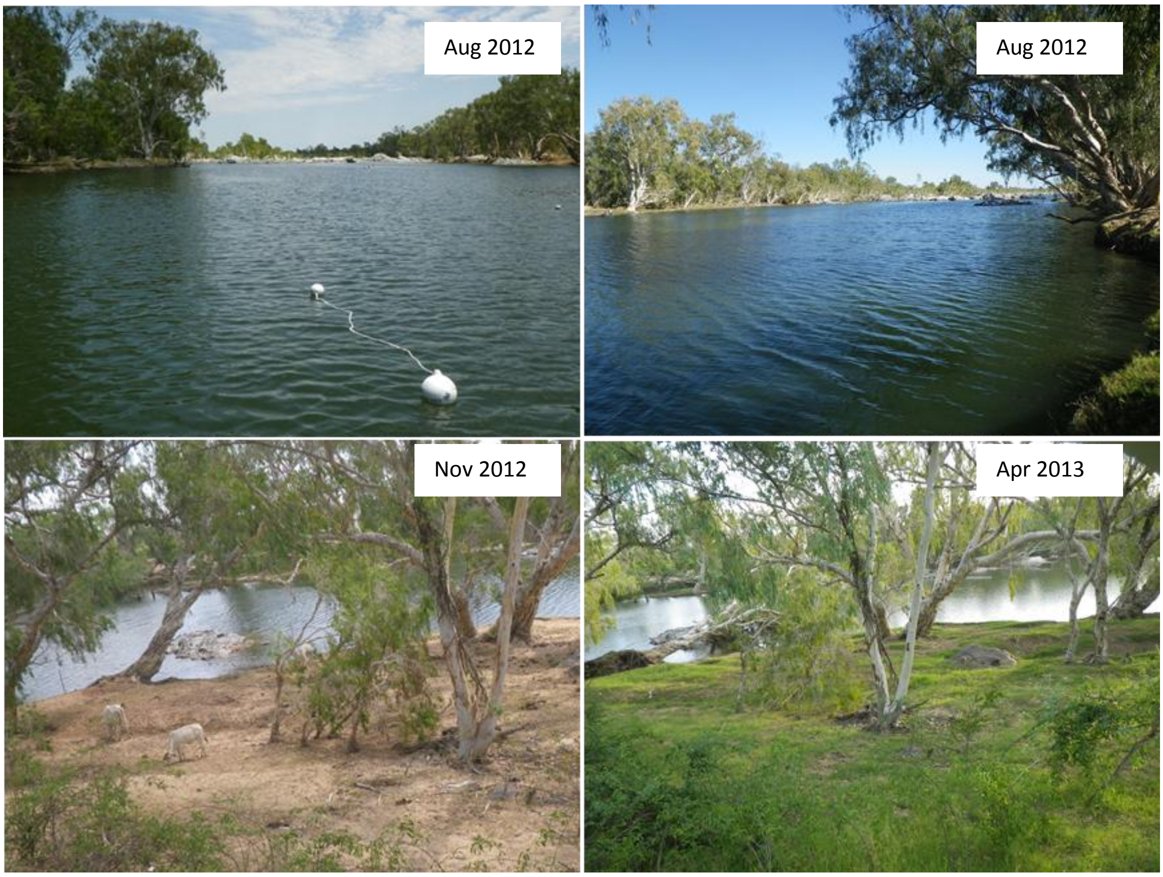


Figure 40 a) GoogleEarth 2011 aerial view of G05. b) Left to right: 1) Downstream from central channel. 2) Looking downstream from right bank.3) From right bank, fixed camera position. 4) From bank, fixed camera position

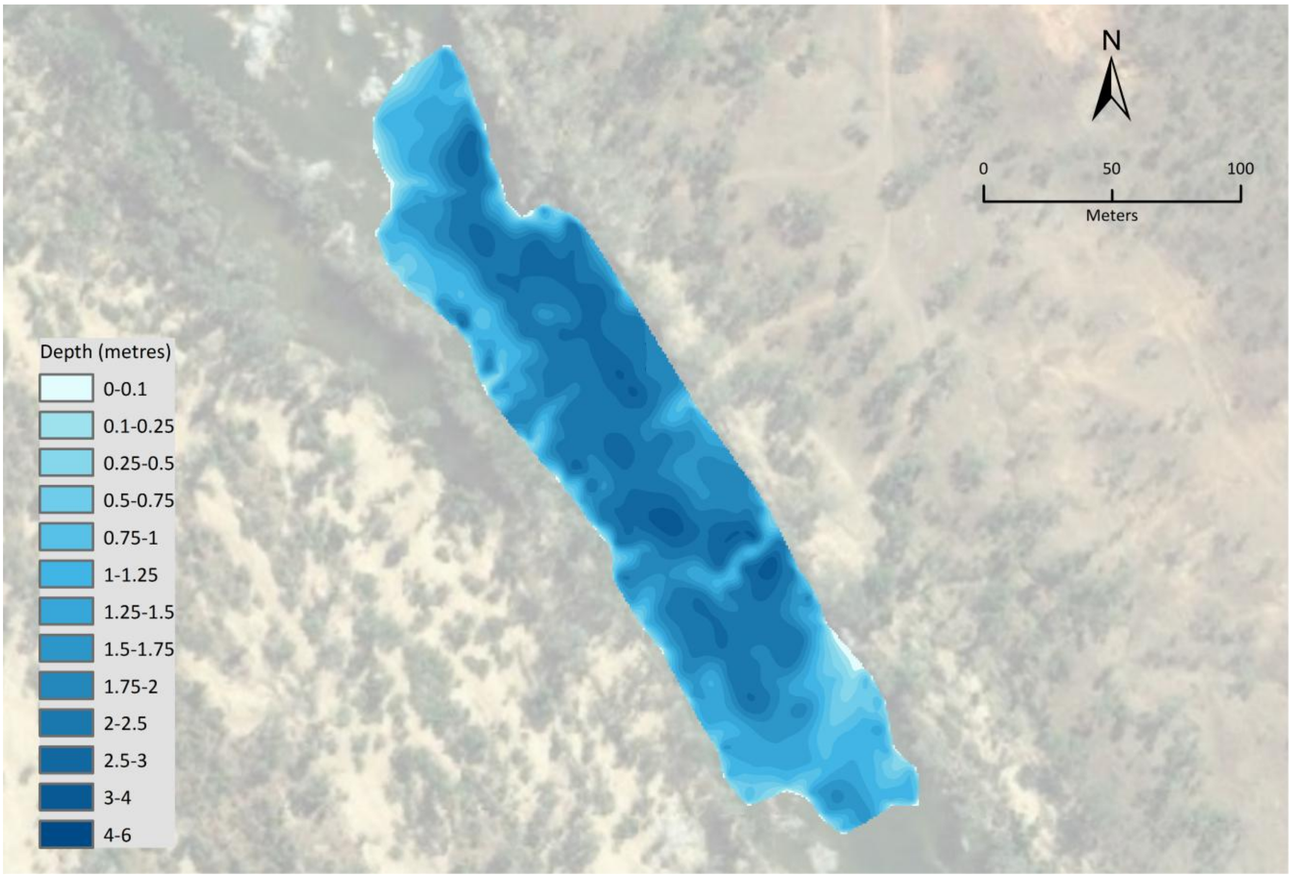


Figure 41 Bathymetry map of waterhole G05. Depth and waterhole perimeter data generated from data collected Oct 2012

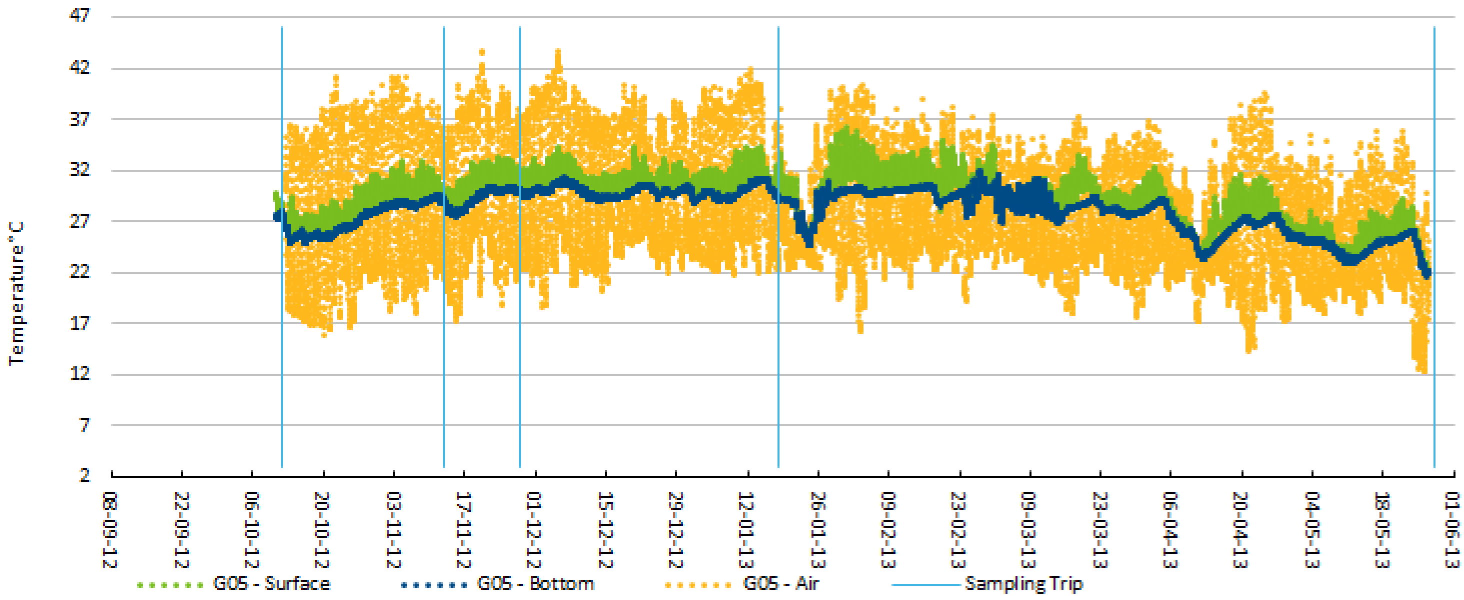
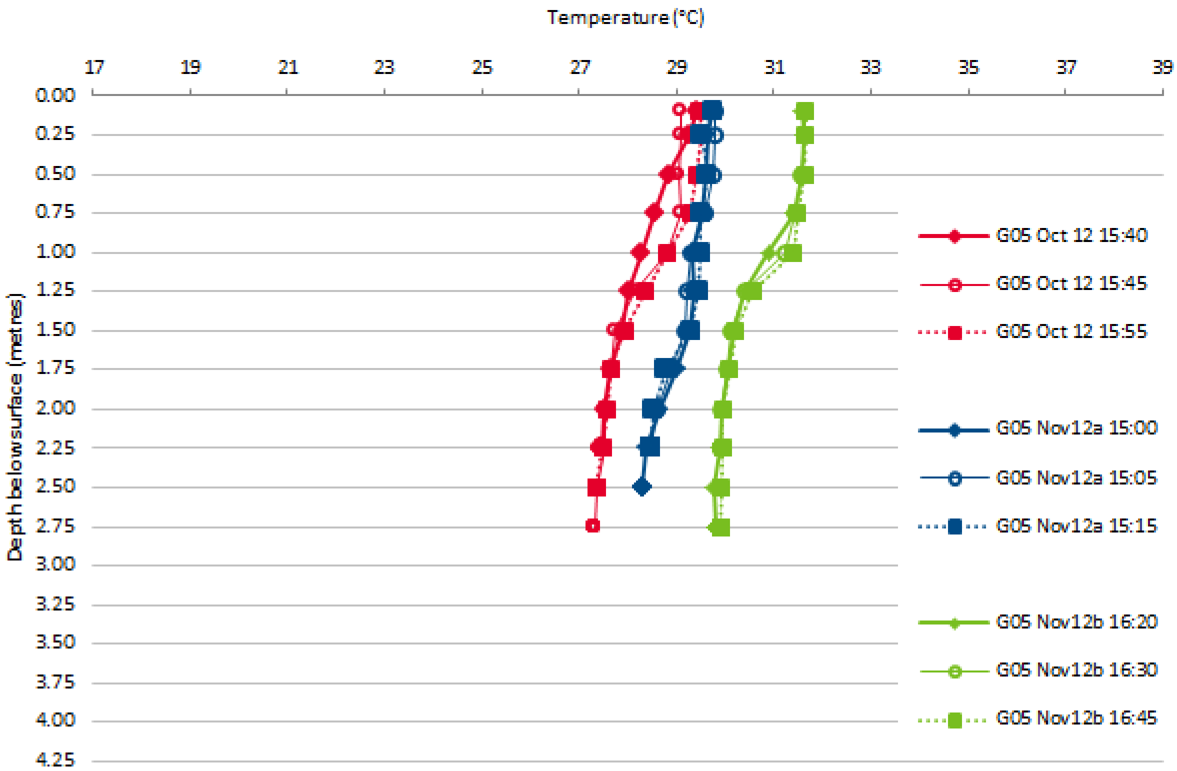


Figure 42 Long term temperature logger data for waterhole G05

Table 5 Continuous water and air temperature logger summary statistics for each survey at waterhole G05.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Oct 12	11-10-12 00:15	13-10-12 00:15	2	20.8	27.8	35.3	26.3	27.6	28.9	26.2	27.1	28.0	-0.1	0.5	1.3	57.2	9.7	0.0
Nov12a	10-11-12 00:15	14-11-12 00:15	4	20.2	28.3	38.7	28.4	29.8	32.2	27.9	29.0	29.7	0.0	0.8	2.7	70.2	35.3	12.8
Nov12b	20-11-12 00:15	24-11-12 00:15	4	19.9	29.6	43.6	29.9	31.2	33.2	29.3	30.0	30.5	0.0	1.2	3.1	88.2	51.6	35.3
Jan 13	15-01-13 00:15	18-01-13 00:15	3	22.1	28.1	36.7	29.8	31.0	32.6	29.1	30.4	31.2	-0.1	0.6	2.7	60.4	22.1	11.5
Feb 13	13-02-13 00:15	18-02-13 00:15	5	20.6	28.3	38.9	30.4	31.6	34.1	30.1	30.4	30.7	0.0	1.3	3.6	82.0	55.1	36.3
May 13	21-05-13 00:15	26-05-13 00:15	5	12.5	22.4	35.9	22.7	25.9	29.2	22.6	25.1	26.1	-0.1	0.8	3.6	56.5	27.7	14.7



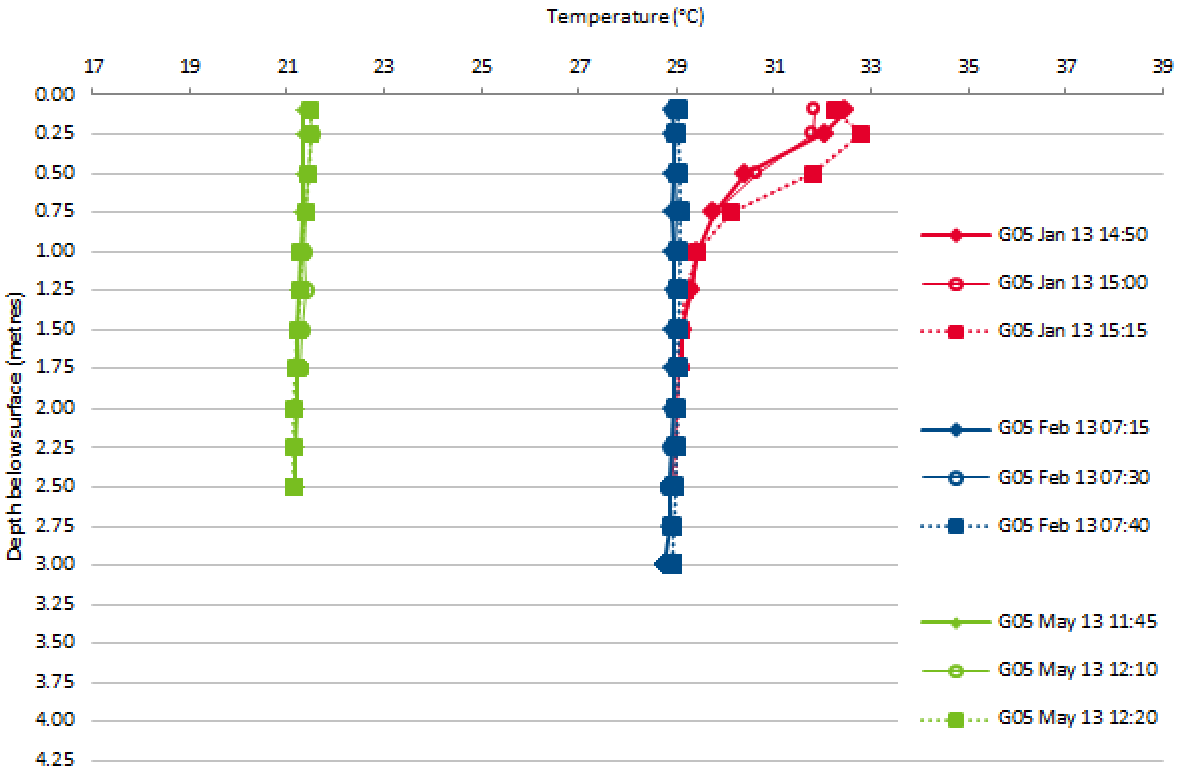
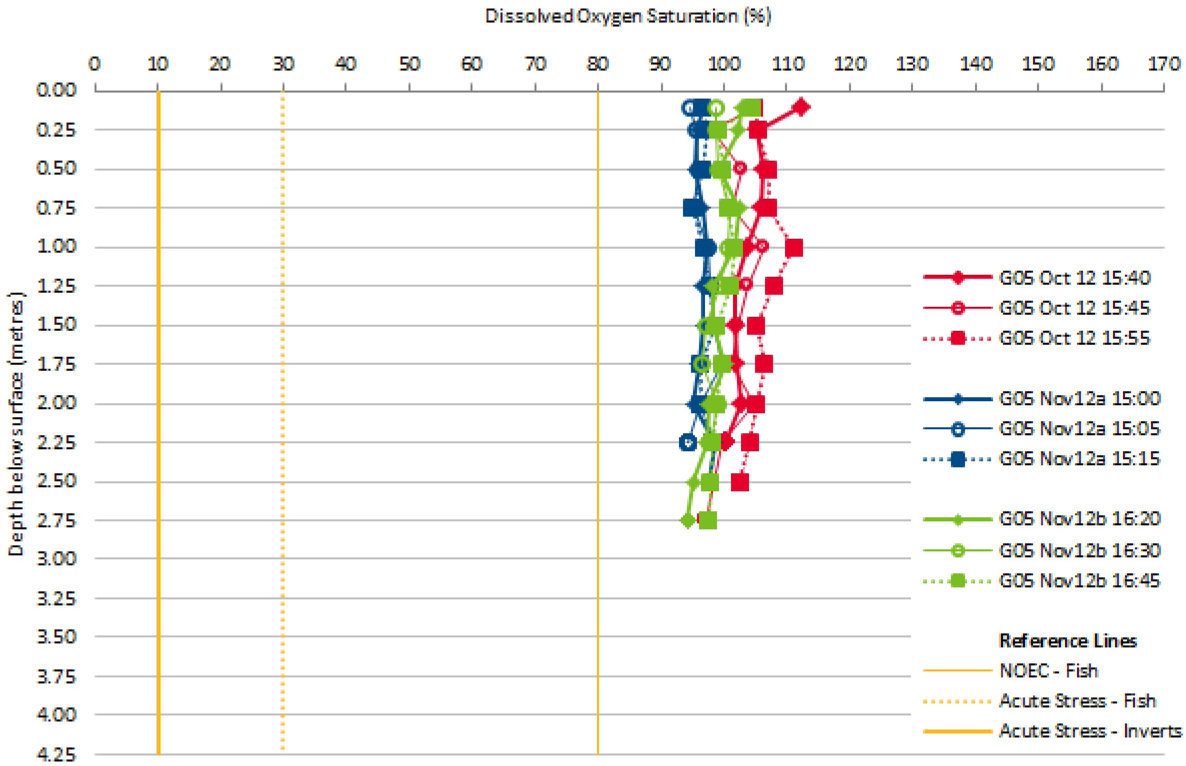


Figure 43 Temperature vertical water column profiles at waterhole G05. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



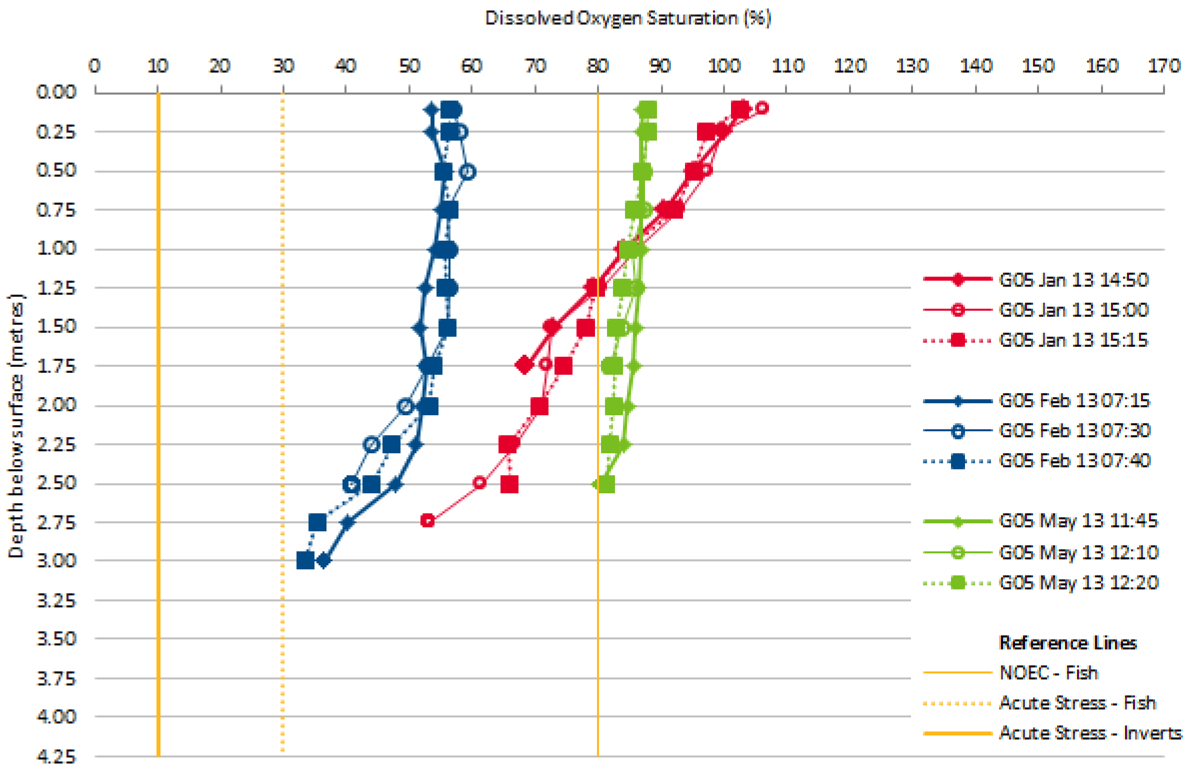
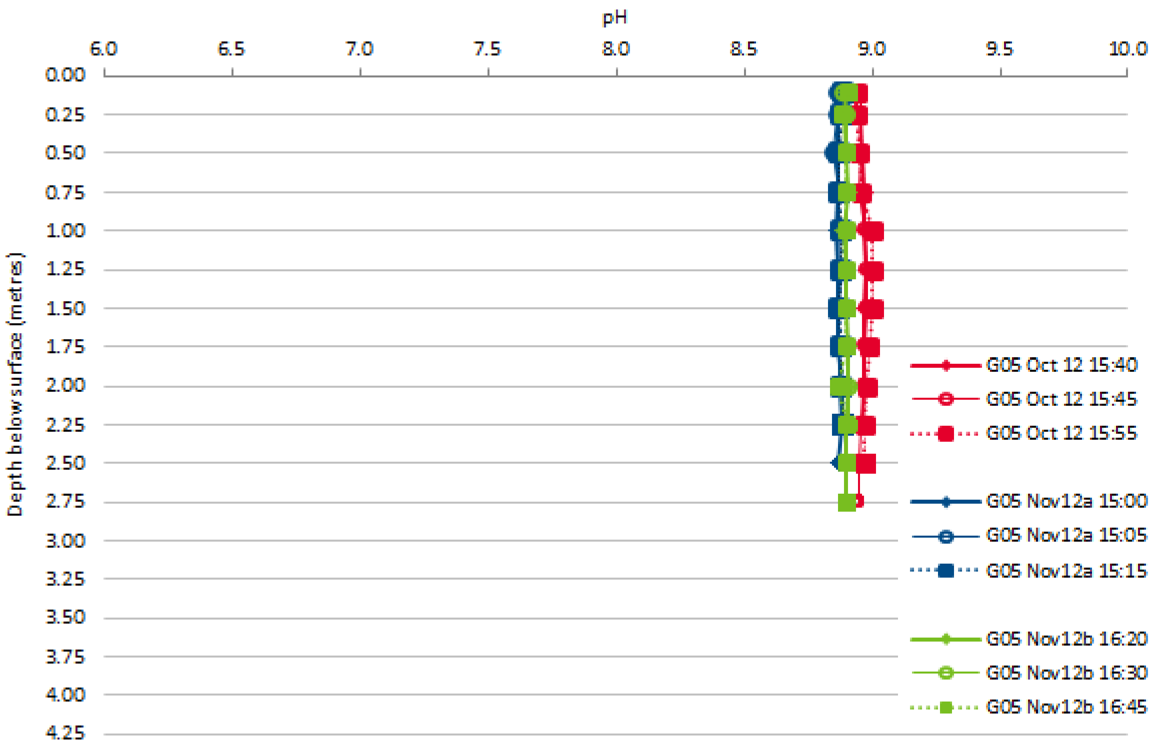


Figure 44 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G05. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



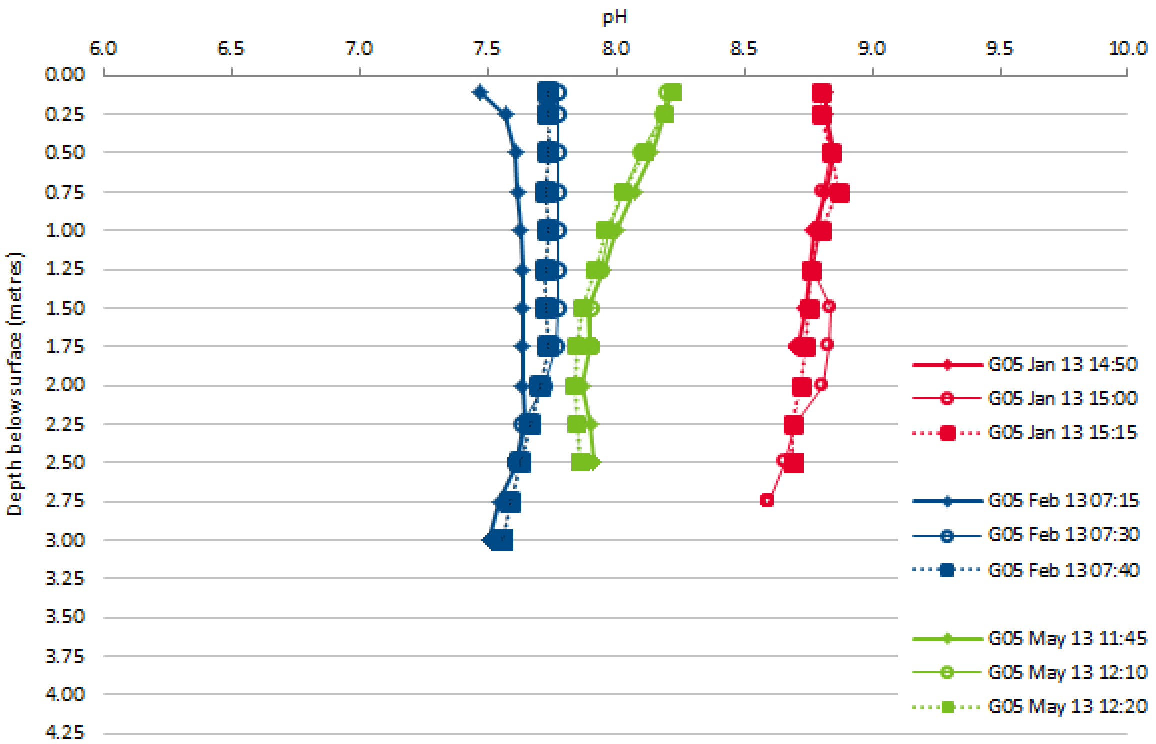
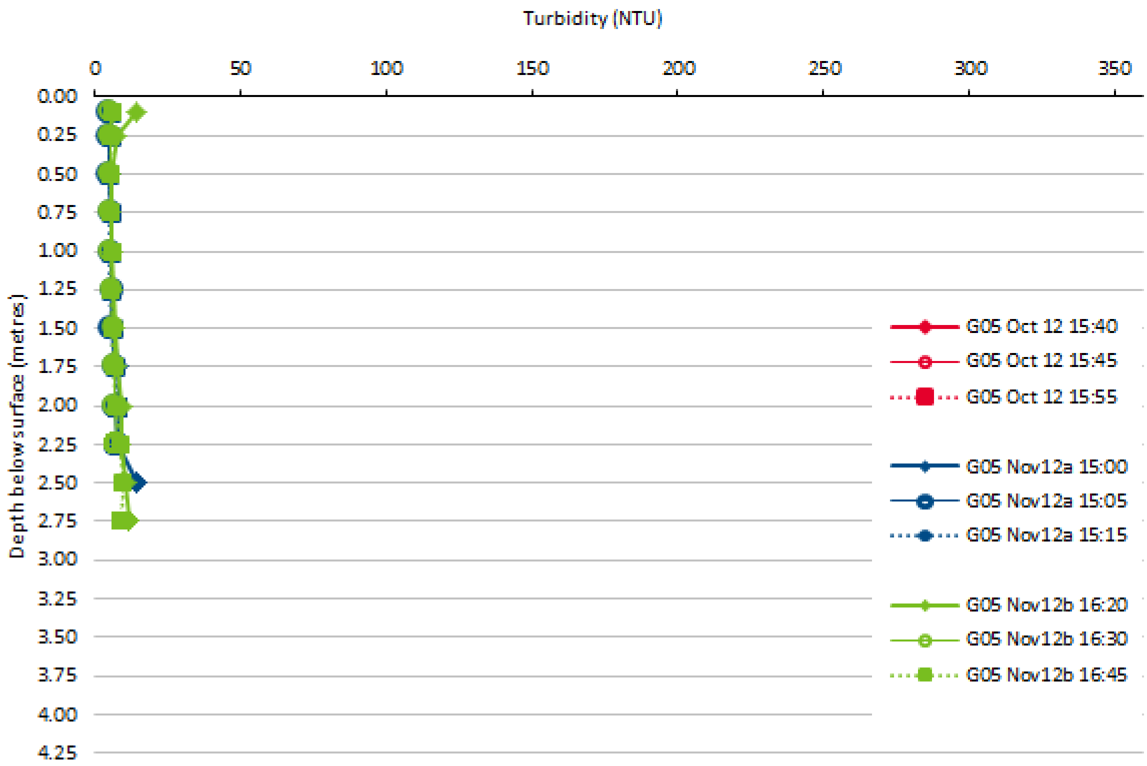


Figure 45 pH vertical water column profiles at waterhole G05. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



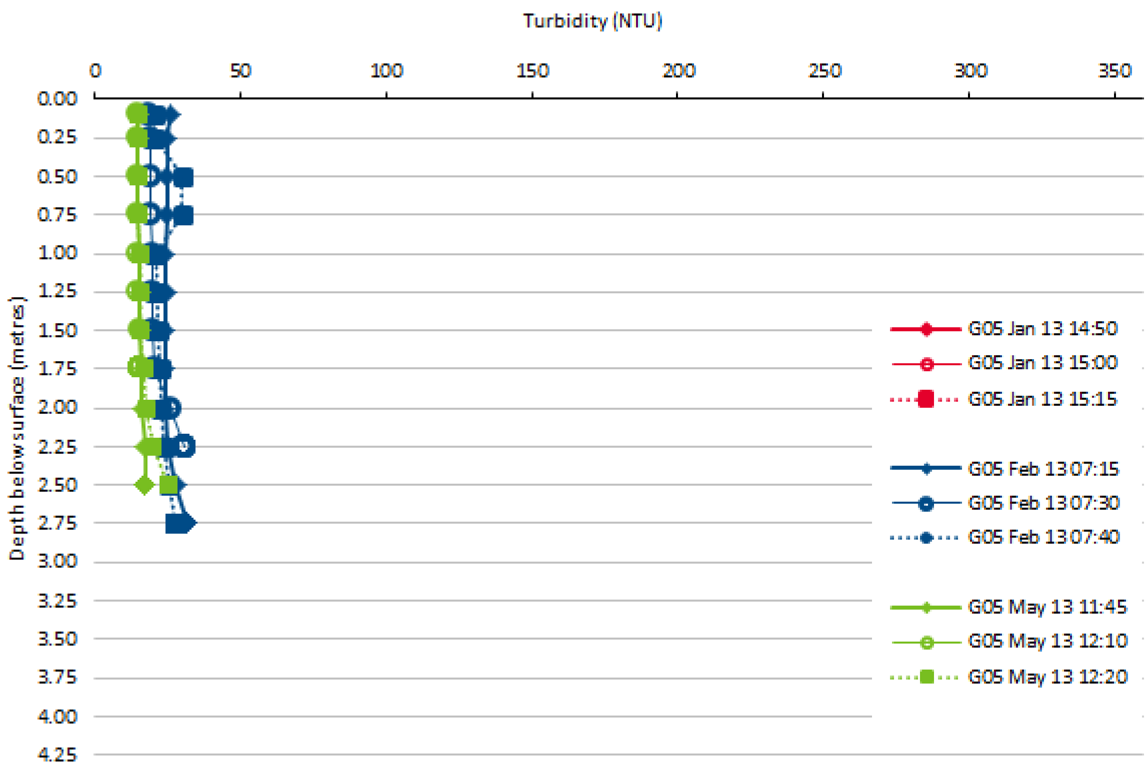
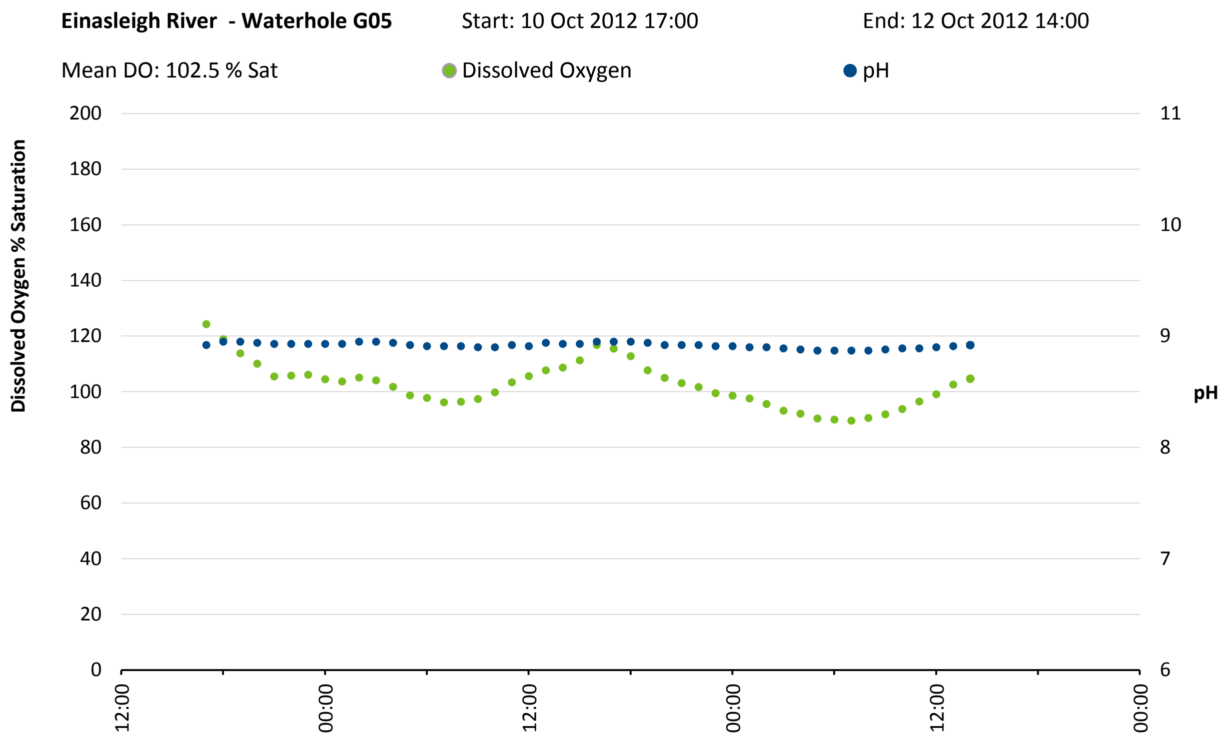


Figure 46 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G05. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



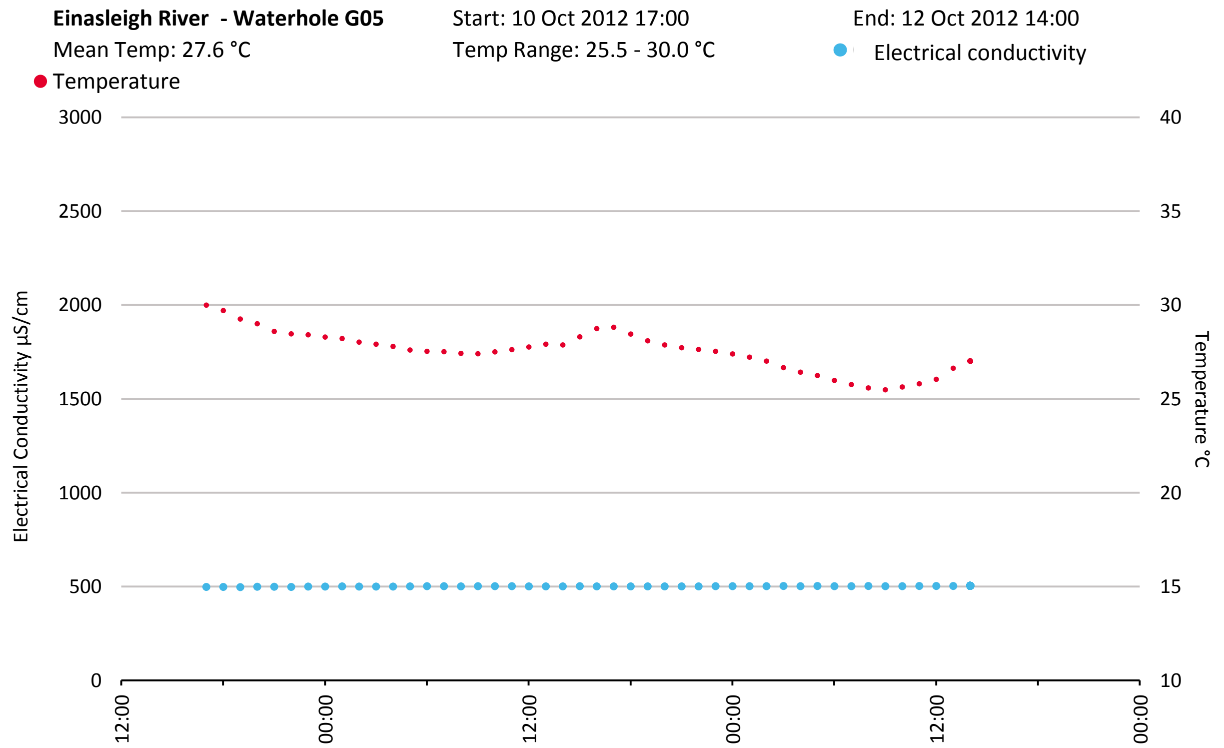
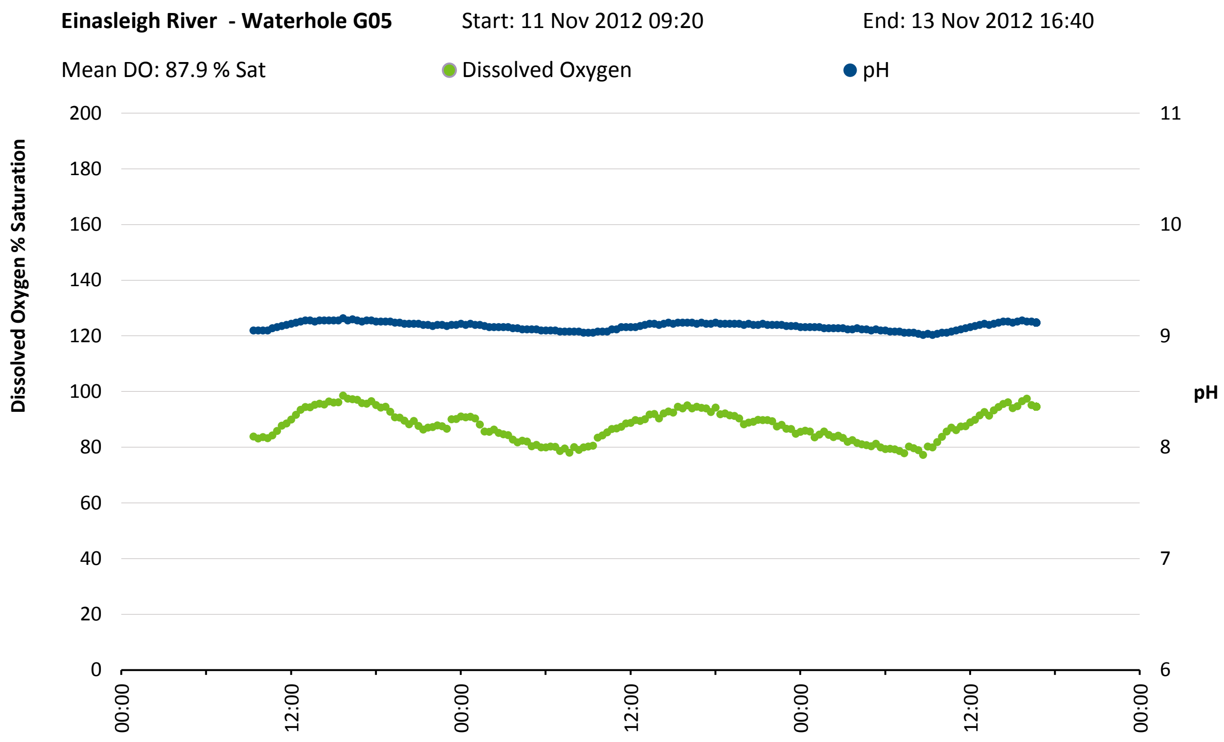


Figure 47 Diel physico-chemical data for waterhole G05, Oct 2012



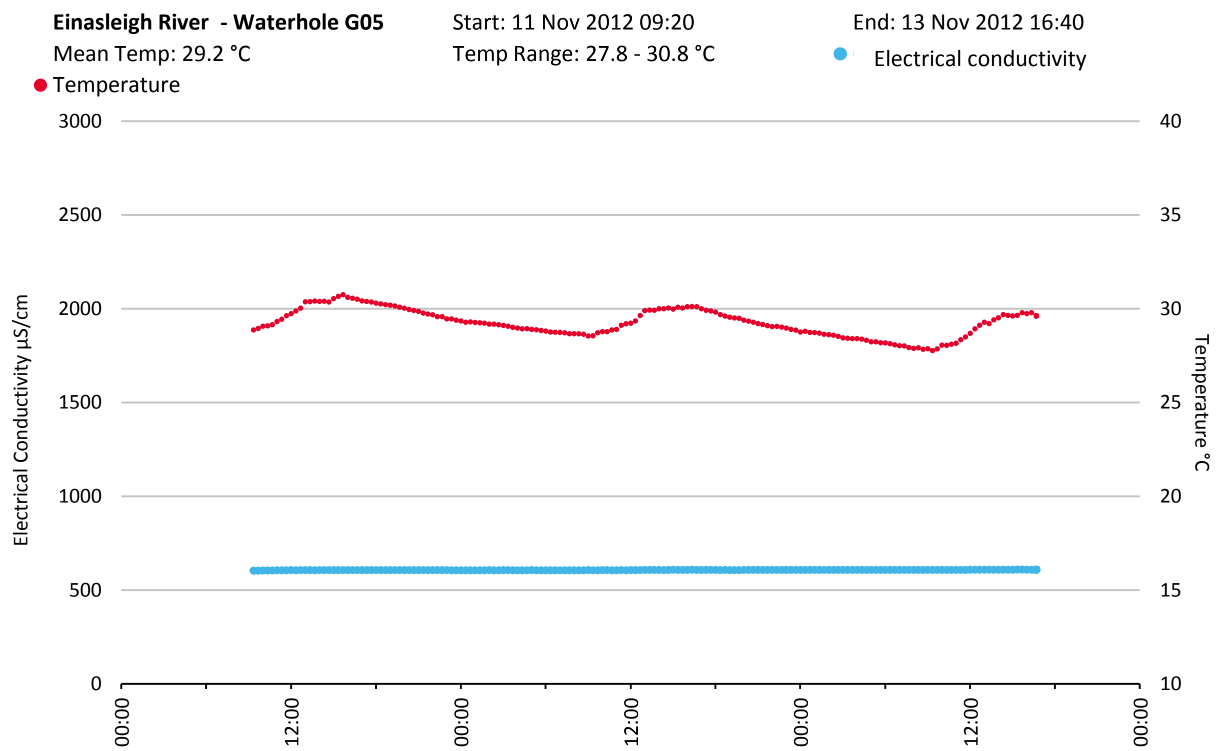
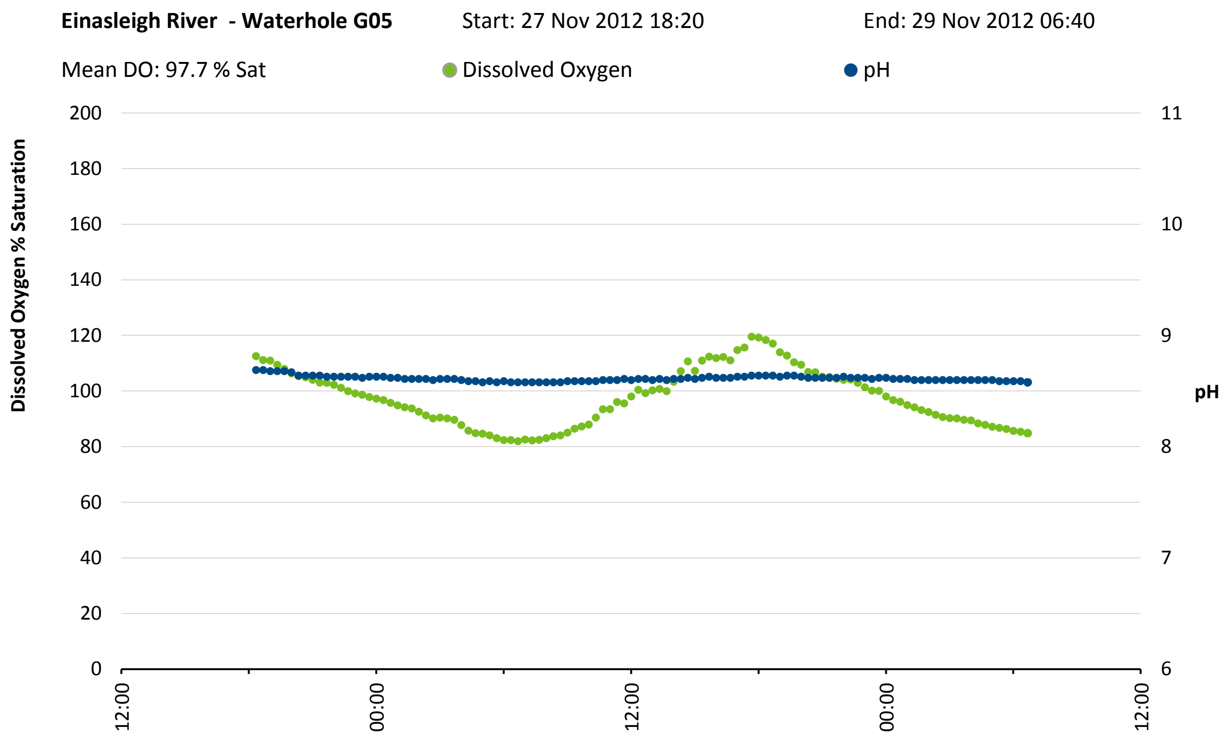


Figure 48 Diel physico-chemical data for waterhole G05, Nov 2012



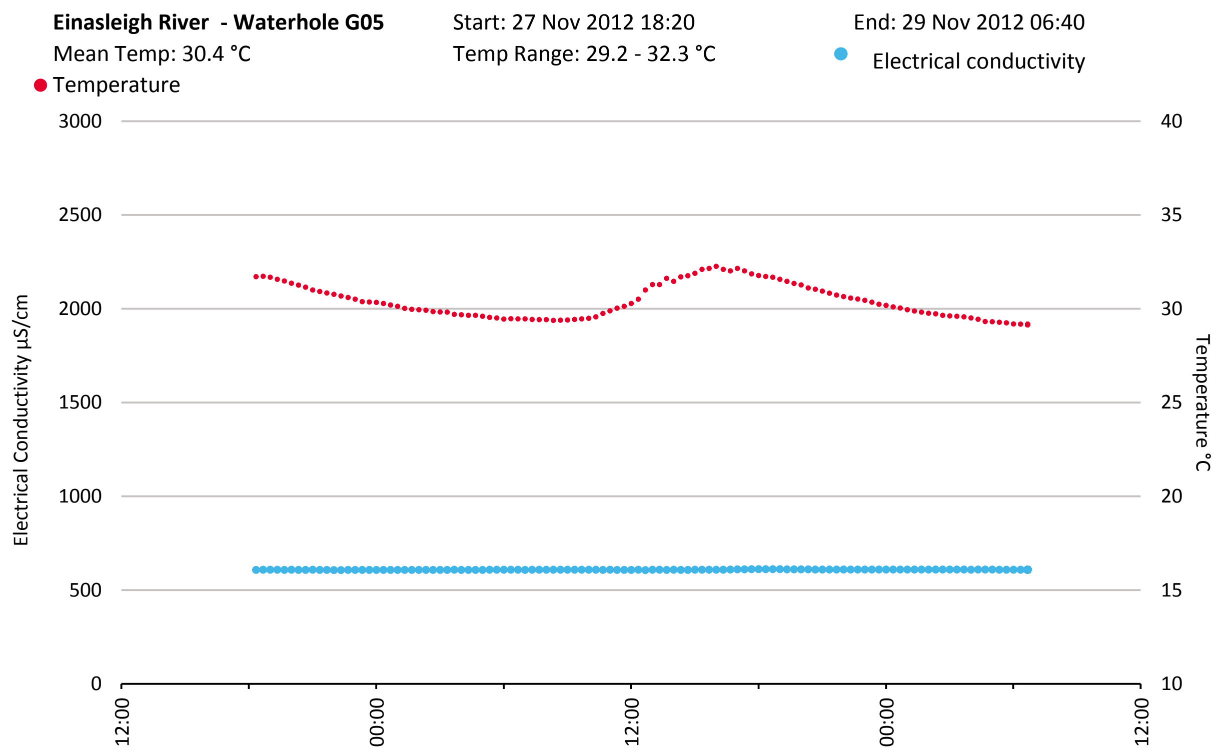
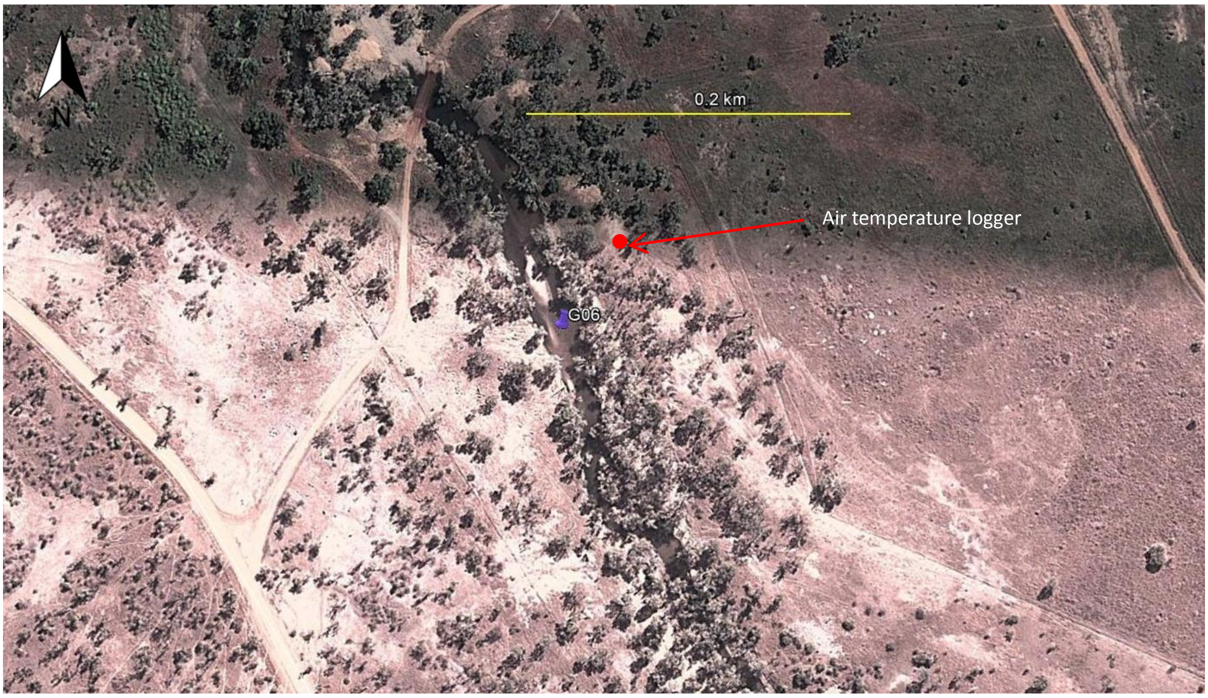


Figure 49 Diel physico-chemical data for waterhole G05, Nov 2012

WATERHOLE G06

FAMILY NAME	SPECIES NAME
Waterhole	G06
Catchment	Gilbert River
Watercourse	Elizabeth Creek
Waterhole location	-18.124632°, 144.291832°, Mt Surprise Station
Waterhole elevation	~430 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 11-Oct-12
	Survey 3: 10-Nov-12
	Survey 5: 27-Nov-12
	Survey 7: 18-Jan-13
	Survey 8: 18-Feb-13
	Survey 9: 27-May-13
Waterhole characteristics	Surface area: ~4300 m^2
(measured Oct 2012)	Waterhole volume: ~1600 m^3
	Wetted perimeter: ~ 360 m
	Maximum depth: 1.8 m
	Average depth: 0.4 m
	Waterhole length: 150 m
Instream habitats	The waterhole has a sandy bottom with a cobbled area close to the road crossing. Algae were dense across the entire waterhole. Filamentous algae was most common (~70% coverage), and epiphytic and epilithic were also present in lower densities. Aquatic macrophytes present included *Eleocharis* sp., *Marsilea mutica, Potamogeton pectinatus* and *Ottellia alismoides,* with the dominant genus being *Myriophyllum* sp.
Riparian zone	The riparian zone is subject to high cattle traffic. It appears that cattle camp adjacent to the creek on the left bank. Groundcover was very sparse, or not present, during dry periods. *Melaleuca* trees overhang the water down the left side of the waterhole. On the right, steep banks and exposed tree roots provide habitat. Riparian trees offer about 20% shade across the water.
Waterhole depth changes	Waterhole depth remained relatively constant across the Assessment period, with a slight peak during February 2013. The creek experiences a relatively high level of groundwater input.
Other notes	A moderate level of cattle damage was evident. On the downstream end of the waterhole is a gravel road crossing.

a)



b)

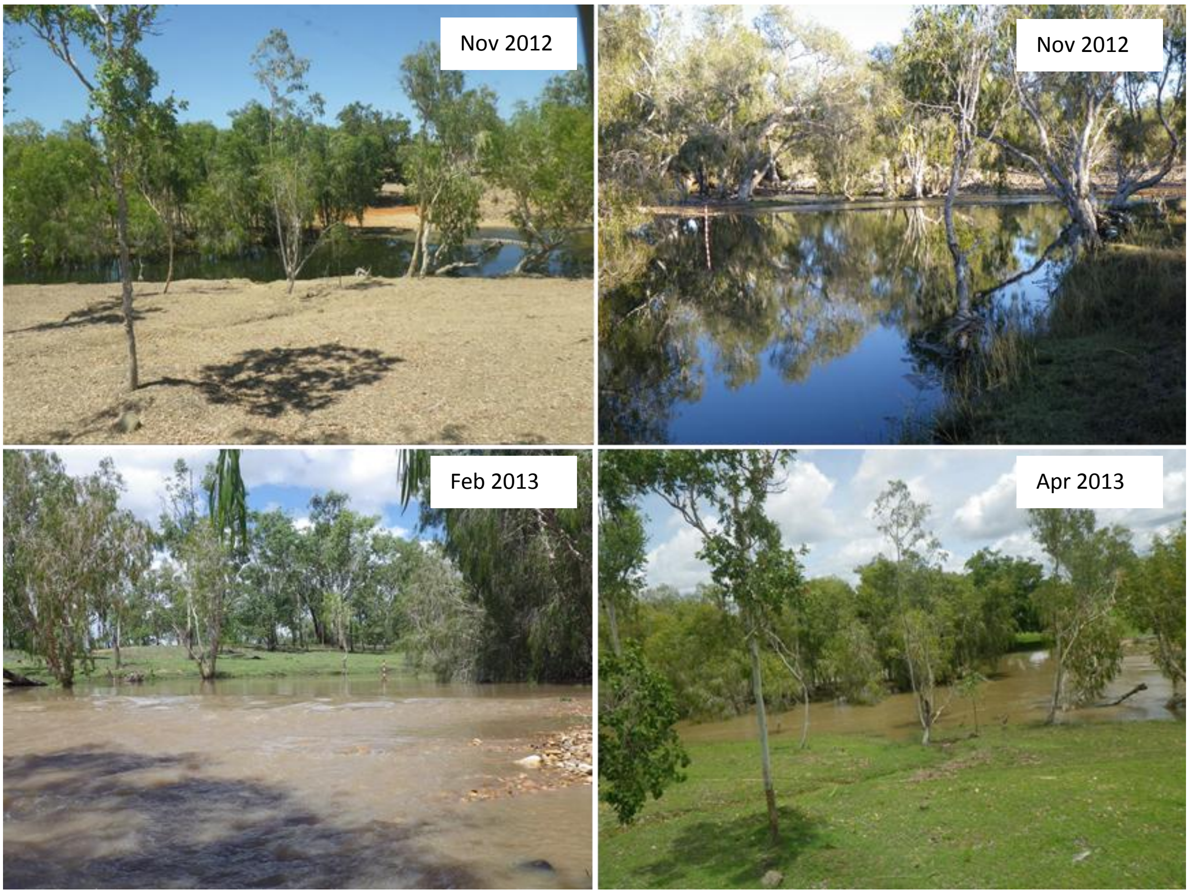


Figure 50 a) GoogleEarth 2009 aerial view of G06. b) Left to right: 1) From fixed camera, right bank. 2) From right bank.3) From right bank at causeway. 4) From fixed camera, right bank

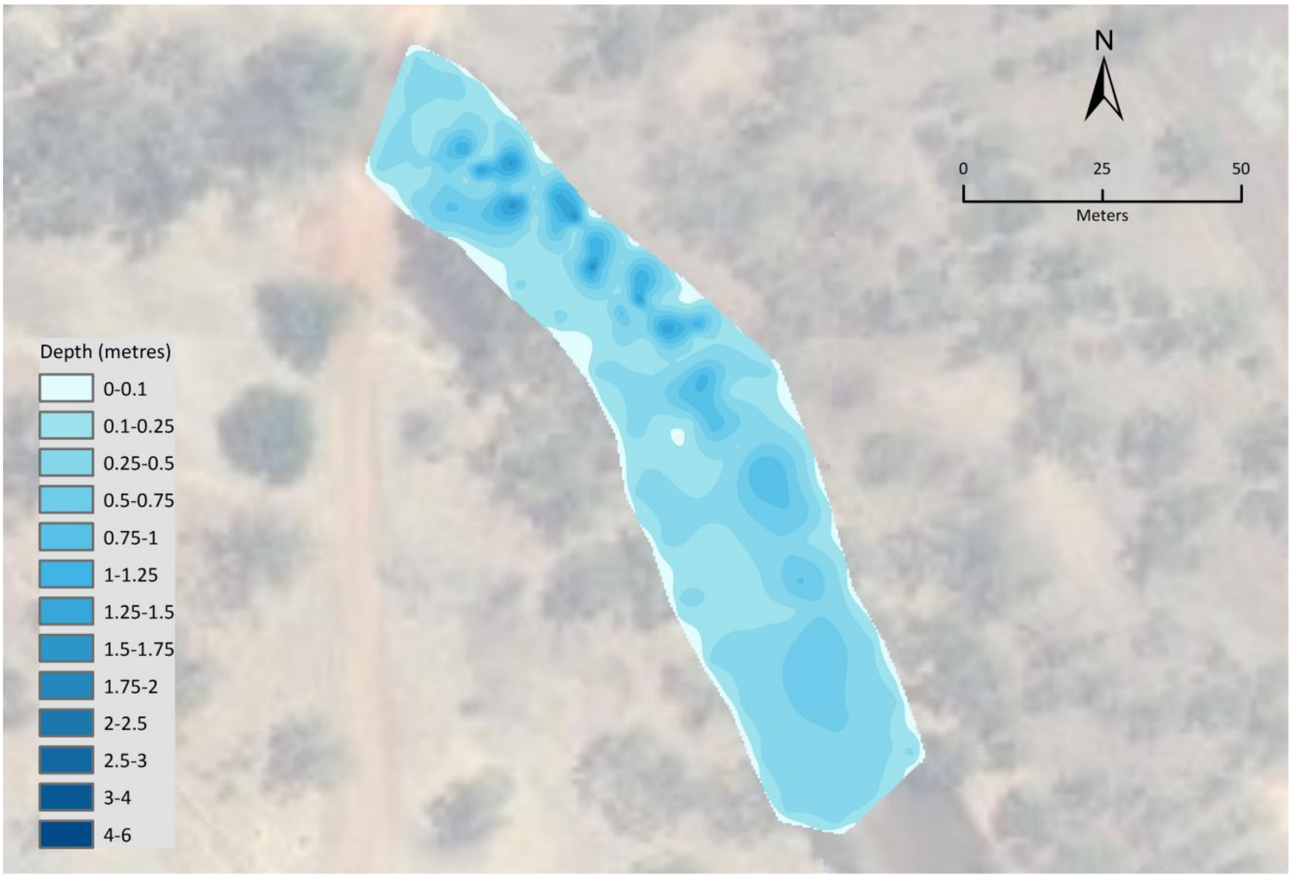


Figure 51 Bathymetry map of waterhole G06. Depth and waterhole perimeter data generated from data collected Oct 2012

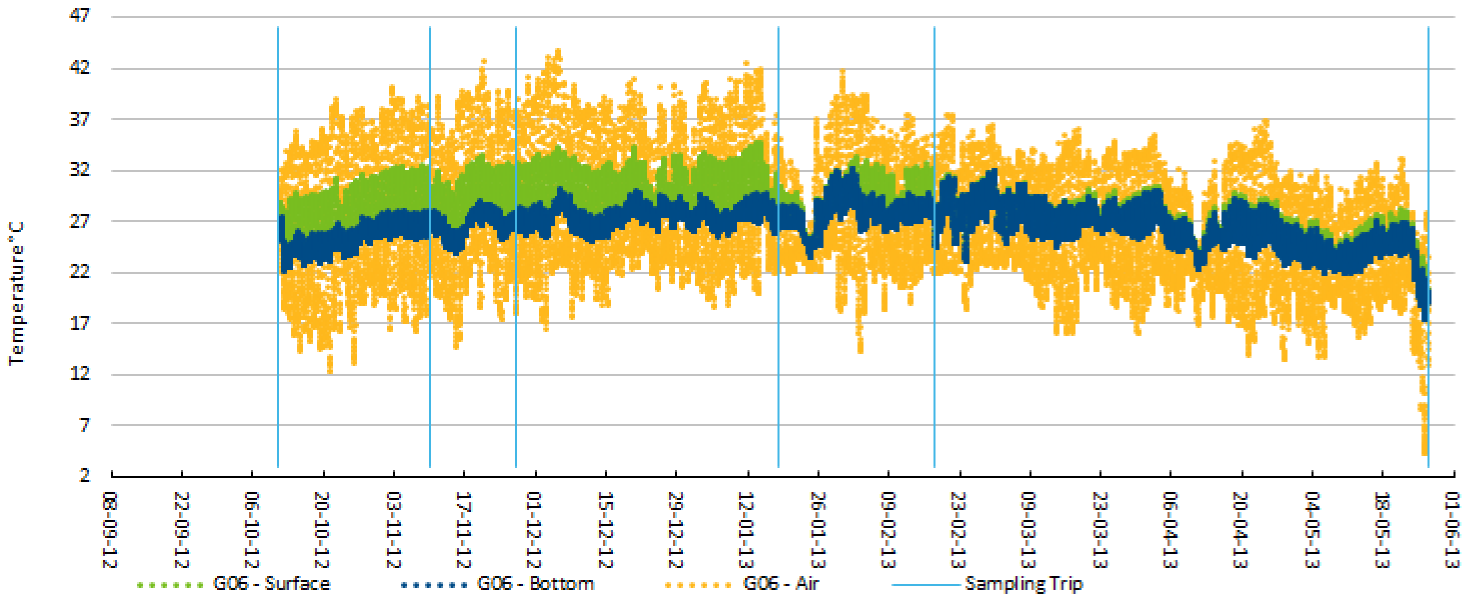
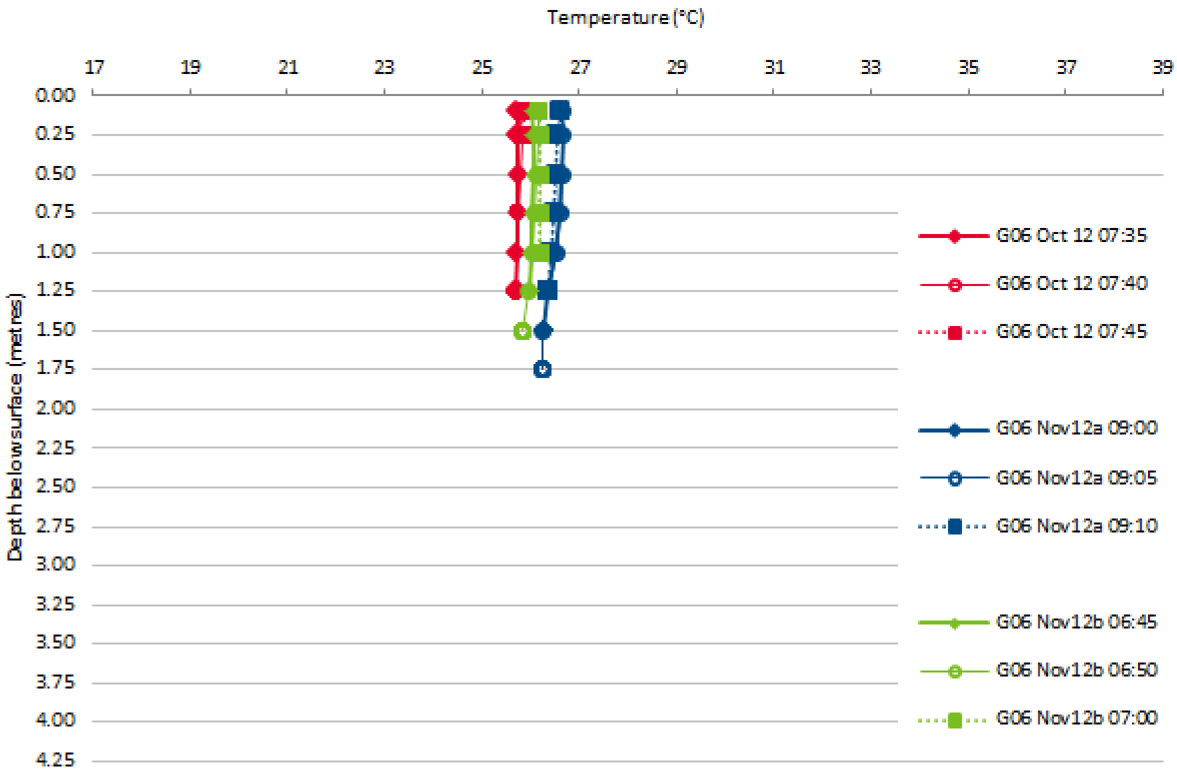


Figure 52 Long term temperature logger data for waterhole G06

Table 6 Continuous water and air temperature logger summary statistics for each survey at waterhole G06.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Oct 12	12-10-12 00:15	20-10-12 00:15	8	14.3	24.9	36.1	22.7	25.6	29.9	22.2	24.1	26.1	0.1	1.4	4.9	50.4	39.5	35.9
Nov12a	01-11-12 00:15	07-11-12 00:15	6	16.5	28.3	40.2	25.8	28.2	32.4	25.3	26.6	28.1	0.1	1.6	5.2	58.9	42.5	38.6
Nov12b	15-11-12 00:15	28-11-12 00:15	13	14.7	28.8	42.6	24.3	28.6	33.4	23.8	27.0	29.0	-0.2	1.6	5.5	68.3	46.2	40.2
Jan 13	15-01-13 00:15	25-01-13 00:15	10	22.0	26.1	37.4	23.7	27.6	32.4	23.6	26.8	29.7	0.0	0.7	4.3	48.7	23.8	15.4
Feb 13	19-02-13 00:15	06-03-13 00:15	15	18.4	27.3	37.5	23.2	28.5	32.0	23.0	28.4	31.9	-0.1	0.1	0.9	5.5	0.0	0.0
May 13	25-05-13 00:15	28-05-13 00:15	3	4.3	16.6	27.8	17.7	20.0	23.6	17.4	19.5	22.3	0.1	0.5	2.3	24.3	17.4	11.8



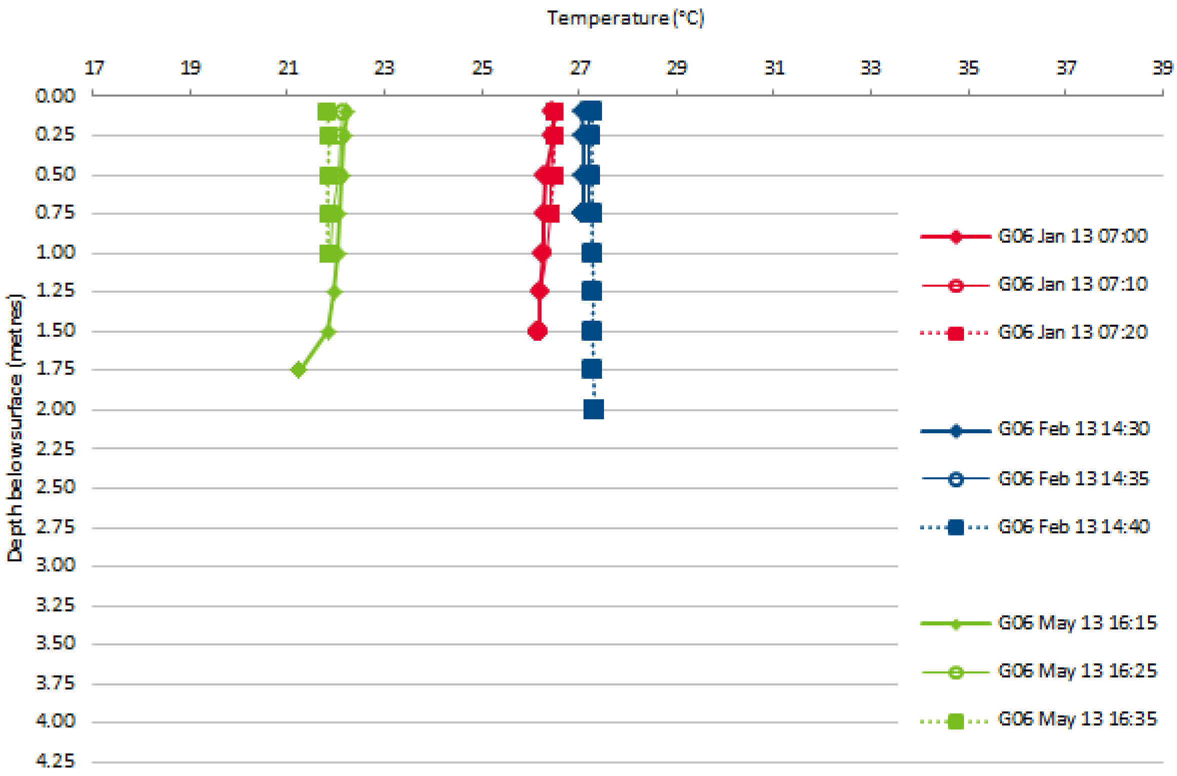
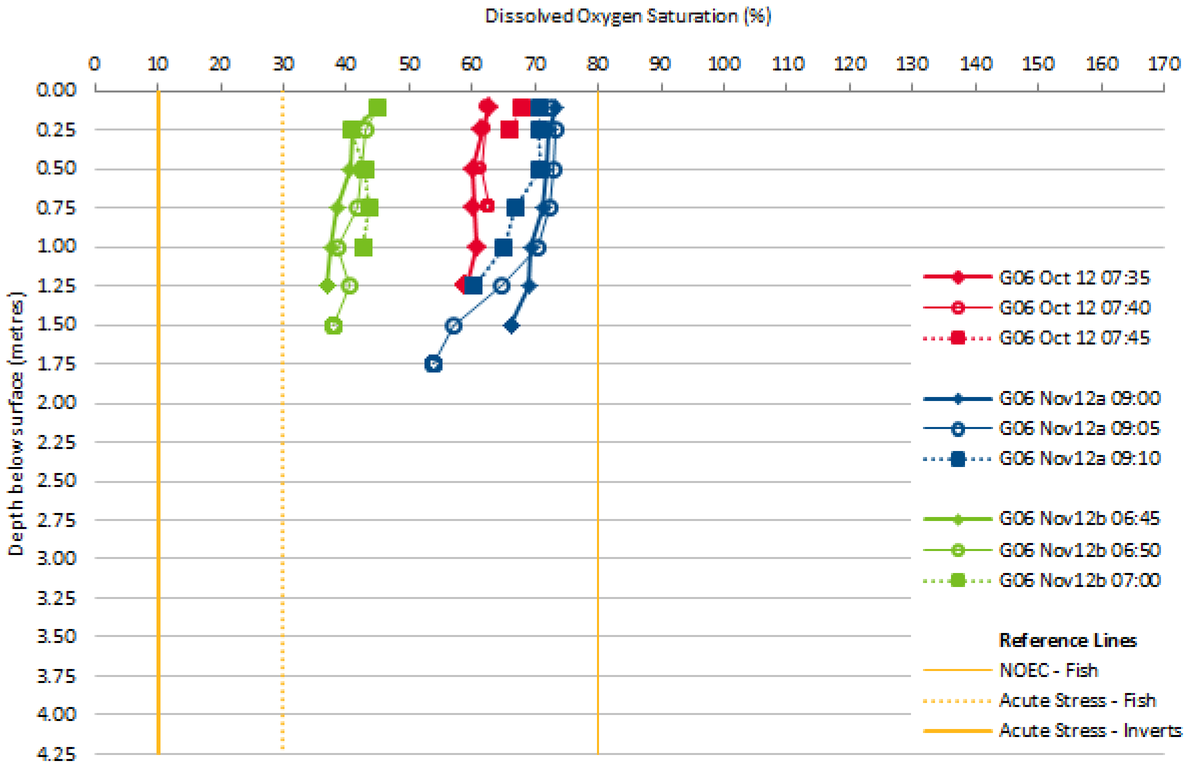


Figure 53 Temperature vertical water column profiles at waterhole G06. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



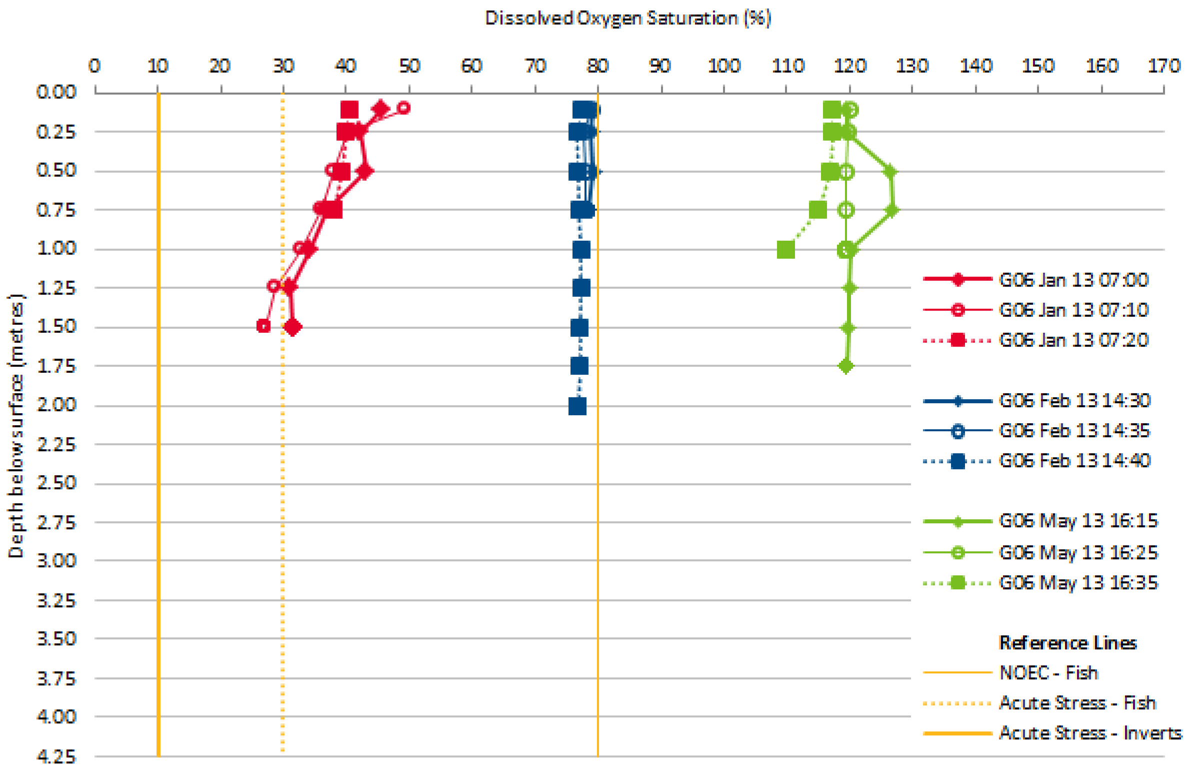
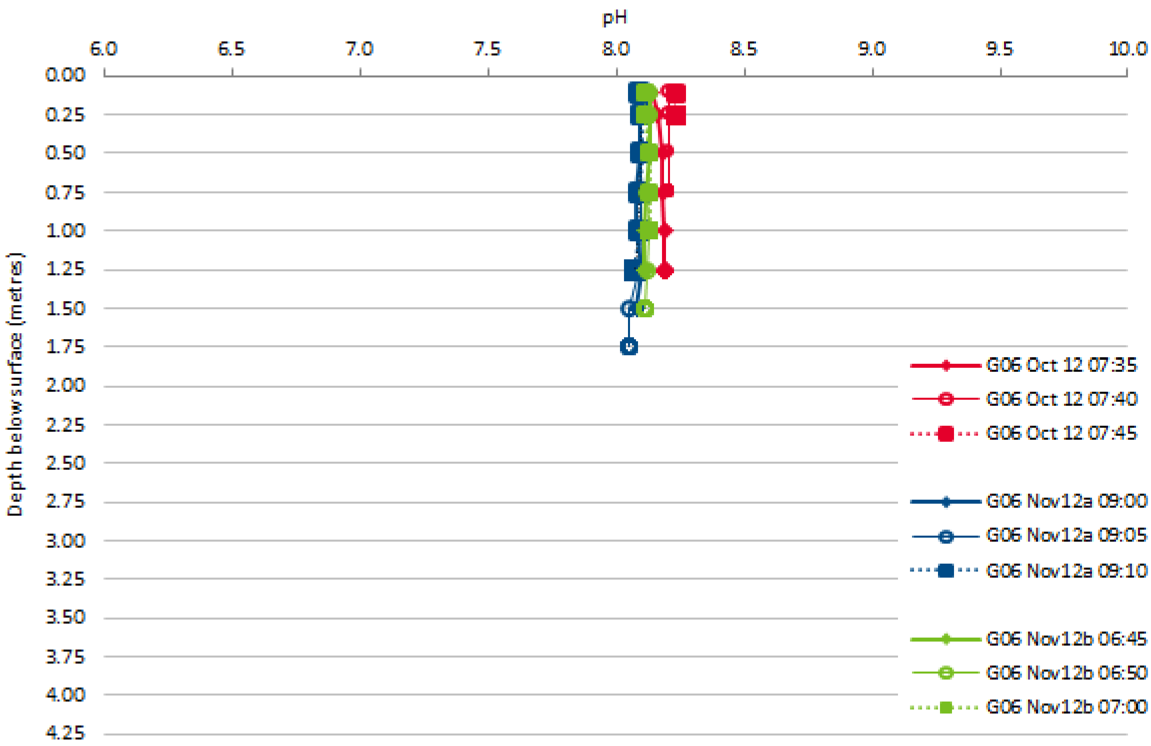


Figure 54 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G06. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



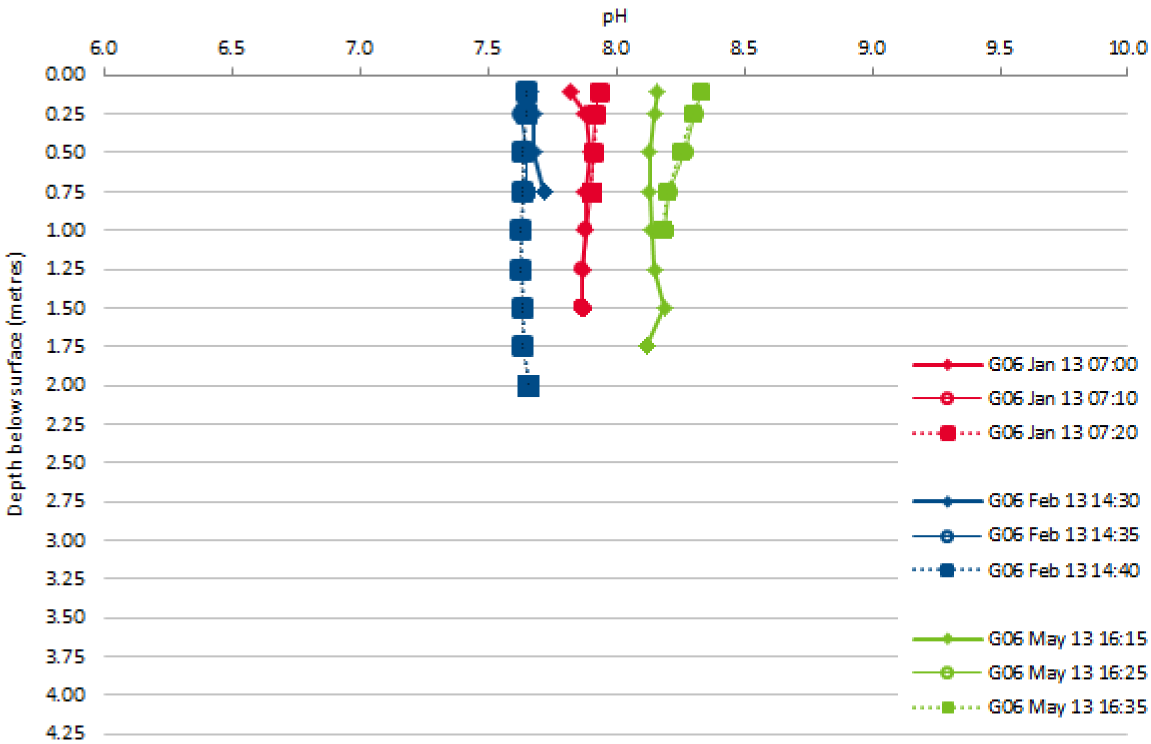
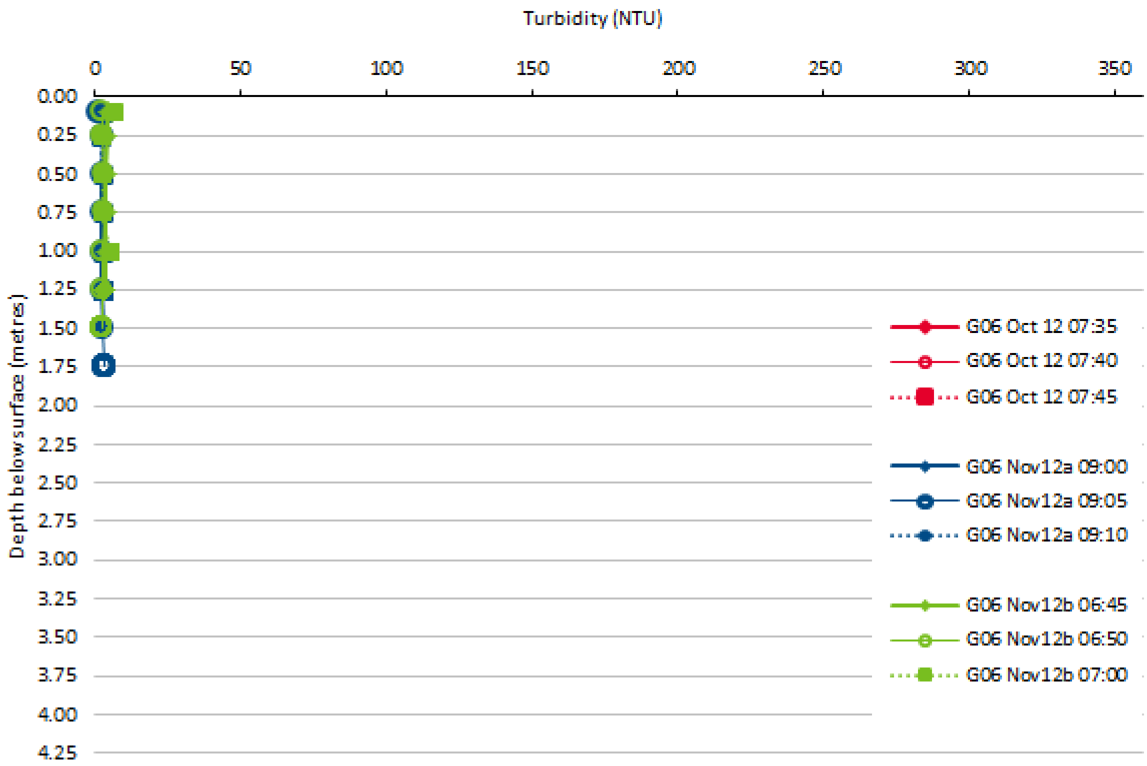


Figure 55 pH vertical water column profiles at waterhole G06. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



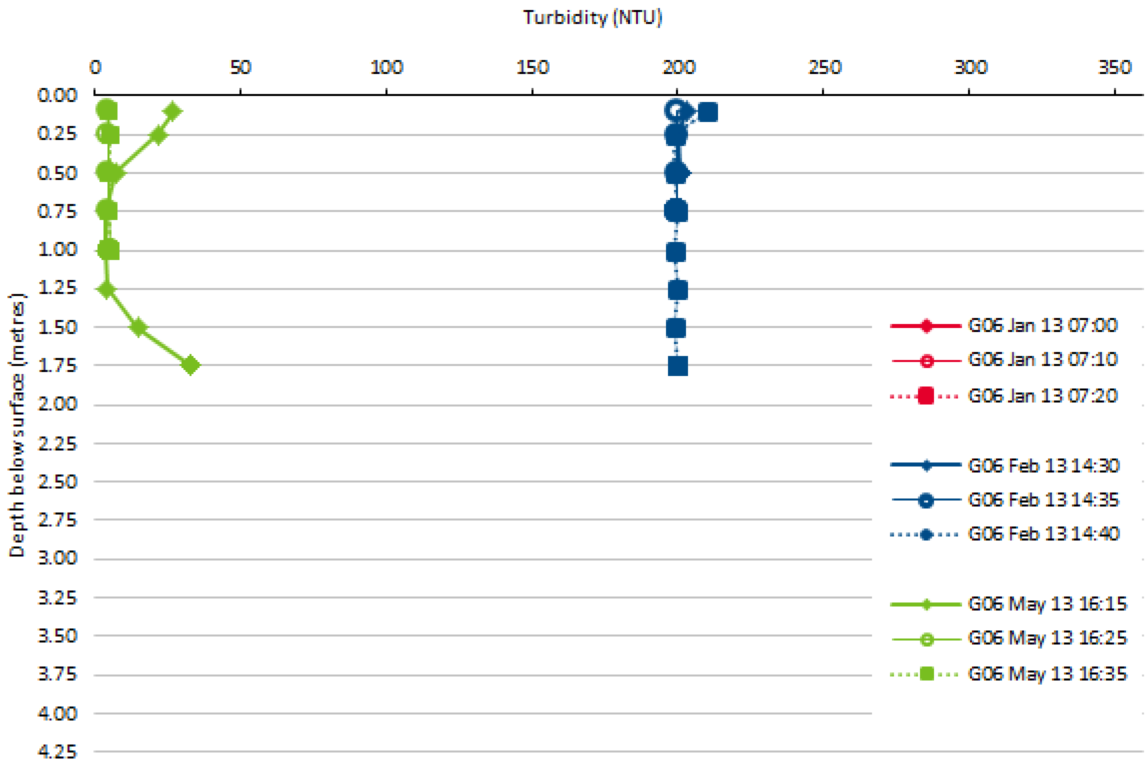
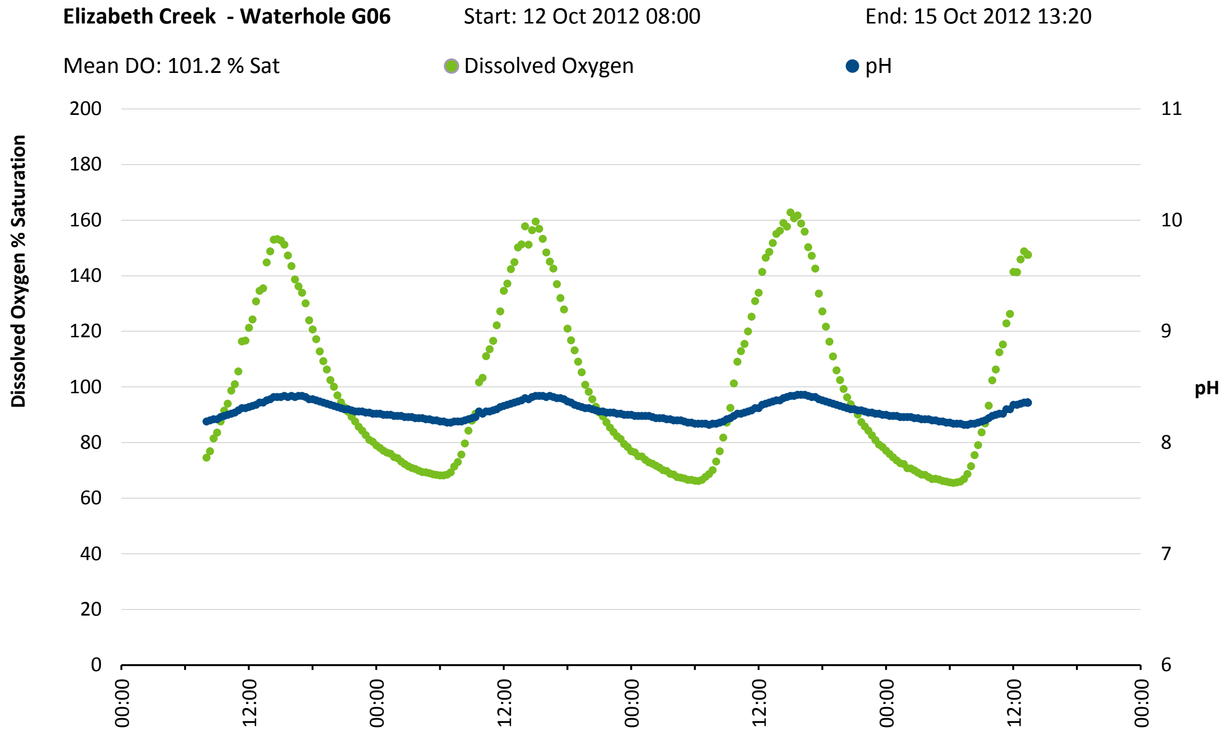


Figure 56 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G06. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



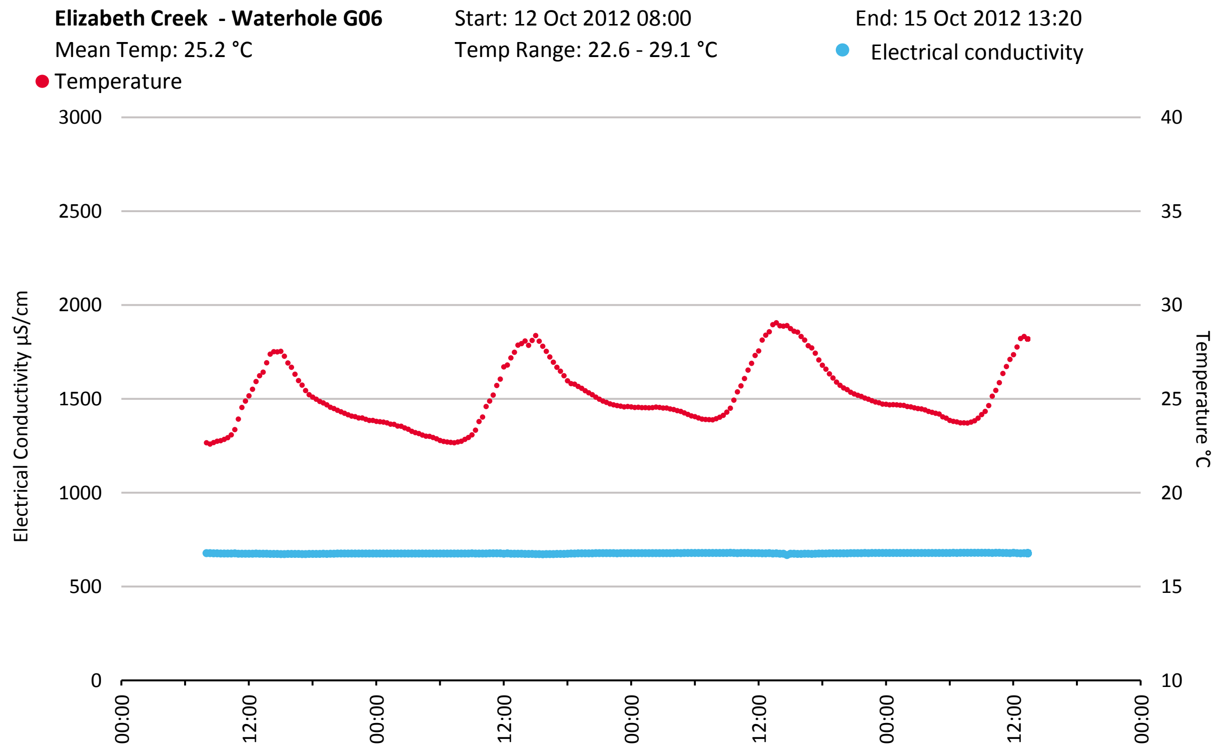
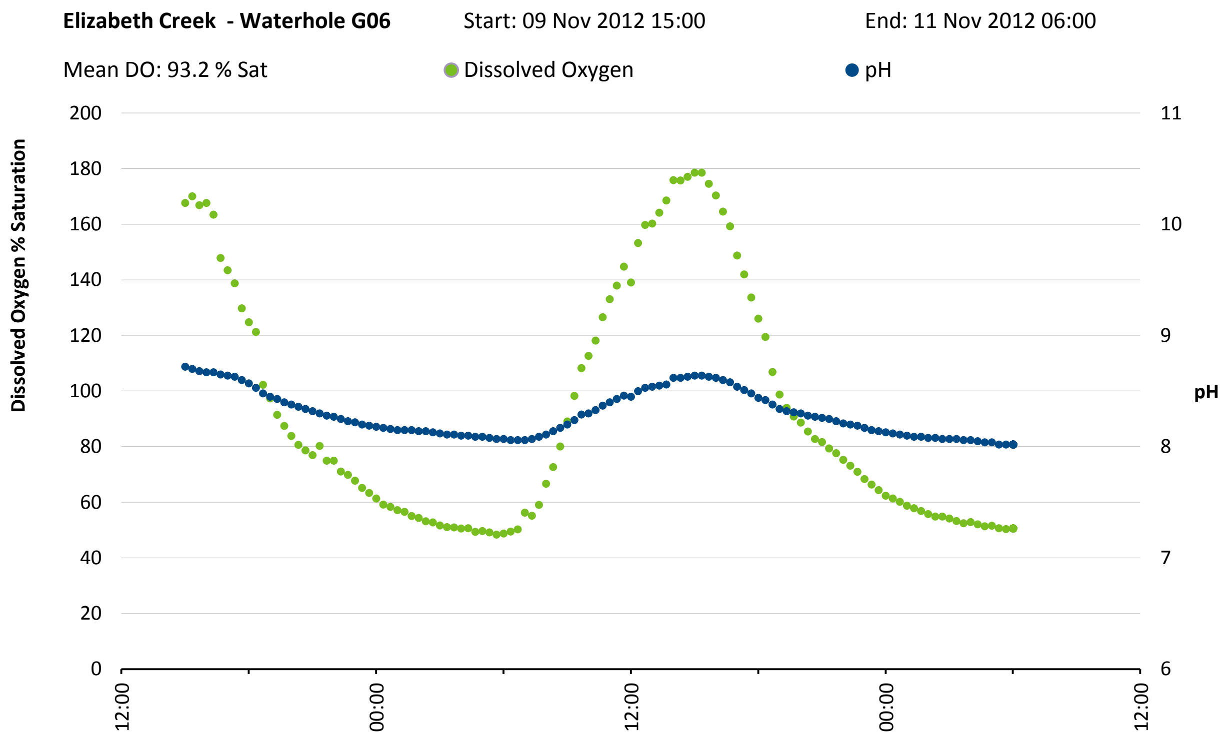


Figure 57 Diel physico-chemical data for waterhole G06, Oct 2012



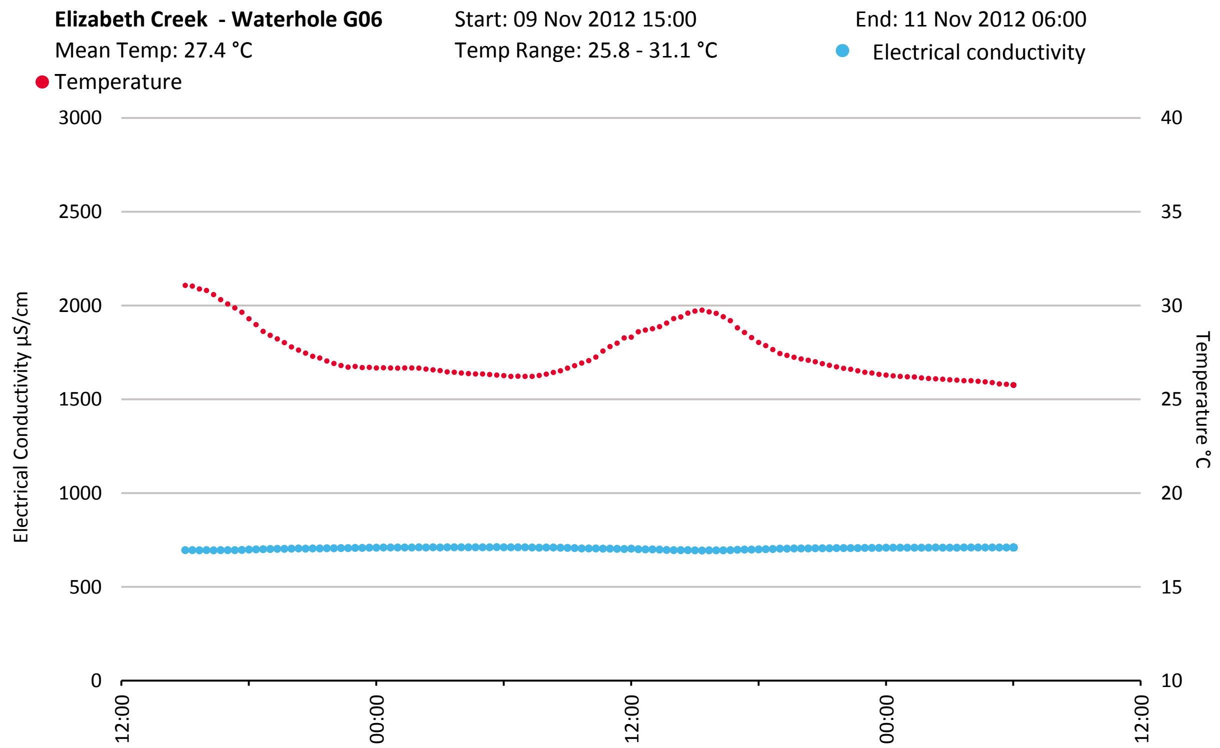
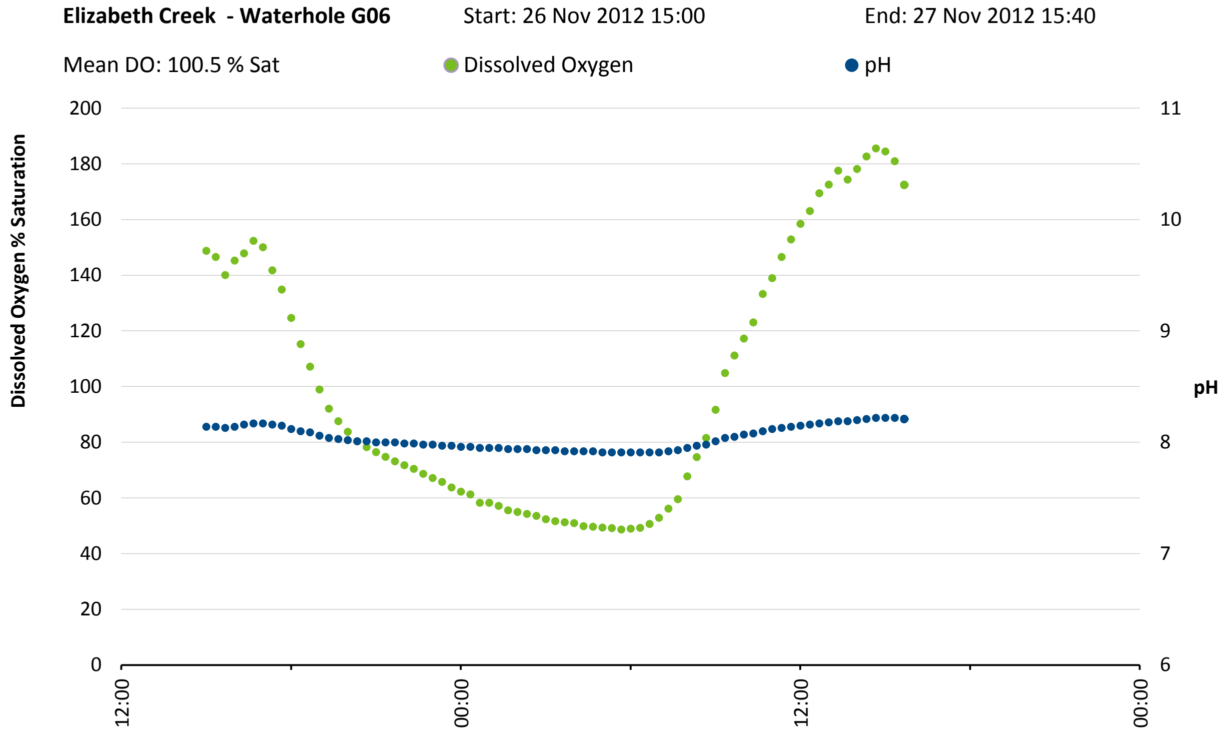


Figure 58 Diel physico-chemical data for waterhole G06, Nov 2012



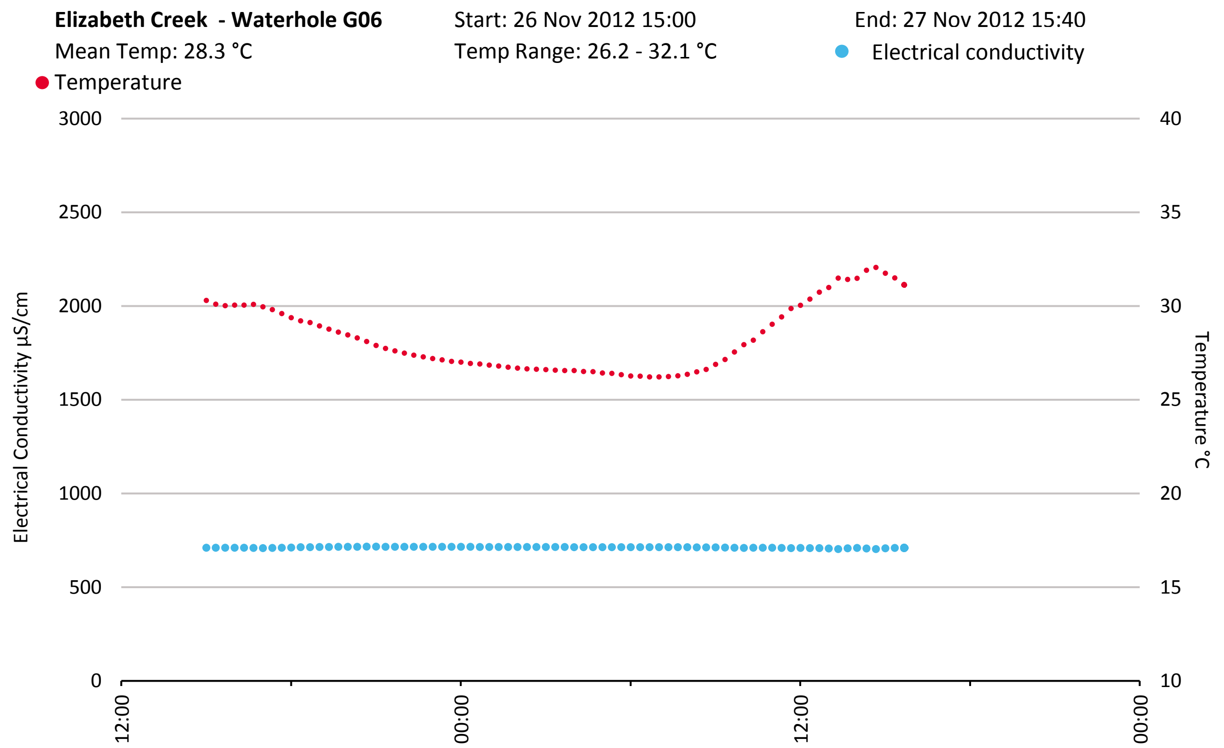
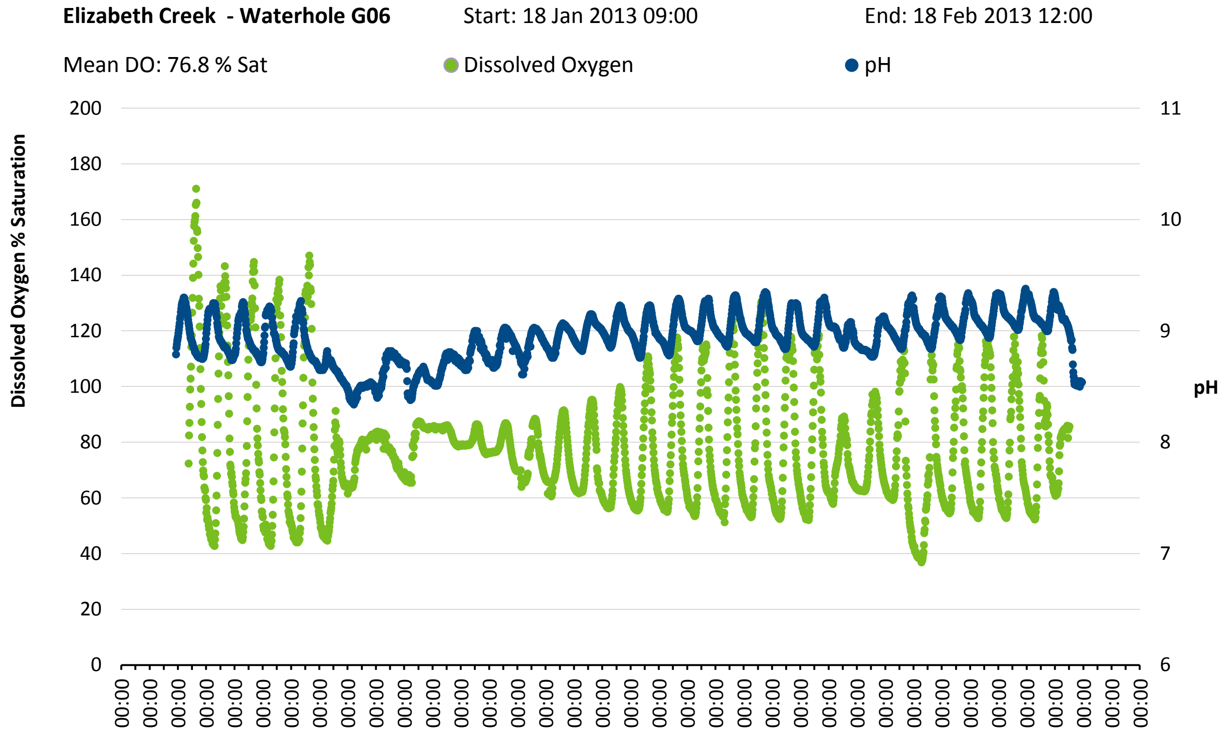


Figure 59 Diel physico-chemical data for waterhole G06, Nov 2012



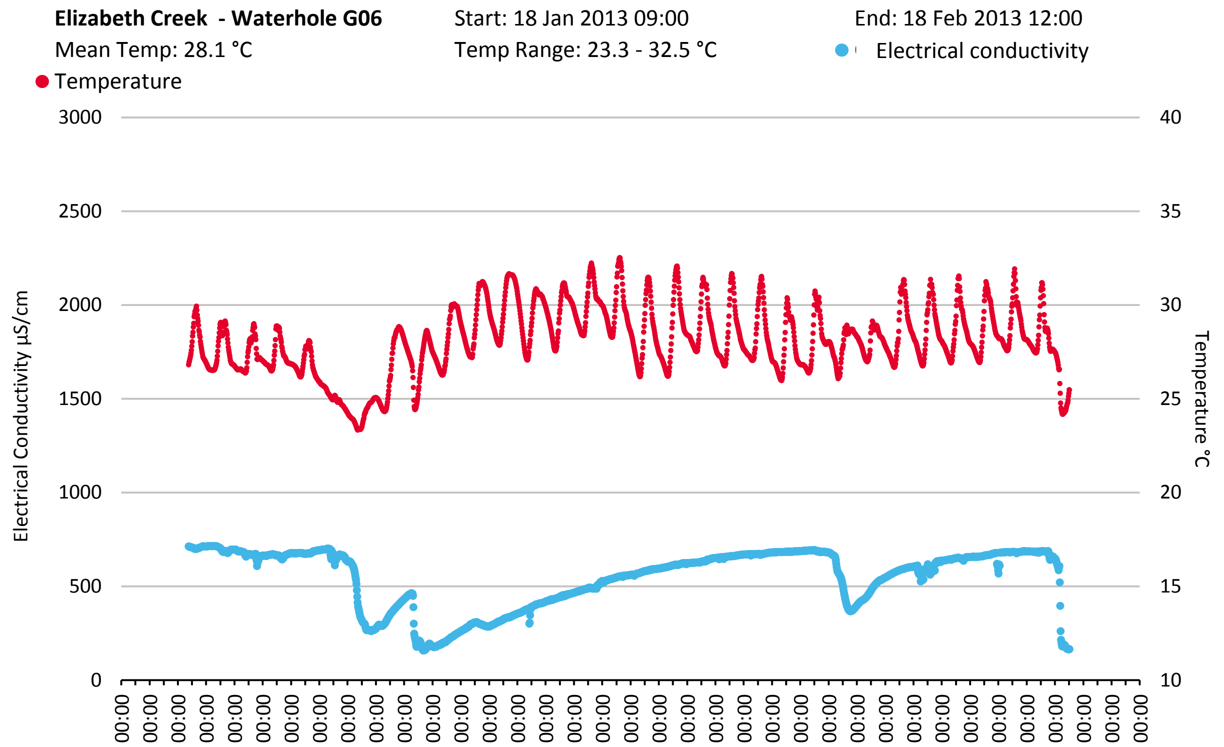


Figure 60 Diel physico-chemical data for waterhole G06, Jan-Feb 2013. Logger deployed for a longer period of time in an attempt to capture a flow event

WATERHOLE G07

FAMILY NAME	SPECIES NAME
Waterhole	G07
Catchment	Gilbert River
Watercourse	Junction Creek
Waterhole location	-18.179826°, 144.241964°. Upstream of the Gulf Development Road
Waterhole elevation	~400 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 11-Oct-12
	Survey 3: 10-Nov-12
	Survey 5: 27-Nov-12
	Survey 7: 20-Jan-13
	Survey 9: 28-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~9300 m^2
	Waterhole volume: ~4200 m^3
	Wetted perimeter: ~ 580 m
	Maximum depth: 1.3 m
	Average depth: 0.4 m
	Waterhole length: 250 m
Instream habitats	The waterhole has a sandy bottom with some boulders present. Algae were dense across the entire waterhole. Epilithic algae was most common (~70% coverage), and epiphytic and filamentous algae were also present in high biomass. Shallow water hosted dense aquatic macrophyte beds, including *Eleocharis* sp., *Potamogeton pectinatus* and *Ottellia alismoides*, with the dominant species being *Myriophyllum* sp.
Riparian zone	The riparian zone is subject to high cattle traffic. Groundcover was very sparse, or not present, during dry periods. Both rubber vine (*Cryptostegia grandiflora*) and thistles were common along the riparian zone. Some *Melaleuca* trees line the waterhole perimeter, and on the right bank a stand of *Casuarina* trees are present. Riparian trees offer about ~5% shade across the water.
Waterhole depth changes	Waterhole depth remained constant across the Assessment period.
Other notes	A moderate level of cattle damage was evident.

a)

b)

Figure 61 a) GoogleEarth 2011 aerial view of G07. b) Left to right: 1) Upstream from left bank. 2) Downstream from left bank. 3) Looking upstream from left bank. 4) Aquatic macrophytes and algae are dense in shallow water

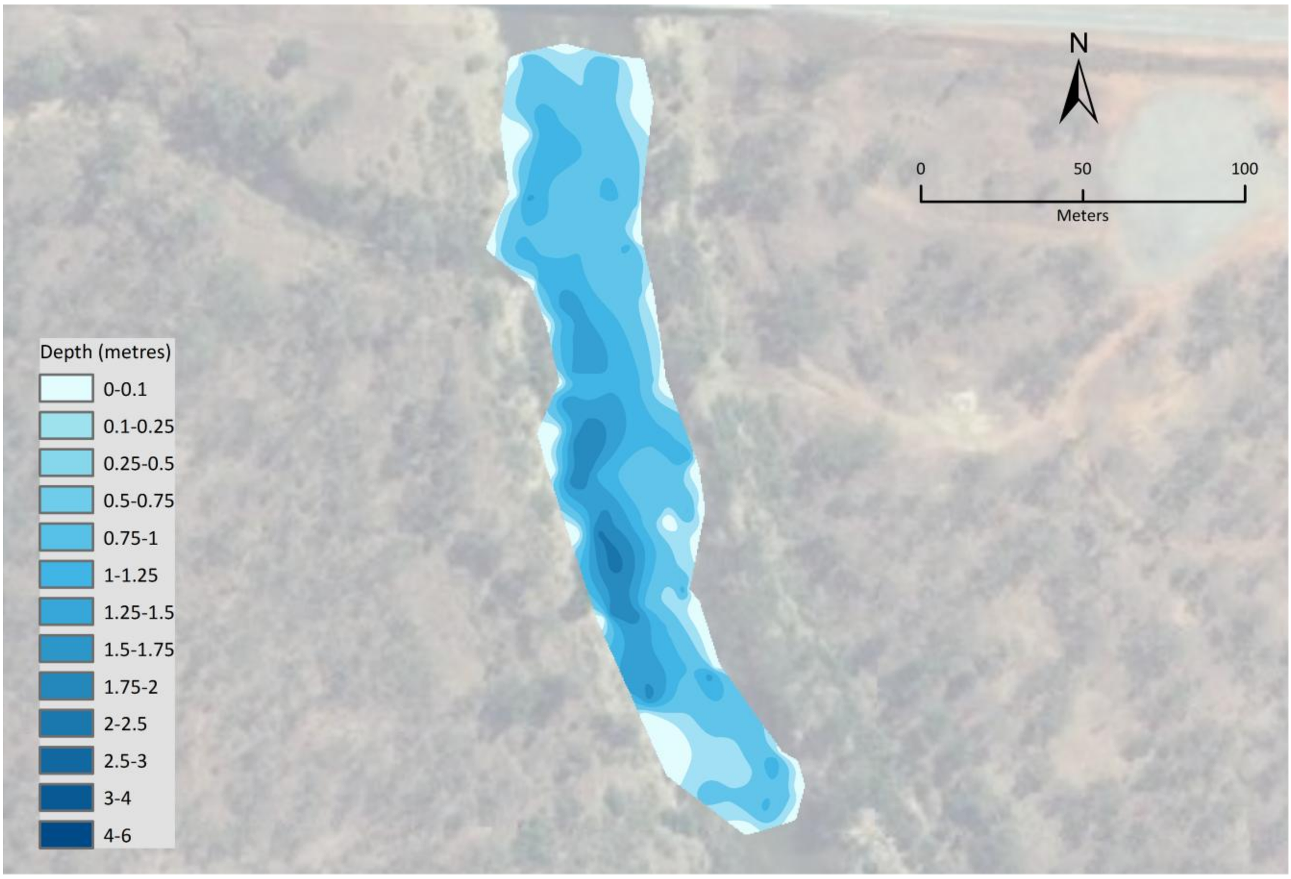


Figure 62 Bathymetry map of waterhole G07. Depth and waterhole perimeter data generated from data collected Oct 2012

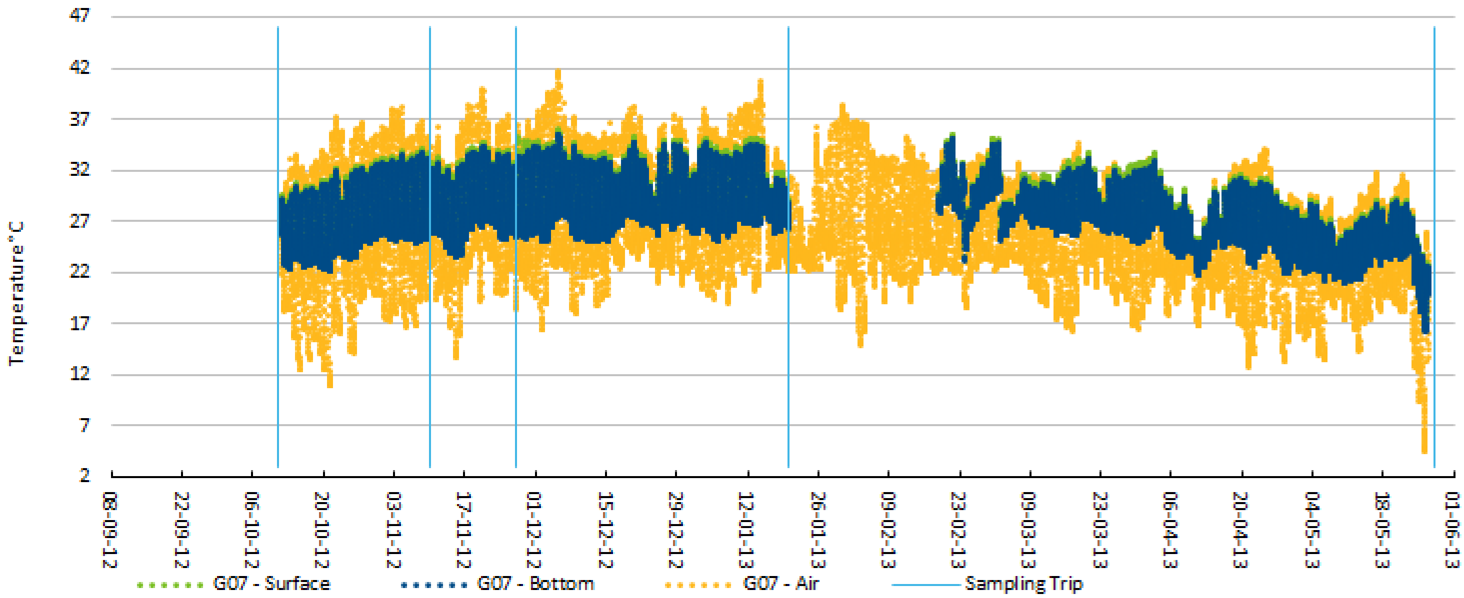
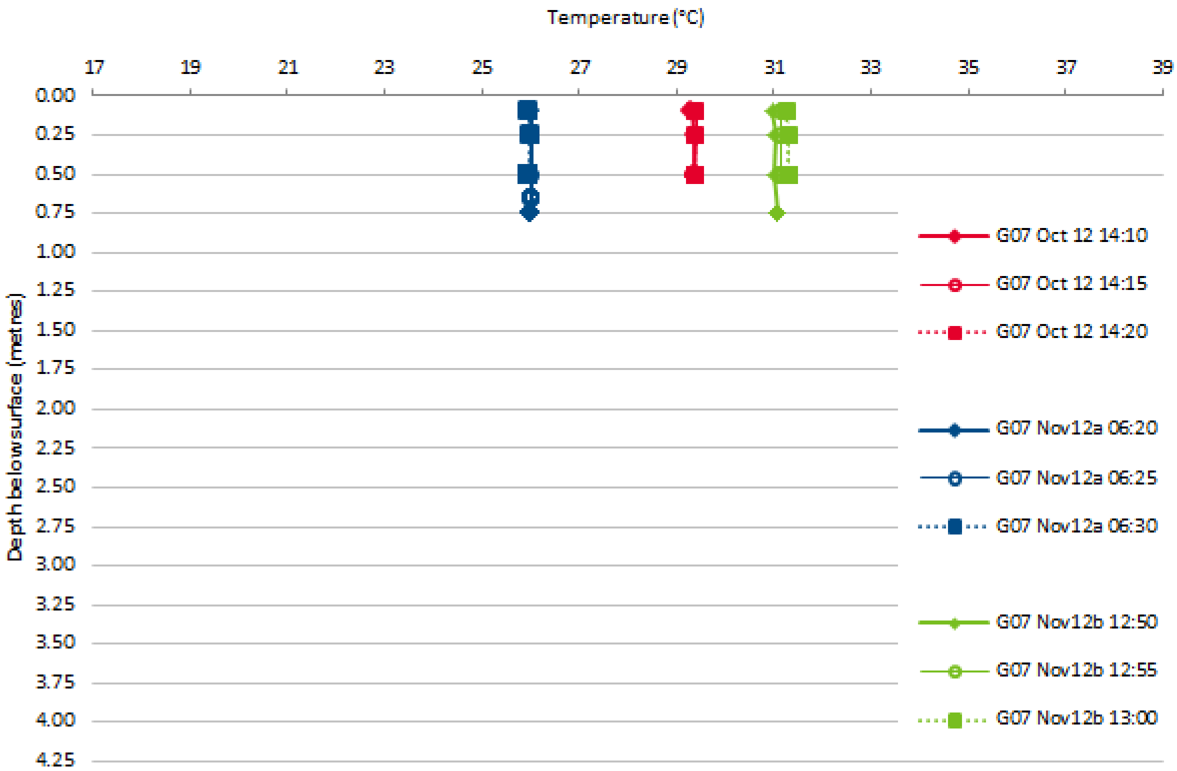


Figure 63 Long term temperature logger data for waterhole G07. Missing data corresponds to logger malfunction

Table 7 Continuous water and air temperature logger summary statistics for each survey at waterhole G07.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Oct 12	12-10-12 00:15	22-10-12 00:15	10	11.0	24.2	35.6	22.3	25.9	31.3	22.1	25.5	31.0	0.1	0.4	0.7	37.0	0.0	0.0
Nov12a	07-11-12 00:15	17-11-12 00:15	10	13.7	26.7	36.8	23.5	28.4	34.1	23.5	28.0	33.7	-0.2	0.4	0.8	36.2	0.0	0.0
Nov12b	22-11-12 00:15	30-11-12 00:15	8	18.5	28.1	37.5	25.4	29.3	35.2	25.2	29.0	33.8	-0.1	0.4	1.9	31.8	1.2	0.9
Jan 13	18-01-13 00:15	26-01-13 00:15	8	22.1	25.4	36.3	26.4	28.6	31.7	26.0	28.2	31.1	0.2	0.4	0.8	34.5	0.0	0.0
May 13	22-05-13 00:15	25-05-13 00:15	3	12.4	21.5	30.8	21.1	24.8	29.0	20.9	24.5	28.7	0.2	0.3	1.0	12.4	0.0	0.0



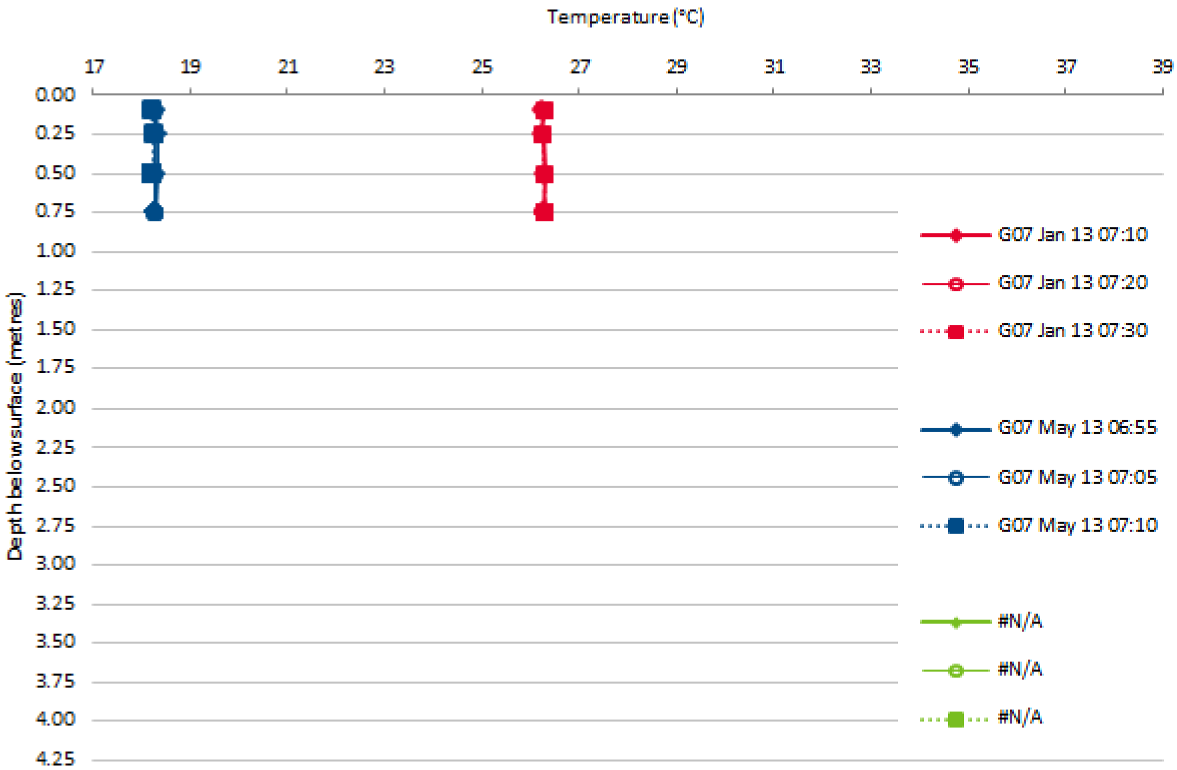
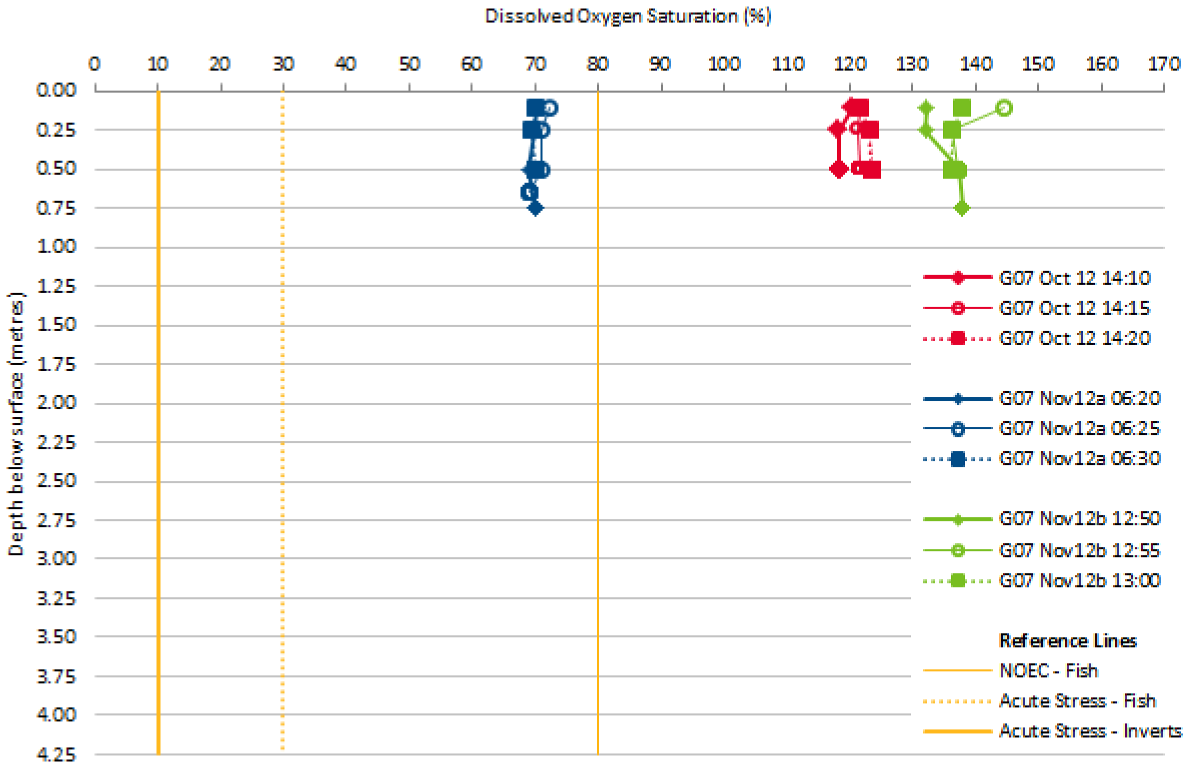


Figure 64 Temperature vertical water column profiles at waterhole G07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



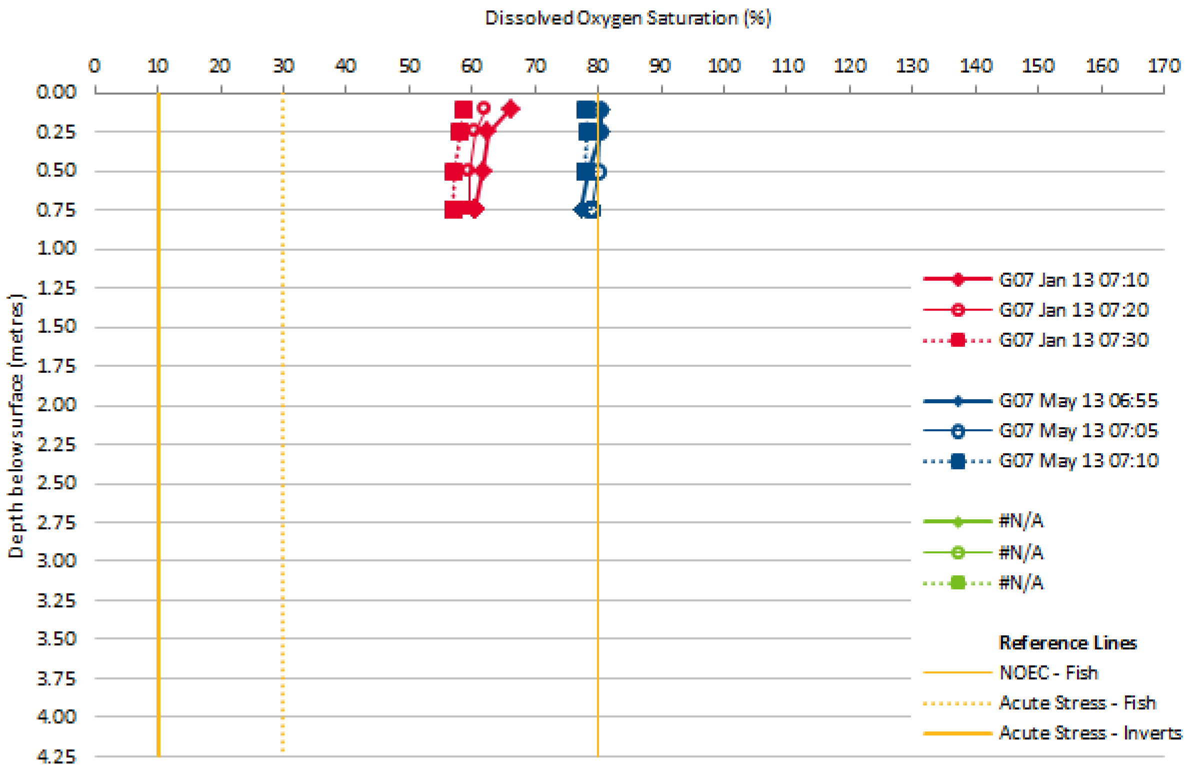


Figure 65 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G07. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

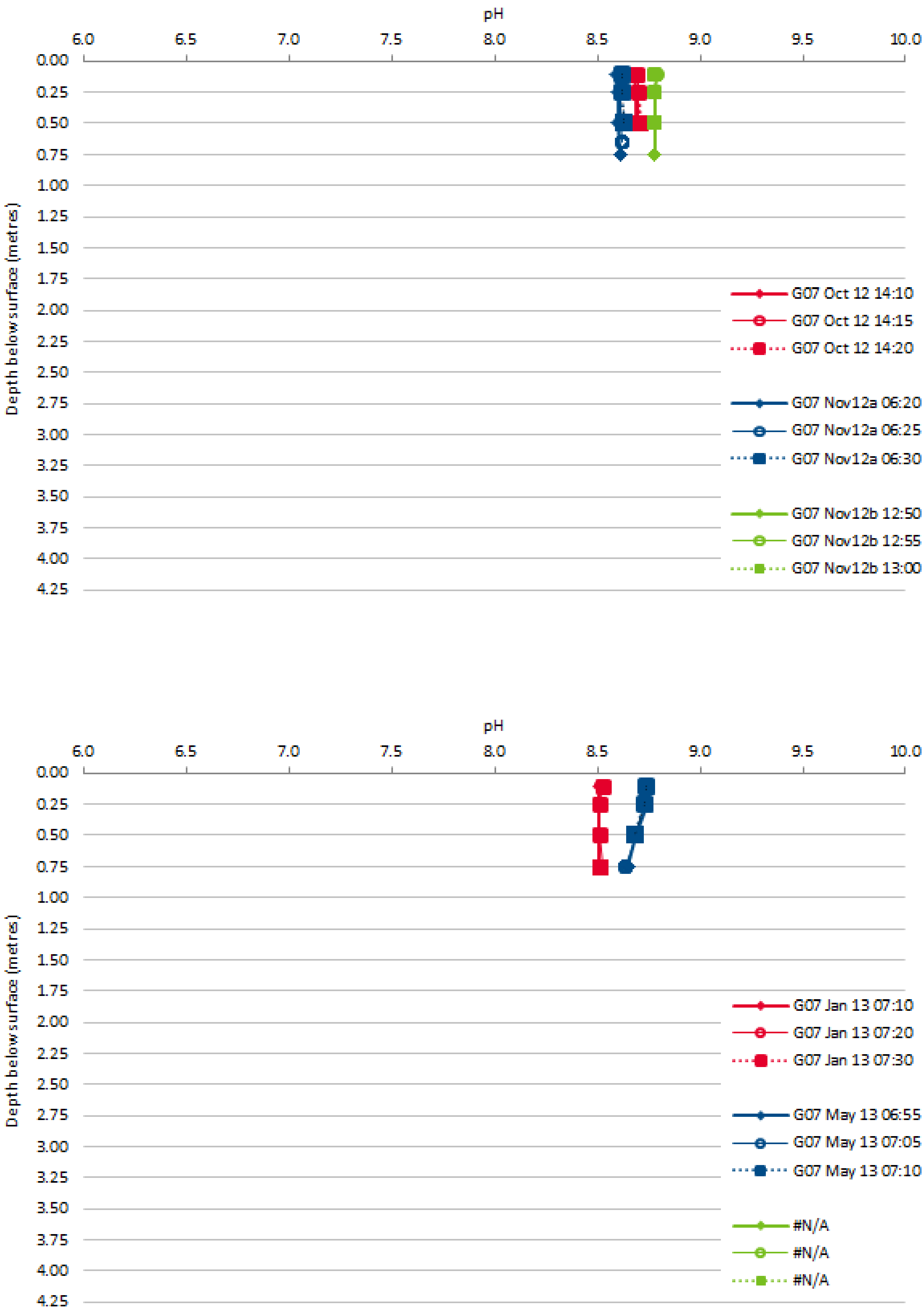
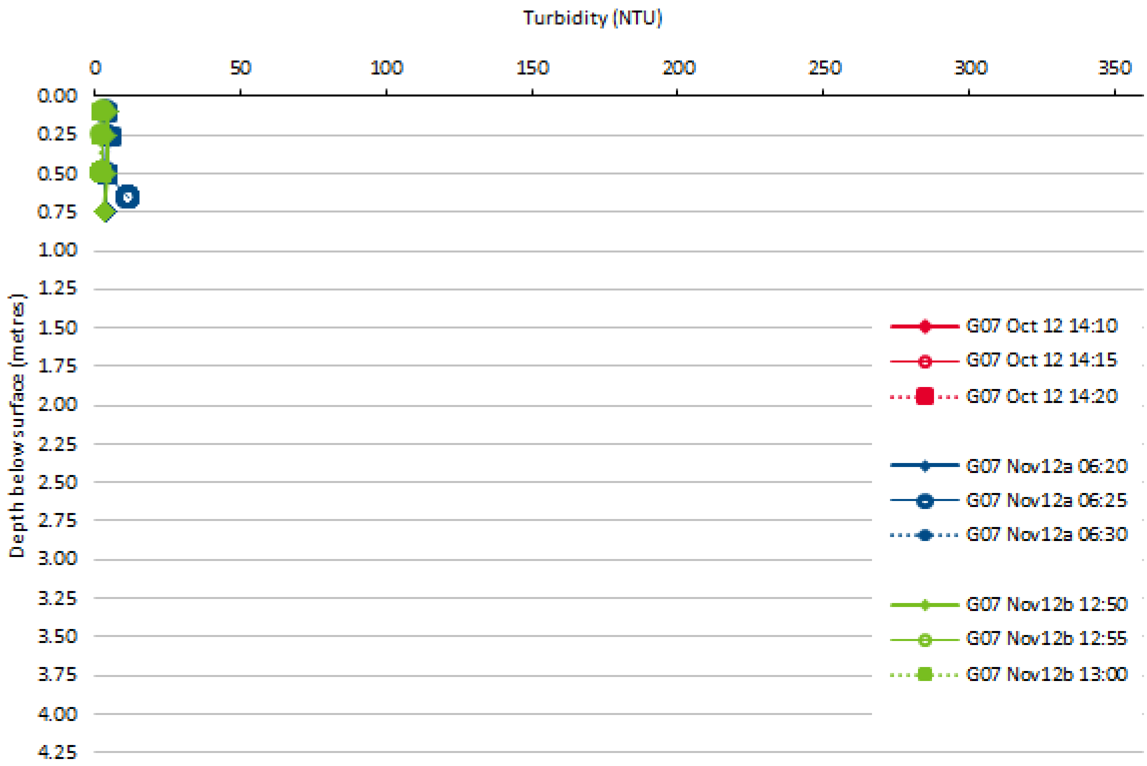


Figure 66 pH vertical water column profiles at waterhole G07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



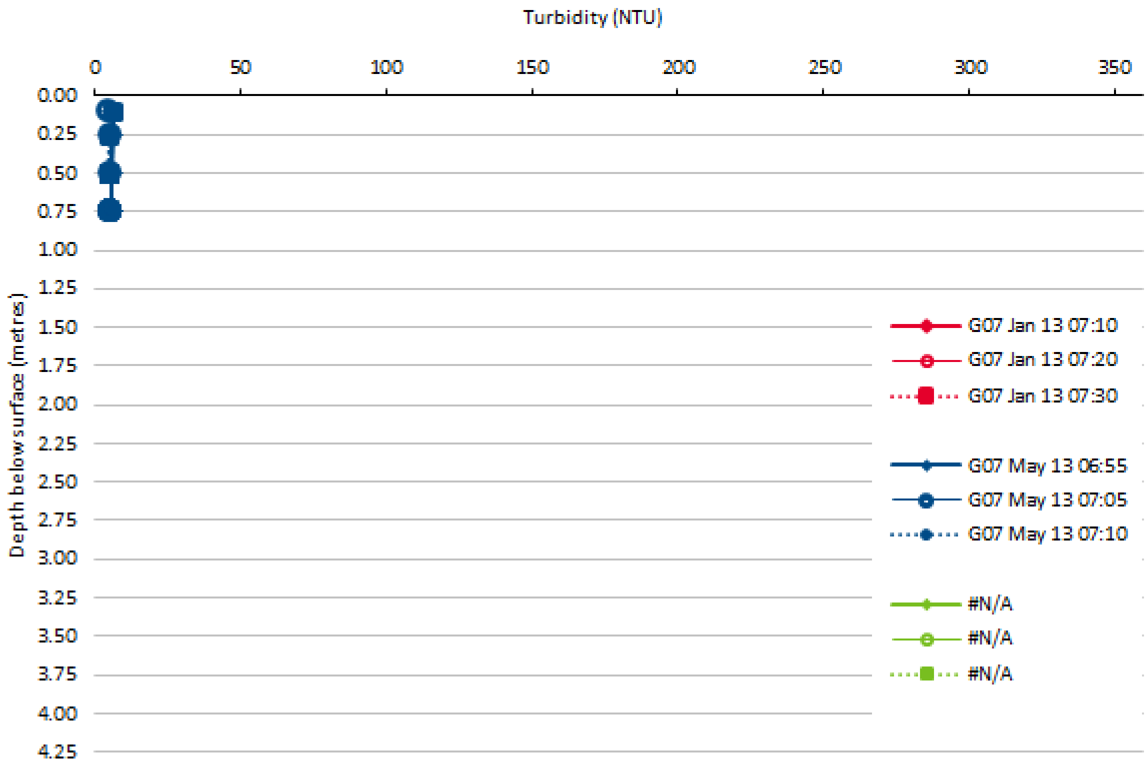
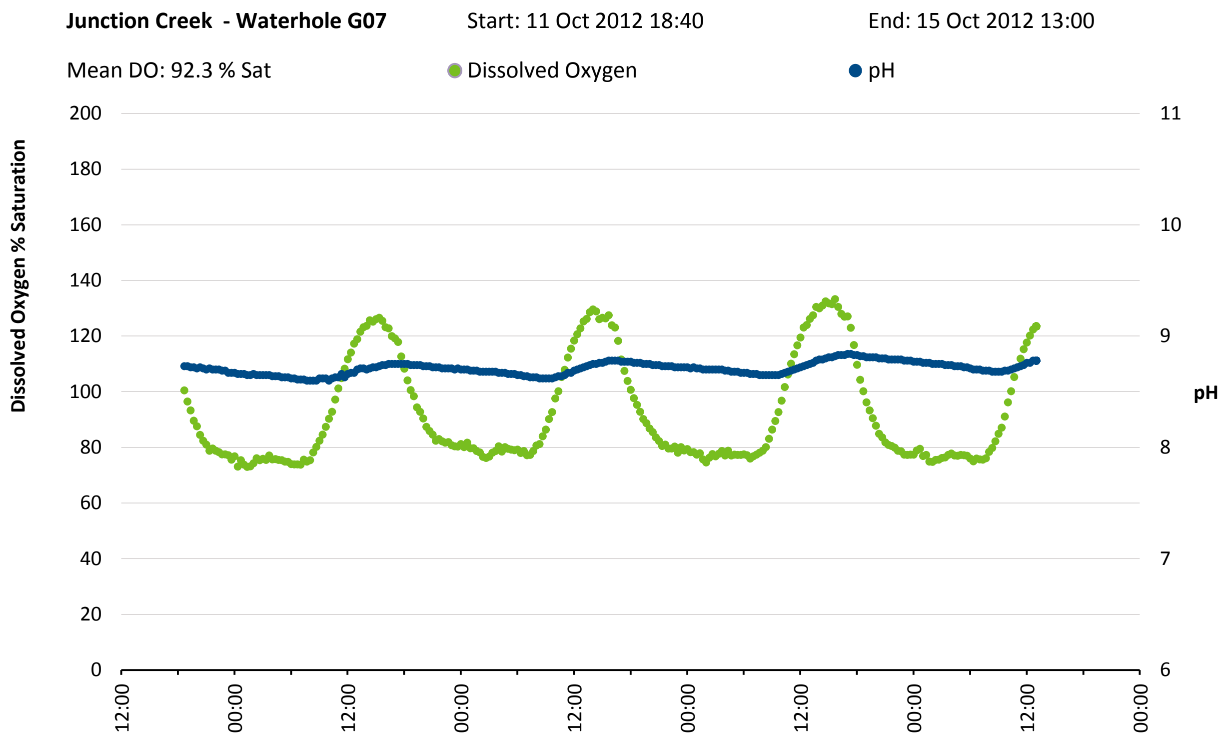


Figure 67 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G07. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



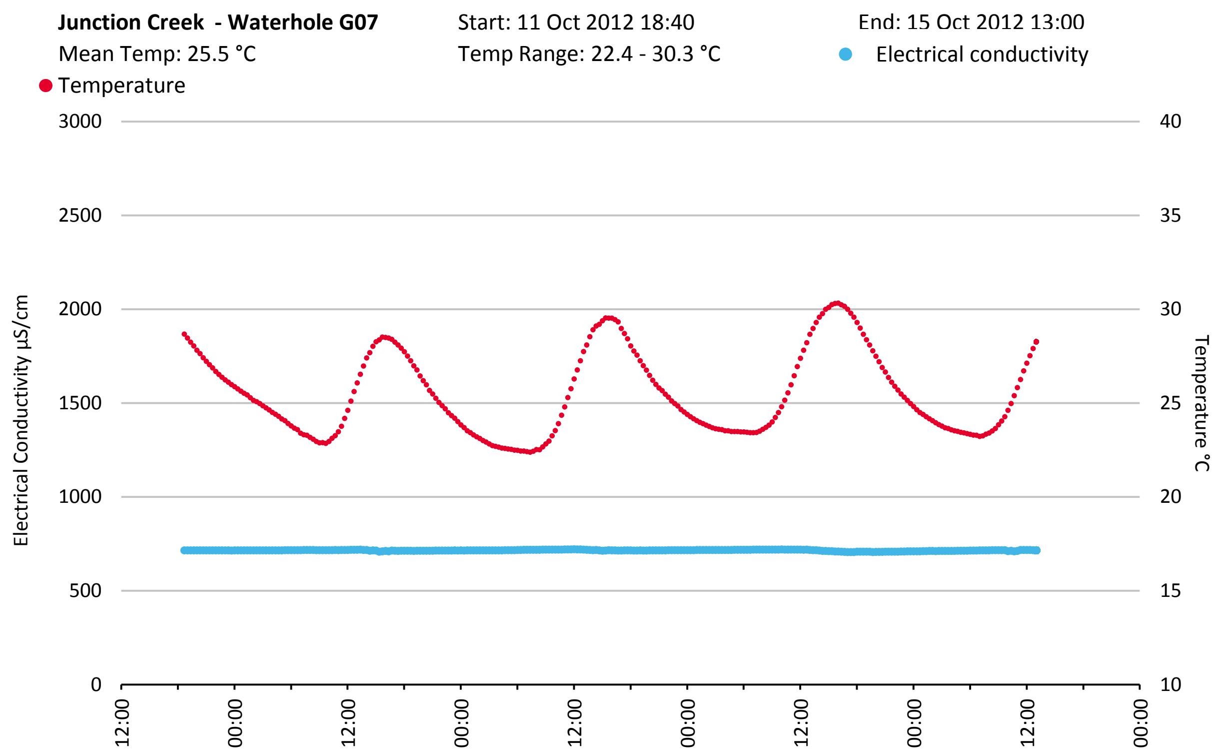
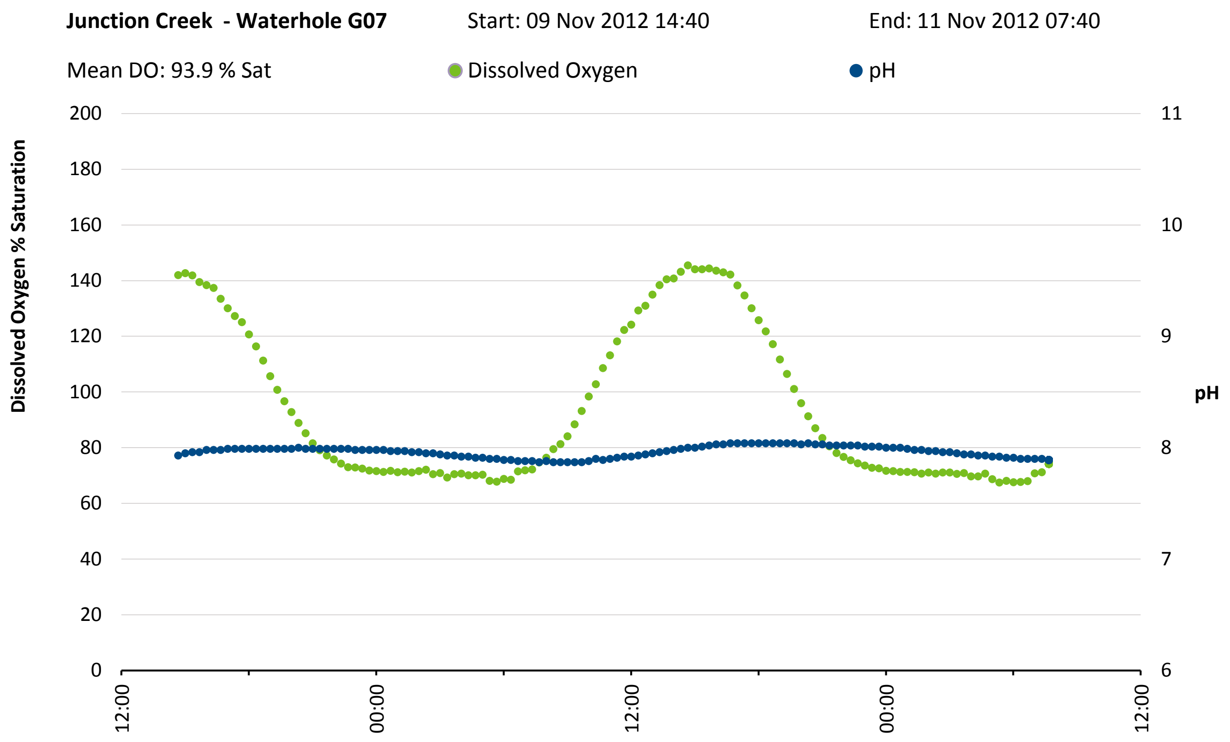


Figure 68 Diel physico-chemical data for waterhole G07, Nov 2012



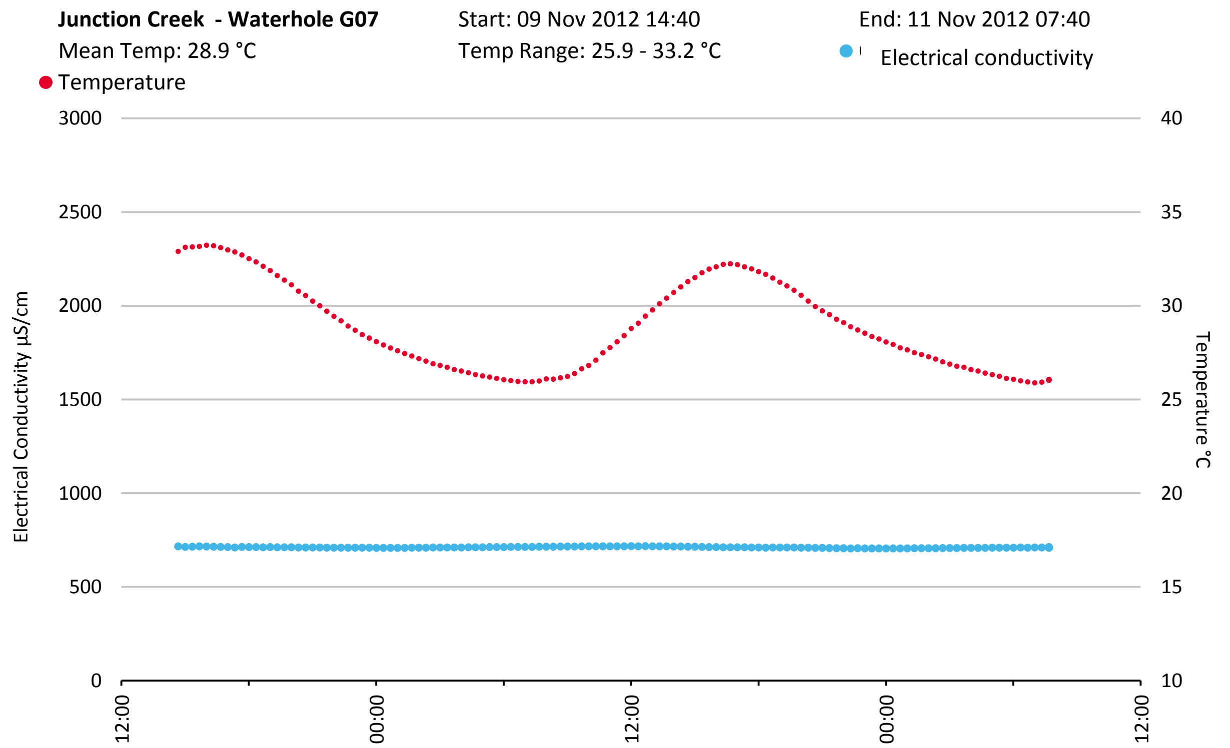
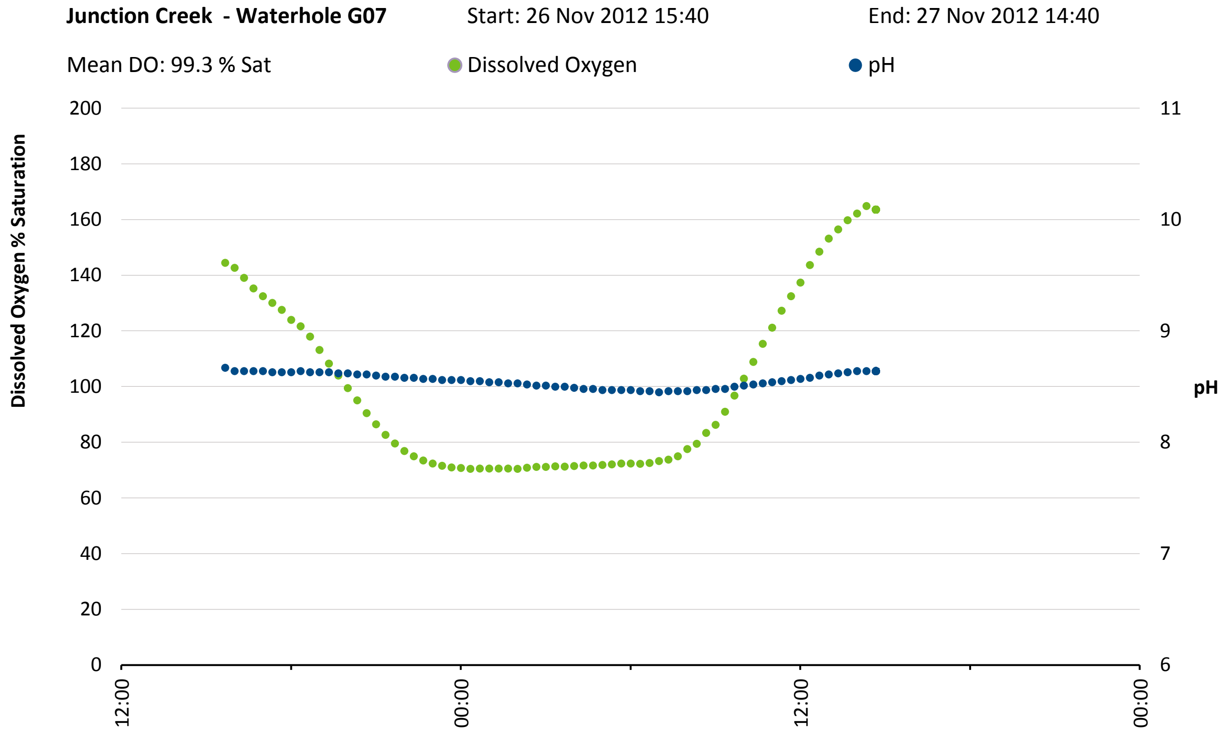


Figure 69 Diel physico-chemical data for waterhole G07, Nov 2012



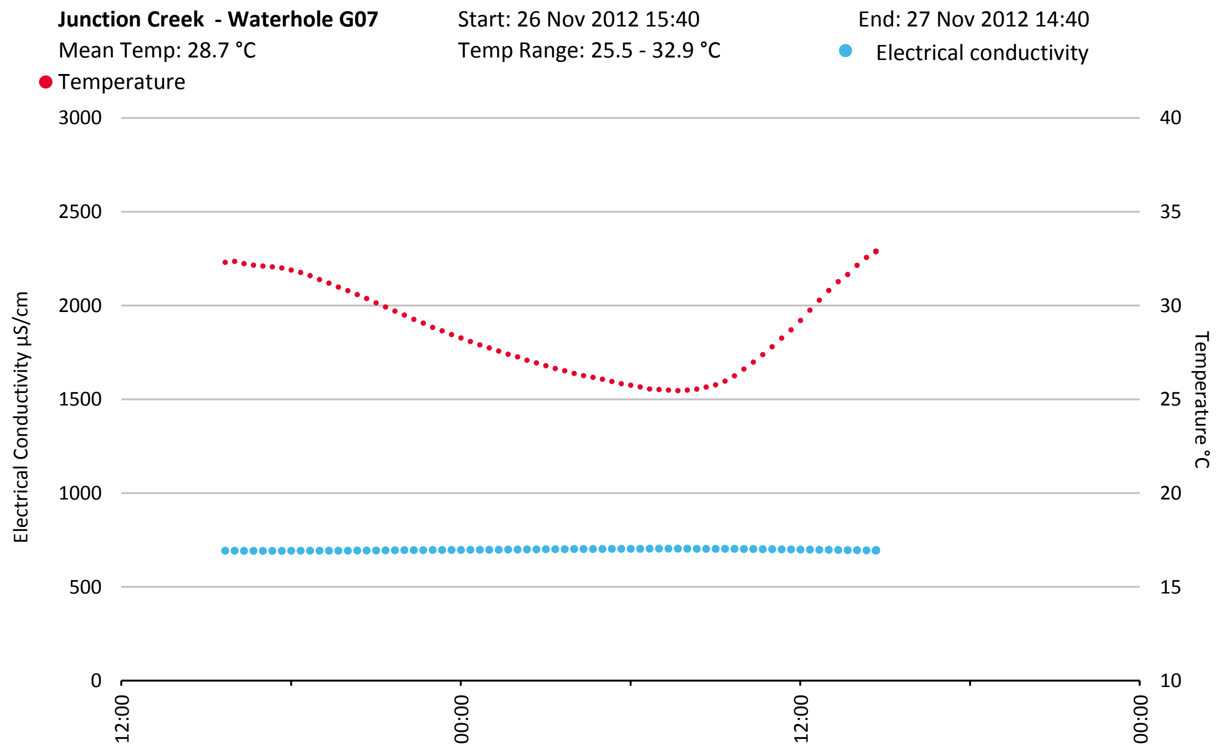


Figure 70 Diel physico-chemical data for waterhole G07, Nov 2012

WATERHOLE G08

FAMILY NAME	SPECIES NAME
Waterhole	G08
Catchment	Gilbert River
Watercourse	Langlovale Creek
Waterhole location	-18.263491°, 142.999861°. Immediately upstream of the junction with the Gilbert River at Langlovale Station
Waterhole elevation	~190 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 11-Oct-12
	Survey 3: 10-Nov-12
	Survey 5: 27-Nov-12
	Survey 7: 20-Jan-13
	Survey 9: 28-May-13
Waterhole characteristics	Surface area: ~29,200 m^2
(measured Oct 2012)	Waterhole volume: ~83,400 m^3
	Wetted perimeter: ~ 2150 m
	Maximum depth: 5.9 m
	Average depth: 2.8 m
	Waterhole length: 1200 m
Instream habitats	In shallow areas at the upstream end of the waterhole pond weeds (*Chara* and *Blyxa* spp.) were present in low densities, but overall few macrophytes were present. Snags and woody debris are very common in the upstream region, and notably present throughout the entire waterhole. Waterhole edges are very steep, with overhanging riparian tree roots offering habitat.
Riparian zone	A very large flying fox colony was camped along the mid to lower reaches of the waterhole. The bats had significantly damaged the riparian trees and lowered canopy cover along the waterhole edges. Shade protection offered in this mid to lower waterhole region is now significantly lower than that offered further upstream. Where the bats were not present, the riparian zone was in good condition with a diverse range of species present including *Melaleuca*, Leichhardt trees (*Nauclea orientalis*), and *Eucalyptus* species. Trees overhang the water, offering around 30% shade to the waterhole.
Waterhole depth changes	Waterhole depth fell slightly between September and December 2012. During January maximum waterhole depth increased by over one meter. Depth then declined toward May 2013.
Other notes	Minimal cattle damage was evident.

a)

b)

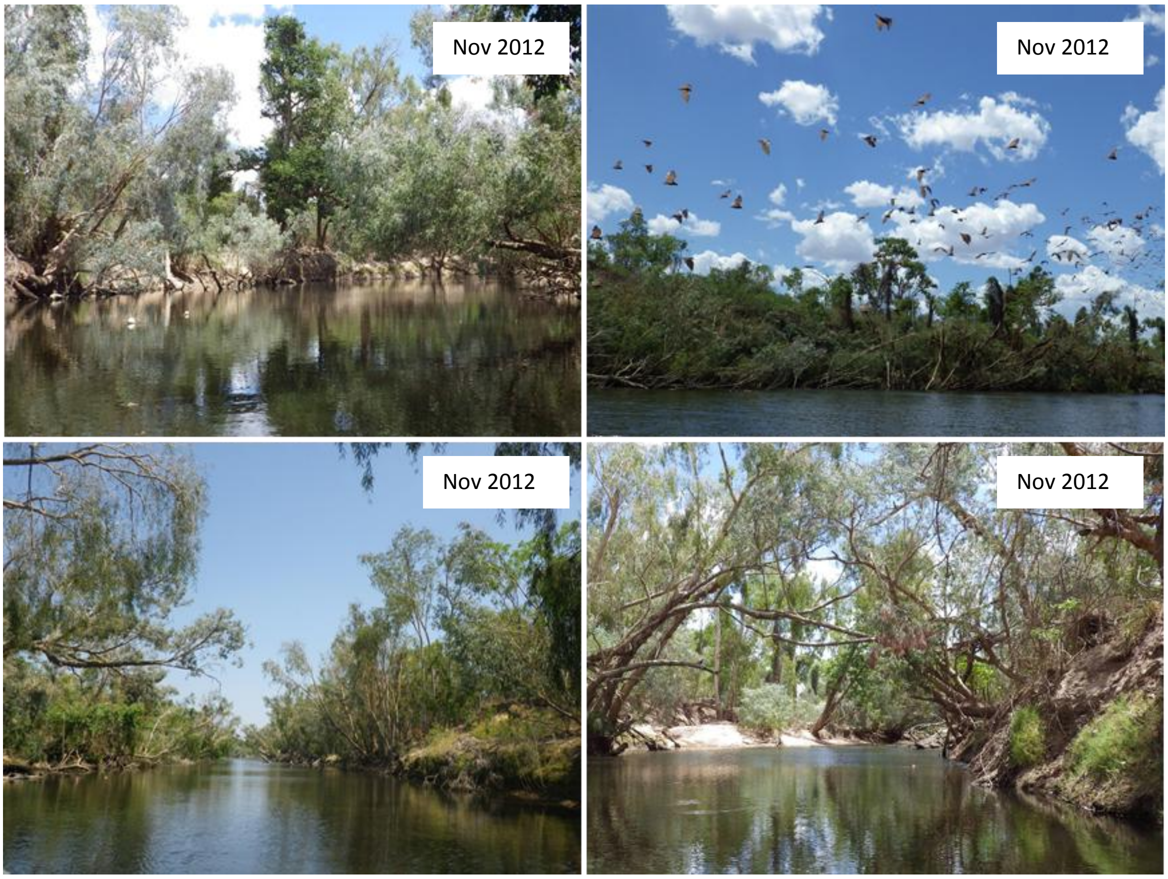


Figure 71 a) GoogleEarth 2010 aerial view of G08 showing relationship to Gilbert River. b) Left to right: 1) Upstream from mid channel. 2) Flying fox damage to the riparian trees at the downstream end of the waterhole. 3) Mid waterhole section from mid channel. 4) Upstream from mid channel

Figure 72 Bathymetry map of waterhole G08. Depth and waterhole perimeter data generated from data collected Oct 2012

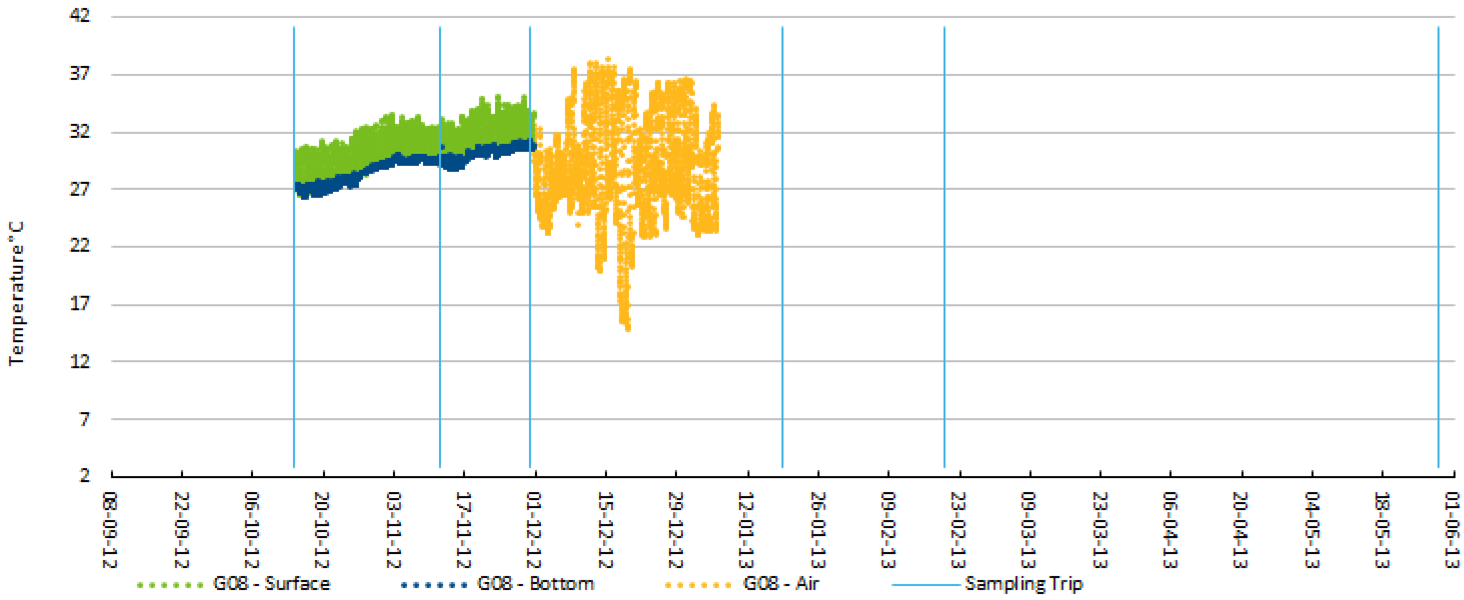
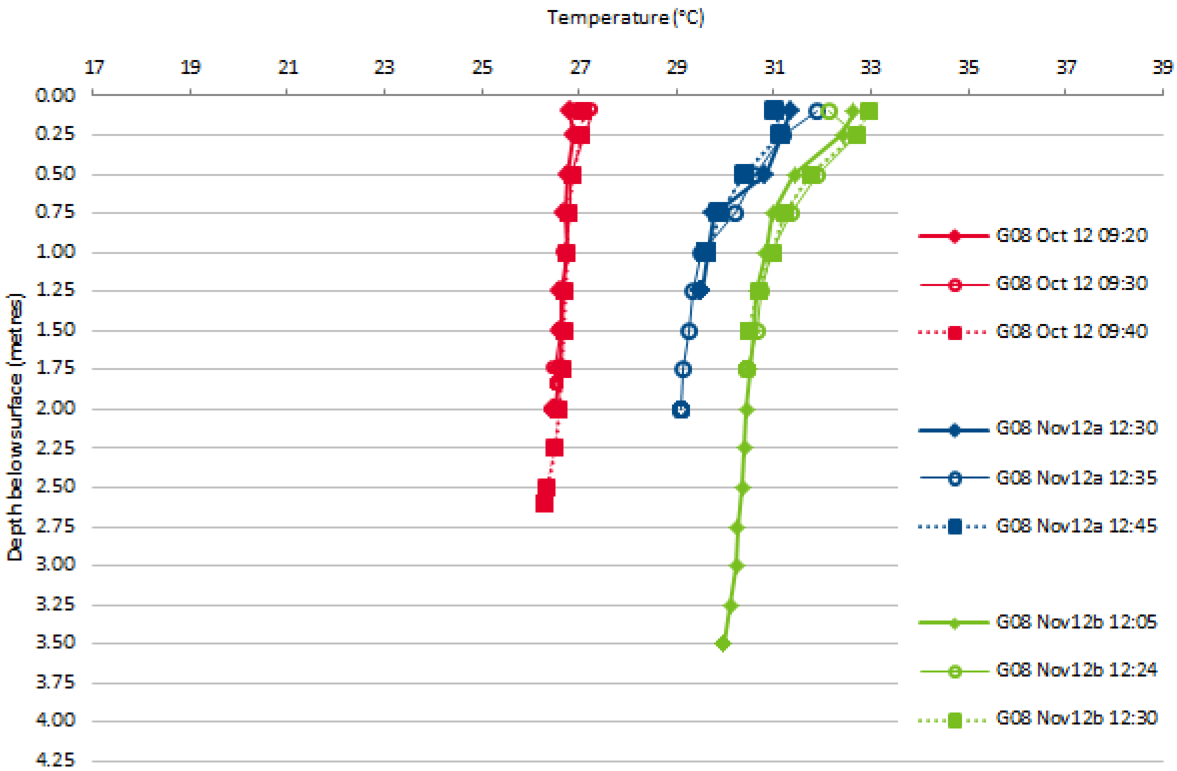


Figure 73 Long term temperature logger data for waterhole G08. Missing data due to logger malfunction

Table 8 Continuous water and air temperature logger summary statistics for each survey at waterhole G08.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	From	To	Days	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	>0.4 °C	>1.0 °C	>1.5 °C
Oct 12	15-10-12 00:15	19-10-12 00:15	4	-	-	-	26.3	28.0	30.7	26.3	27.0	27.7	-0.1	1.0	4.0	54.3	37.7	30.8
Nov12a	08-11-12 00:15	13-11-12 00:15	5	-	-	-	29.3	30.6	33.1	29.2	29.6	30.8	-0.1	1.0	3.6	63.4	43.5	31.0
Nov12b	20-11-12 00:15	27-11-12 00:15	7	-	-	-	29.8	31.7	35.0	29.9	30.4	31.0	-0.1	1.3	4.7	68.9	50.3	39.0



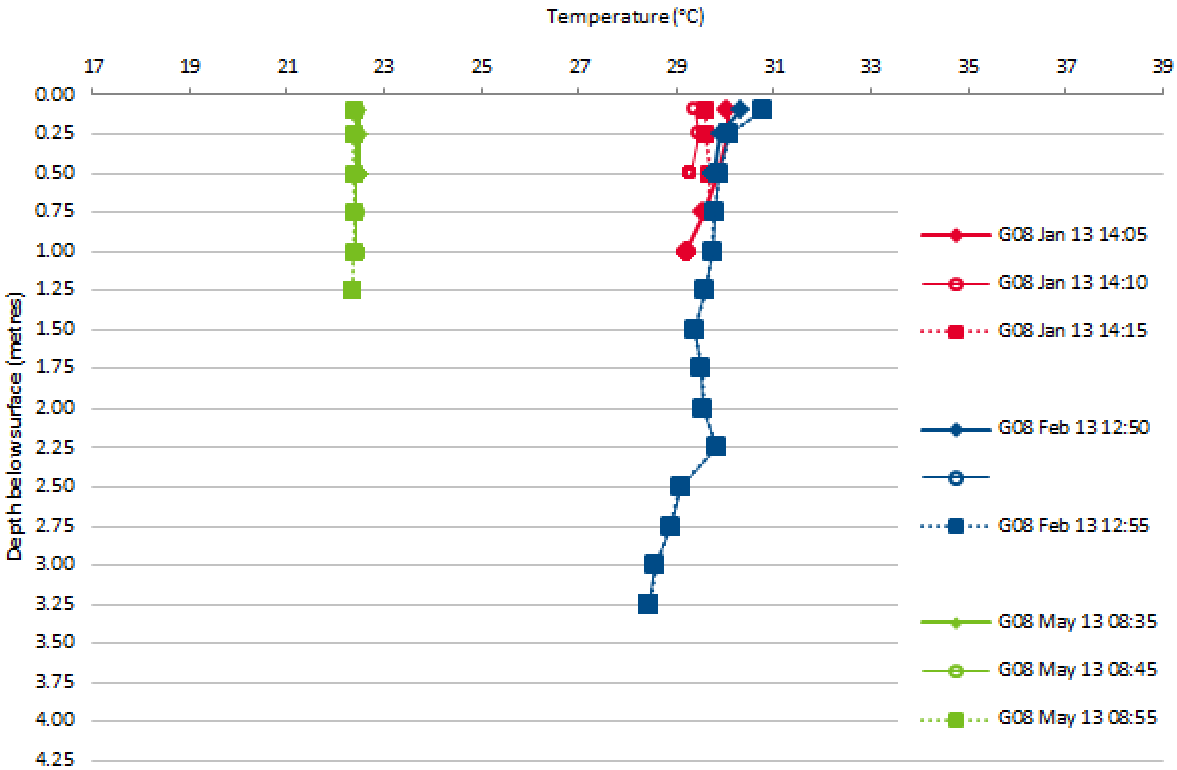


Figure 74 Temperature vertical water column profiles at waterhole G08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

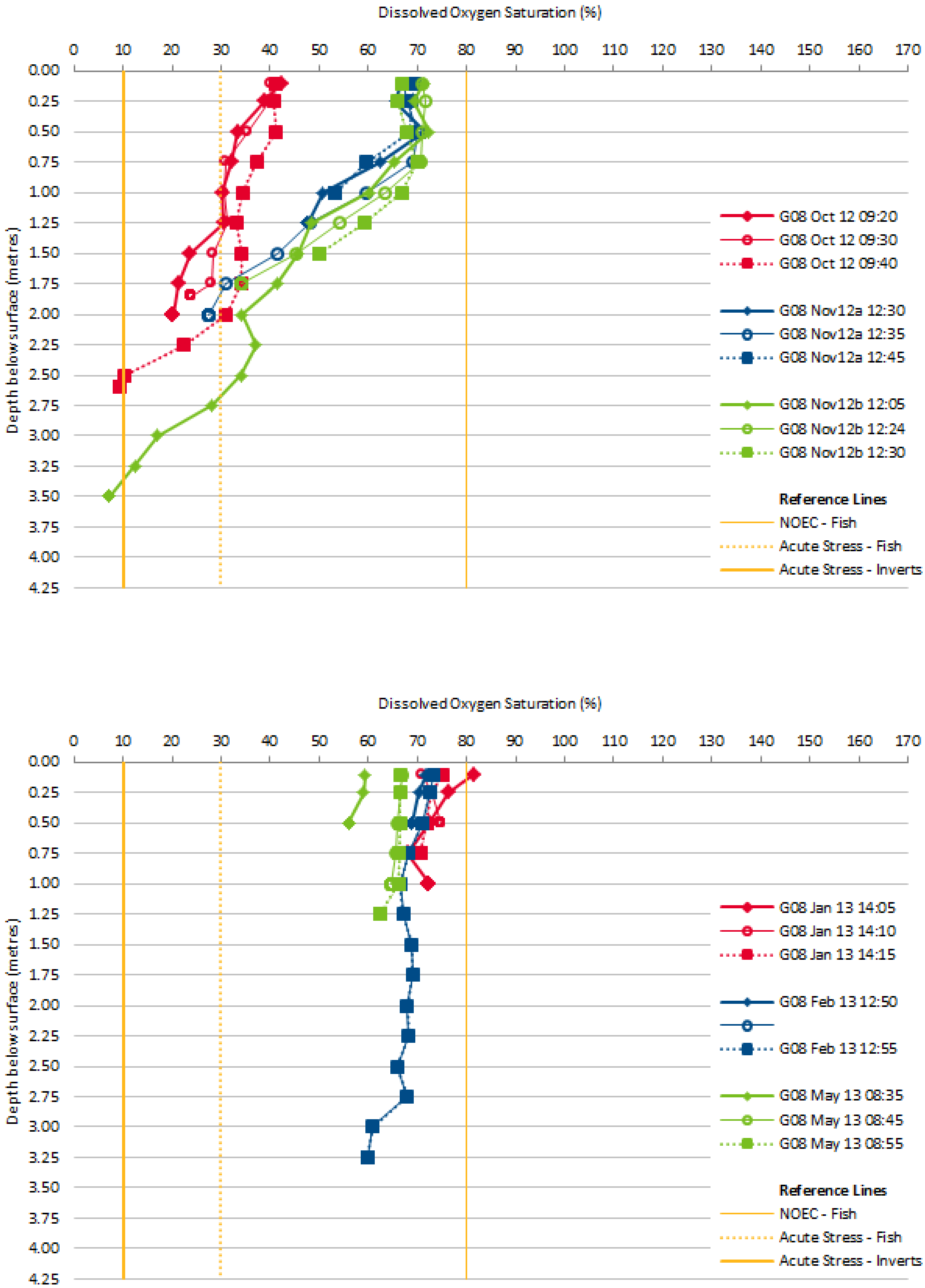


Figure 75 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G08. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

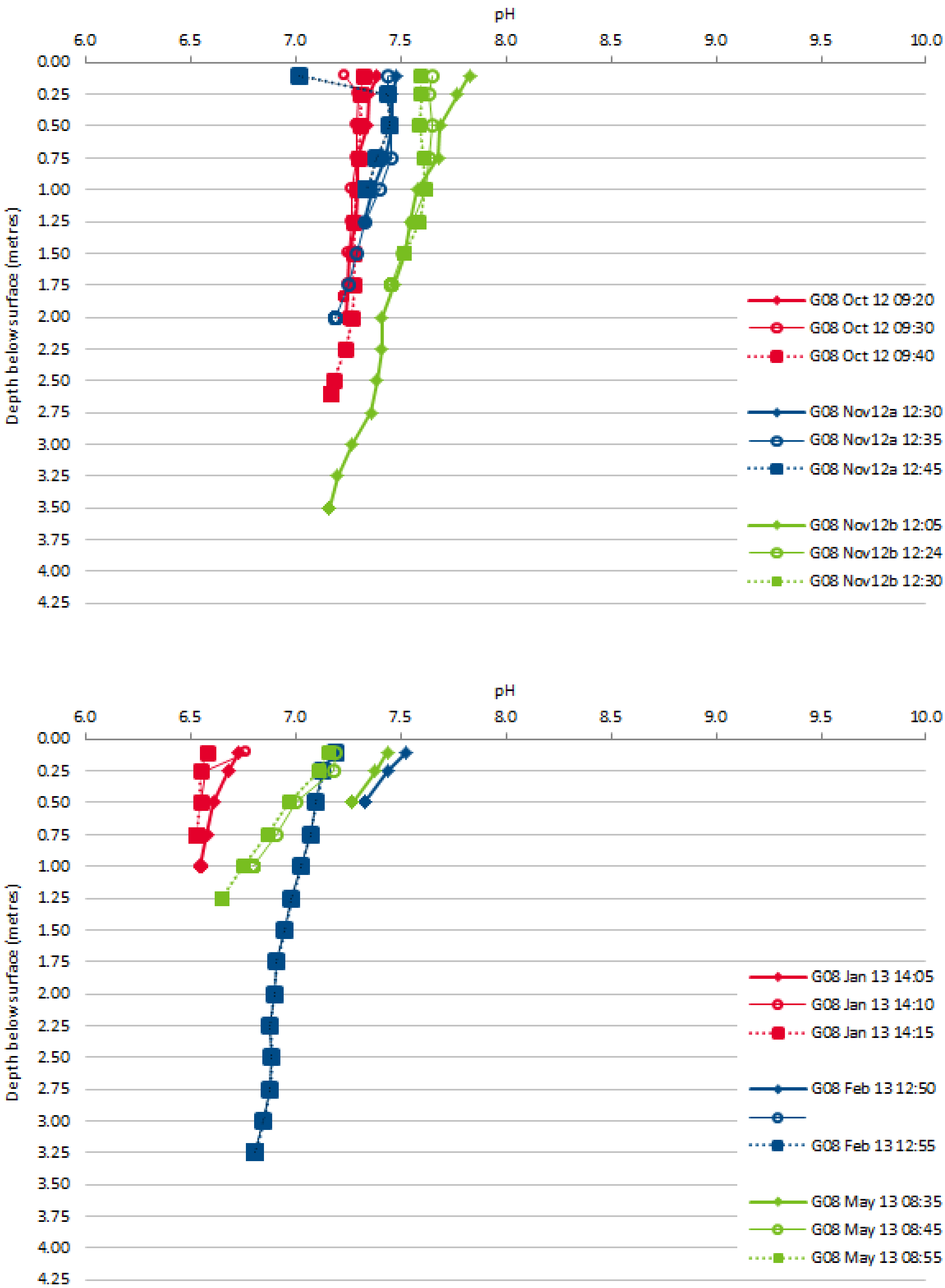


Figure 76 pH vertical water column profiles at waterhole G08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

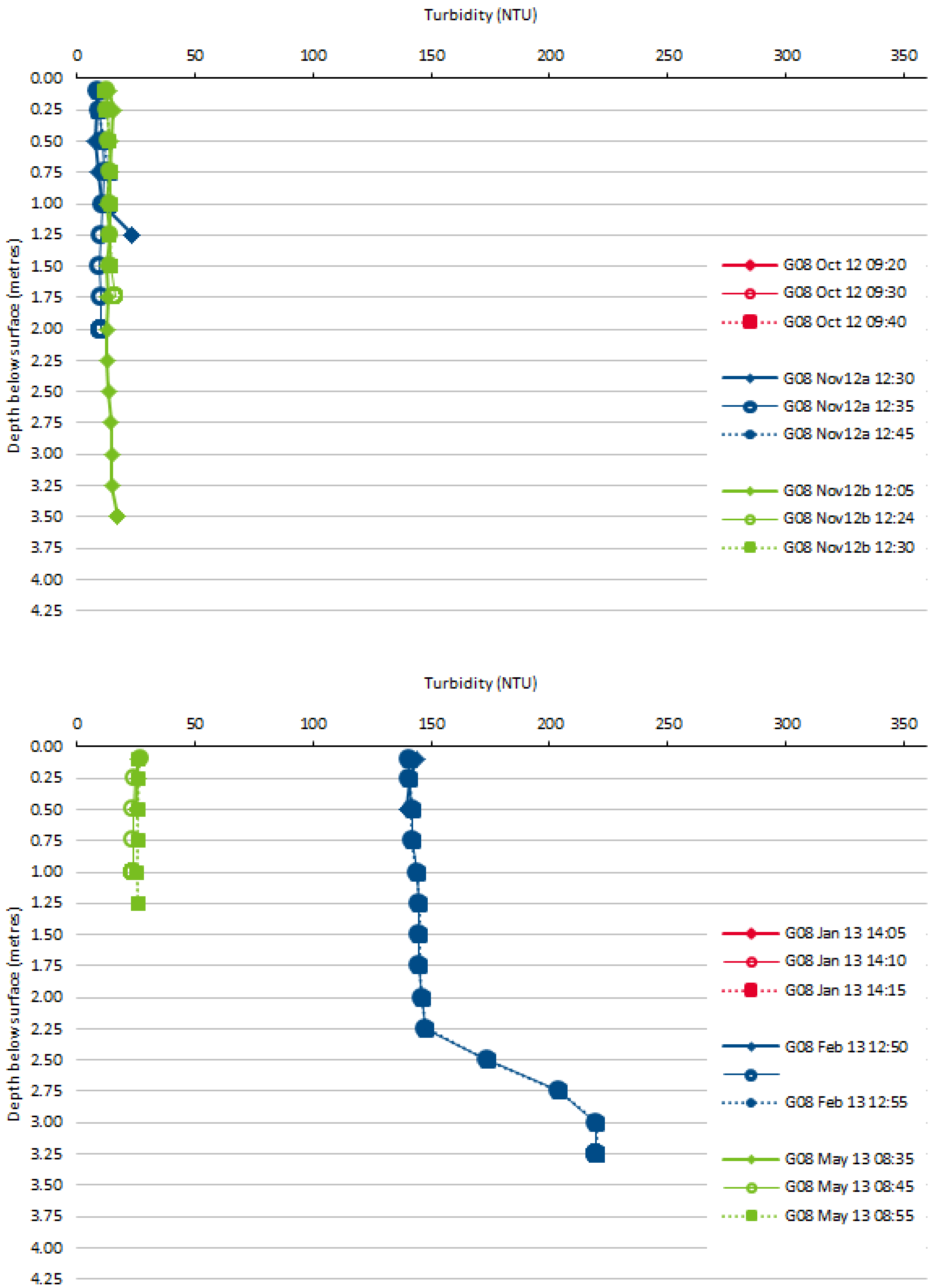
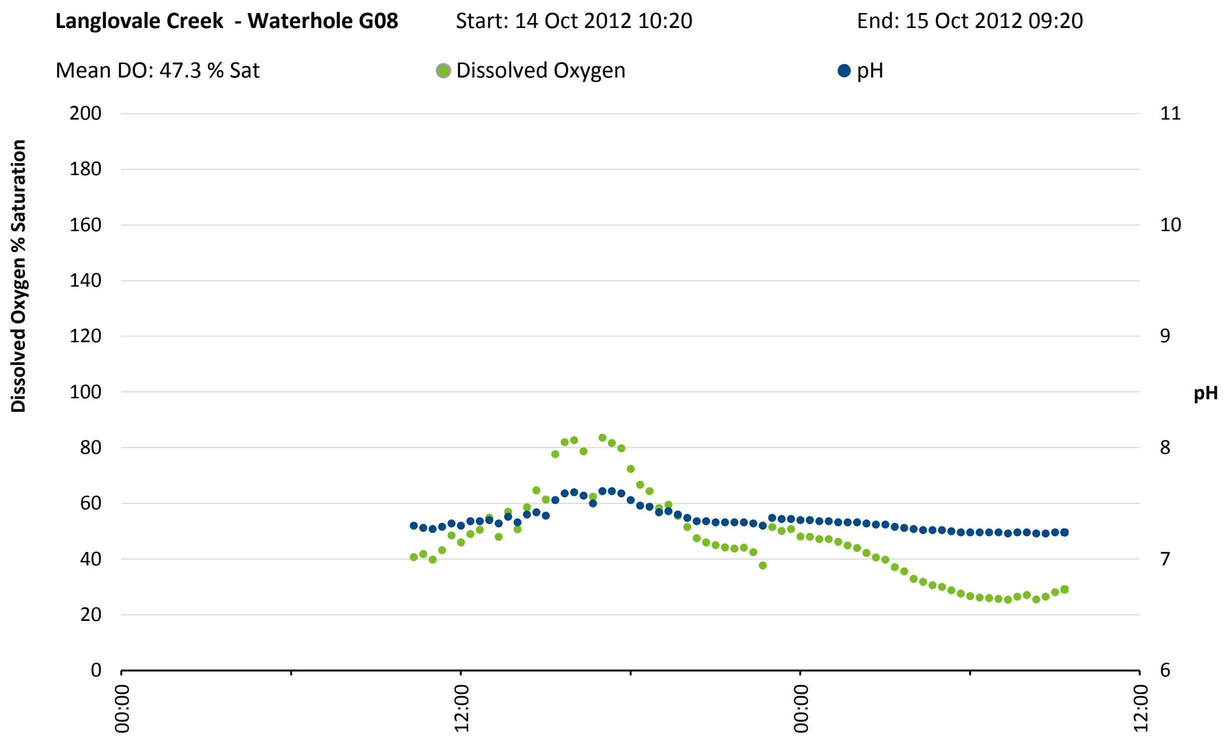


Figure 77 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G08. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



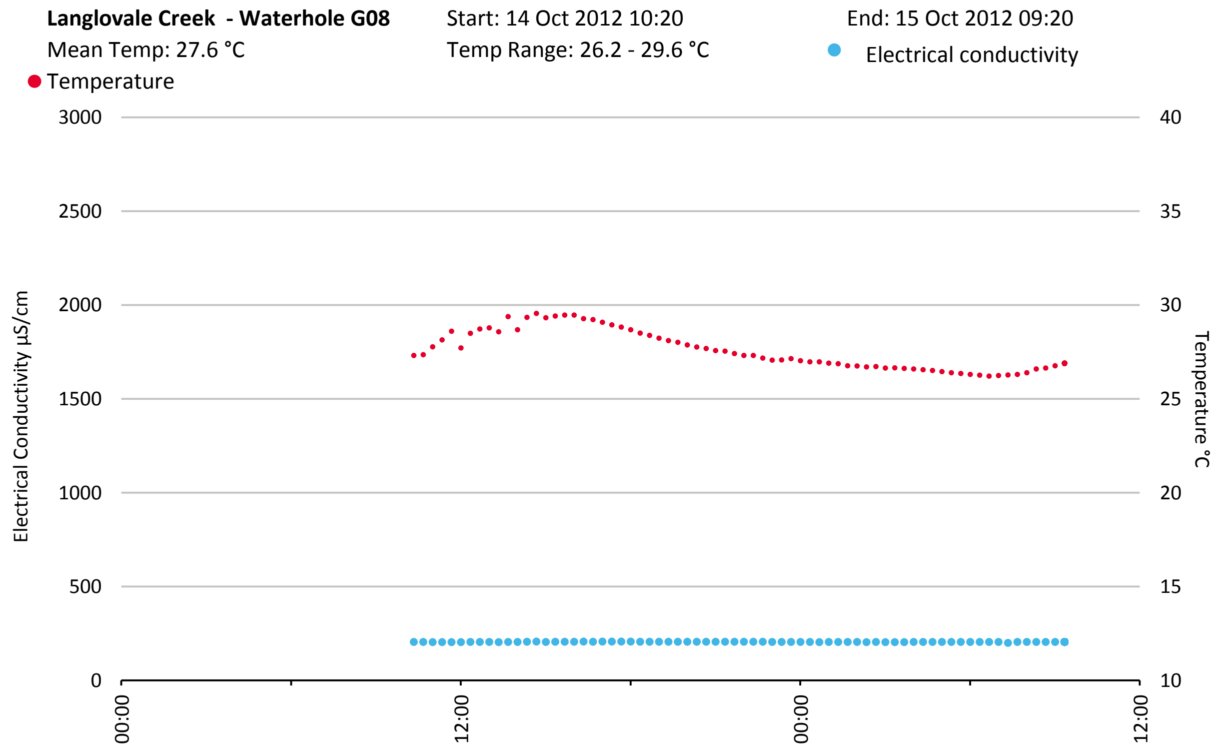


Figure 78 Diel physico-chemical data for waterhole G08, Oct 2012

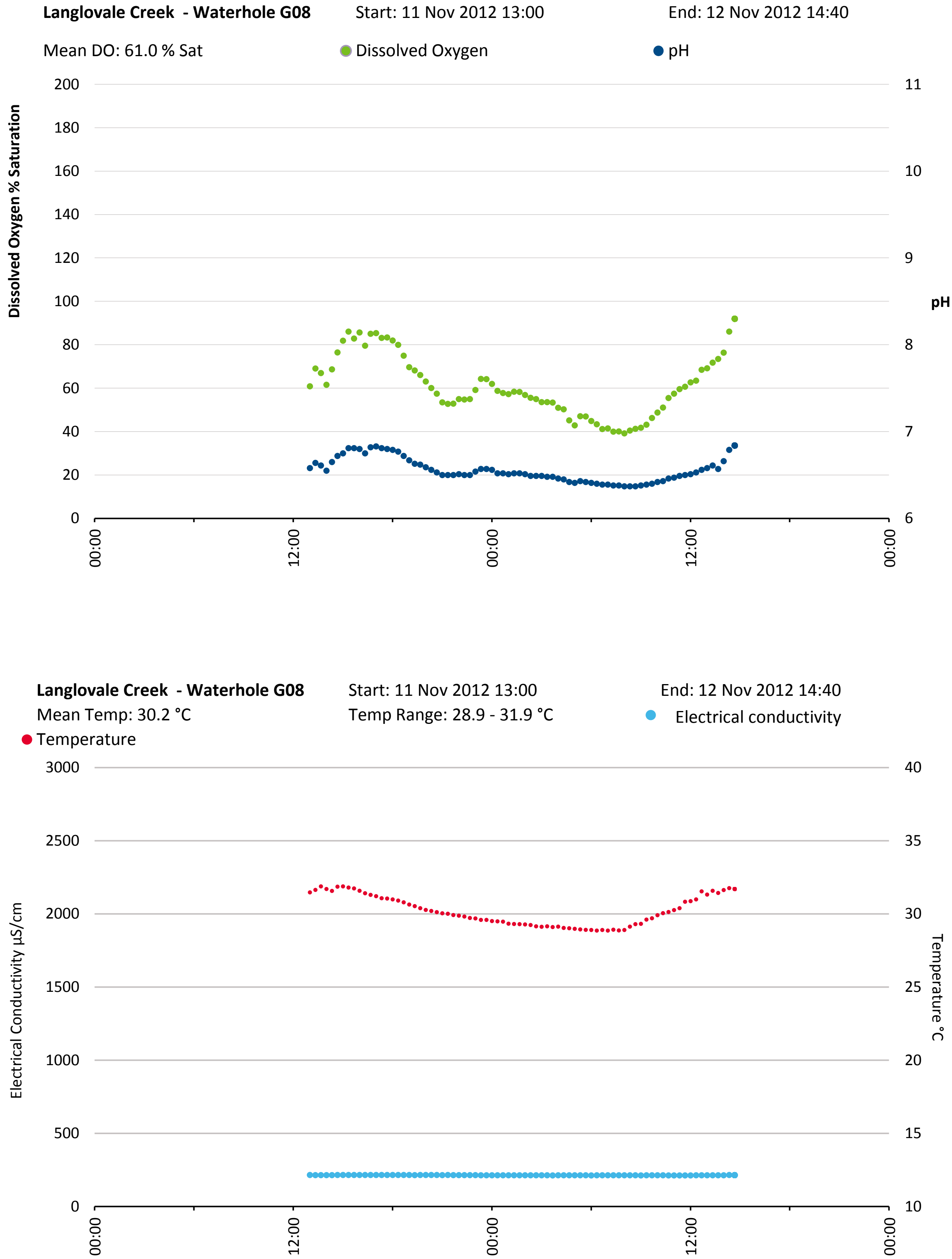
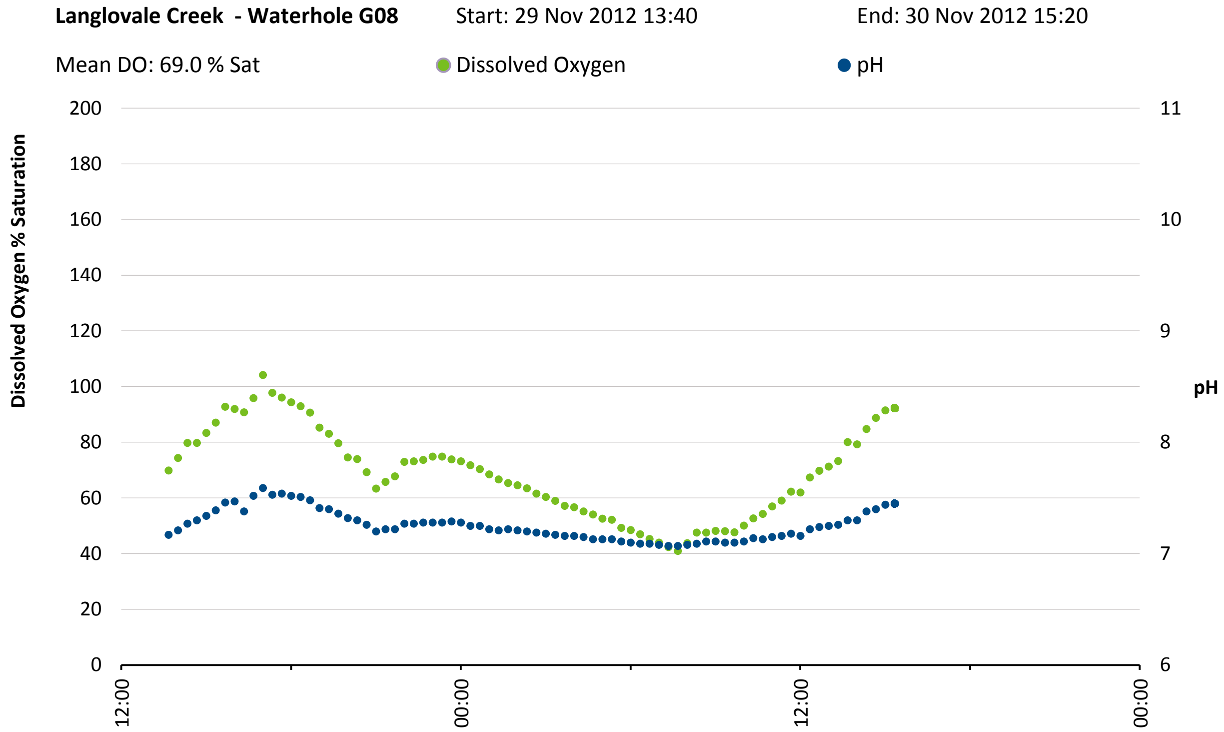


Figure 79 Diel physico-chemical data for waterhole G08, Nov 2012



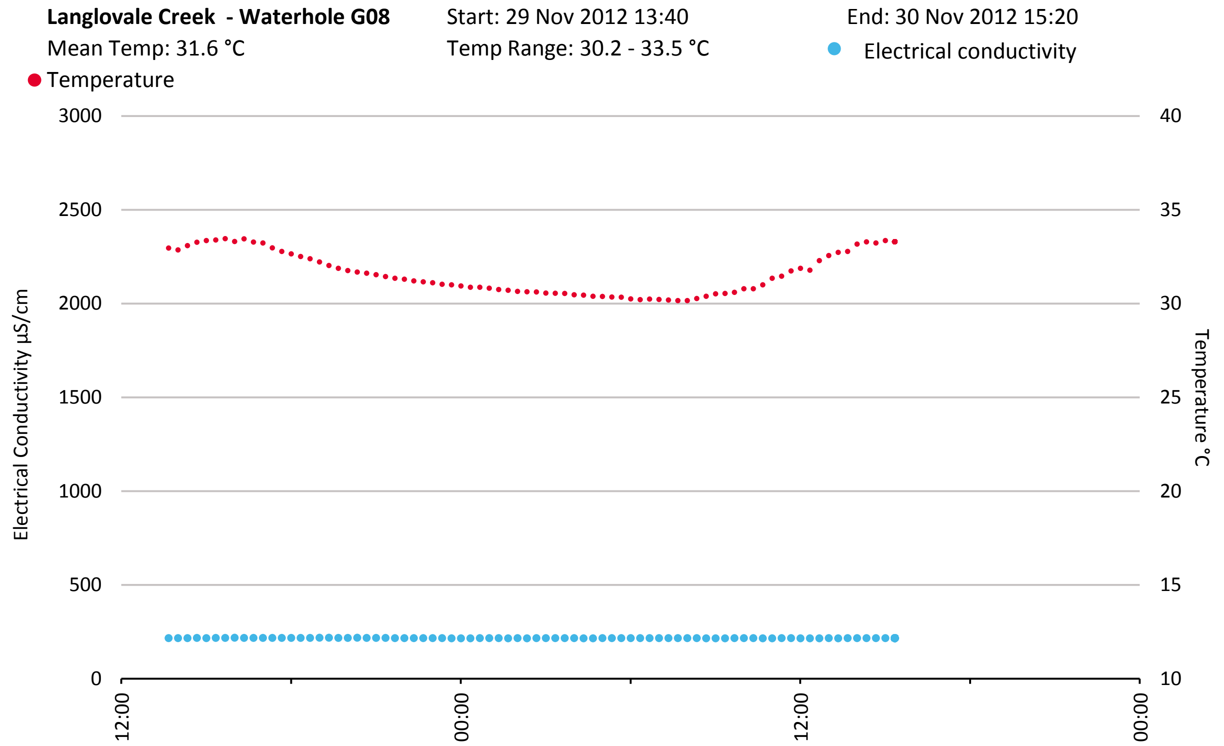


Figure 80 Diel physico-chemical data for waterhole G08, Nov 2012

WATERHOLE G09

FAMILY NAME	SPECIES NAME
Waterhole	G09
Catchment	Gilbert River
Watercourse	Pleasant Creek
Waterhole location	-18.112130°, 142.799004°, Lake Carlo Station
Waterhole elevation	~160 m (GoogleEarth elevation data, ± 30 m accuracy)
Dates surveyed	Survey 2: 14-Oct-12
	Survey 3: 12-Nov-12
	Survey 5: 30-Nov-12
	Survey 7: 19-Jan-13
	Survey 8: 20-Feb-13
	Survey 9: 29-May-13
Waterhole characteristics (measured Oct 2012)	Surface area: ~12,300 m^2
	Waterhole volume: ~8800 m^3
	Wetted perimeter: ~ 1980 m
	Maximum depth: 1.9 m
	Average depth: 0.6 m
	Waterhole length: 960 m
Instream habitats	This waterhole has a substrate of sand and gravel, along with 50% of the waterhole bottom being bedrock. Aquatic macrophytes were very rare, with only one species identified, *Potamogeton crispus*. Epilithic algae were fairly dense, particularly in the downstream end of the waterhole (~40% coverage). Some steep banks with overhanging roots provide habitat. Limited snags and woody debris are available.
Riparian zone	A flying fox colony was camped in the riparian vegetation at this waterhole; however the damage to riparian trees was minimal. Land managers have undertaken a significant rubber vine (*Cryptostegia grandiflora*) management program over the past two years. Prior to this management regime, the area was reported as being heavily infested with rubber vine. Cattle traffic is minimal, although some impacts of cattle accessing the water hole are obvious in the downstream end of the waterhole where no groundcover remains. Further upstream both understory and tree condition is in fair. Riparian trees are dominated by *Melaleuca* species, offering ~10% shade across the water hole
Waterhole depth changes	Waterhole depth fell slightly between September and December 2012, peaked during January 2013 then declined toward May 2013.
Other notes	Cattle access this waterhole at the downstream end.

a)

b)

Figure 81 a) GoogleEarth 2010 aerial view of G09. Gilbert River is visible in the top right corner. b) Left to right: 1) From fixed camera, right bank. 2) Looking downstream during high water level conditions. 3) From fixed camera, right bank. 4) Upstream from right bank, high water conditions

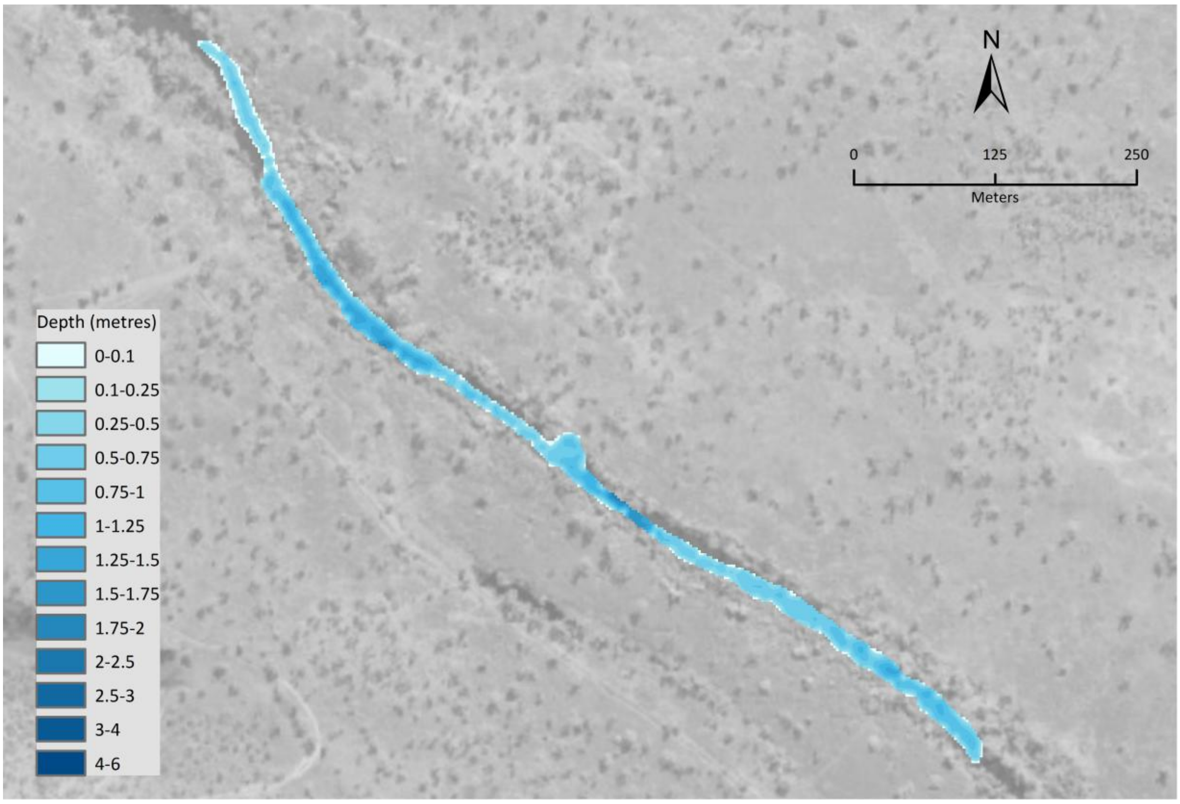


Figure 82 Bathymetry map of waterhole G09. Depth and waterhole perimeter data generated from data collected Oct 2012

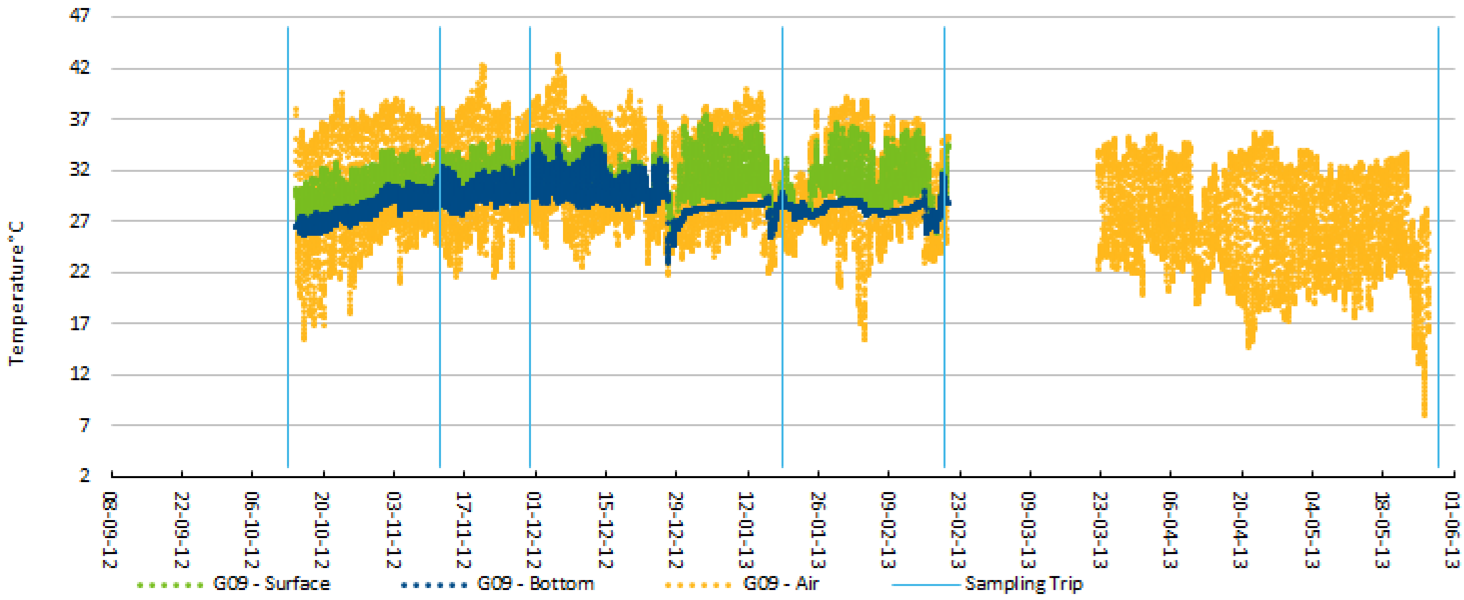
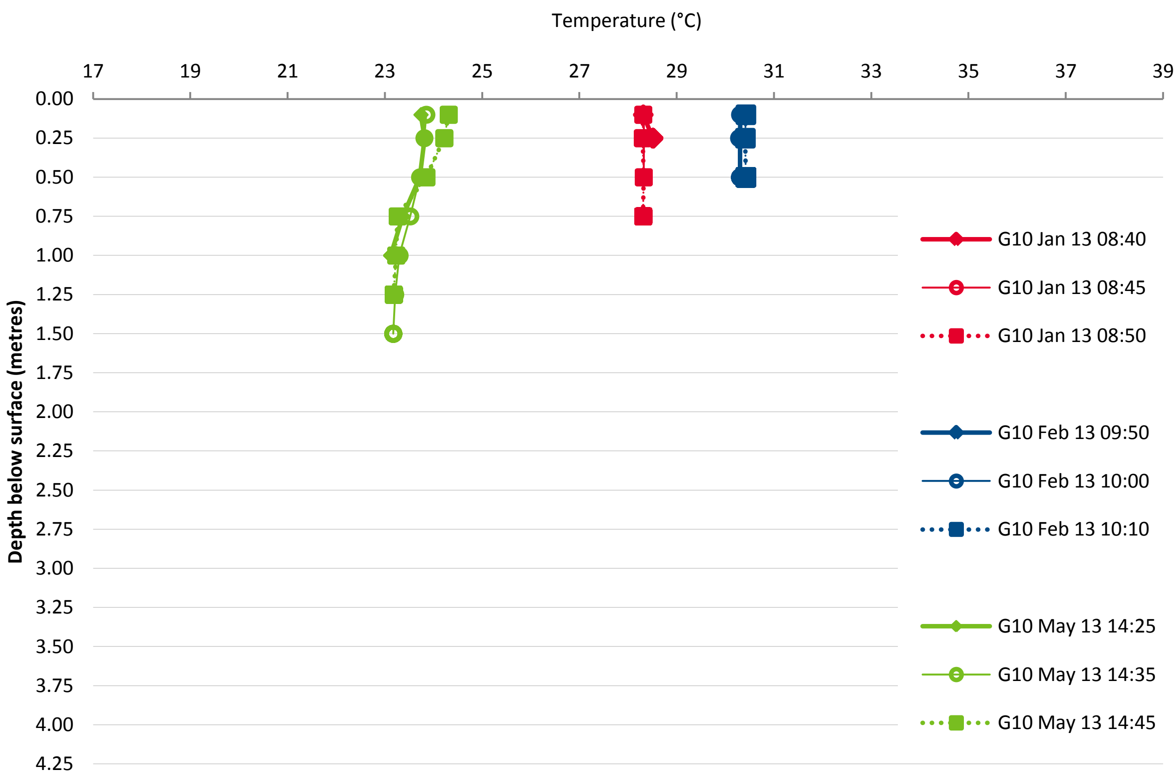


Figure 83 Long term temperature logger data for waterhole G09. Missing data corresponds to logger malfunction

Table 9 Continuous water and air temperature logger summary statistics for each survey at waterhole G09.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 & 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Oct 12	15-10-12 00:15	18-10-12 00:15	3	15.6	27.2	35.8	25.8	27.9	31.2	25.7	26.7	27.5	-0.1	1.2	3.8	57.1	45.6	36.4
Nov12a	07-11-12 00:15	11-11-12 00:15	4	24.4	30.2	37.4	28.4	30.0	33.1	28.2	29.4	30.5	-0.1	0.6	3.1	37.0	24.9	18.0
Nov12b	24-11-12 00:15	29-11-12 00:15	5	22.5	30.5	38.6	29.0	31.1	34.7	28.8	30.6	32.6	-0.1	0.5	2.7	37.4	26.3	17.7
Jan 13	19-01-13 00:15	24-01-13 00:15	5	23.7	27.3	32.4	27.3	28.6	33.1	27.3	28.2	29.5	-0.3	0.4	4.7	31.6	13.4	8.7
Feb 13	18-02-13 00:15	20-02-13 00:15	2	23.9	27.7	34.9	25.9	28.4	31.9	26.0	28.4	31.6	-0.1	0.0	0.7	6.9	0.0	0.0



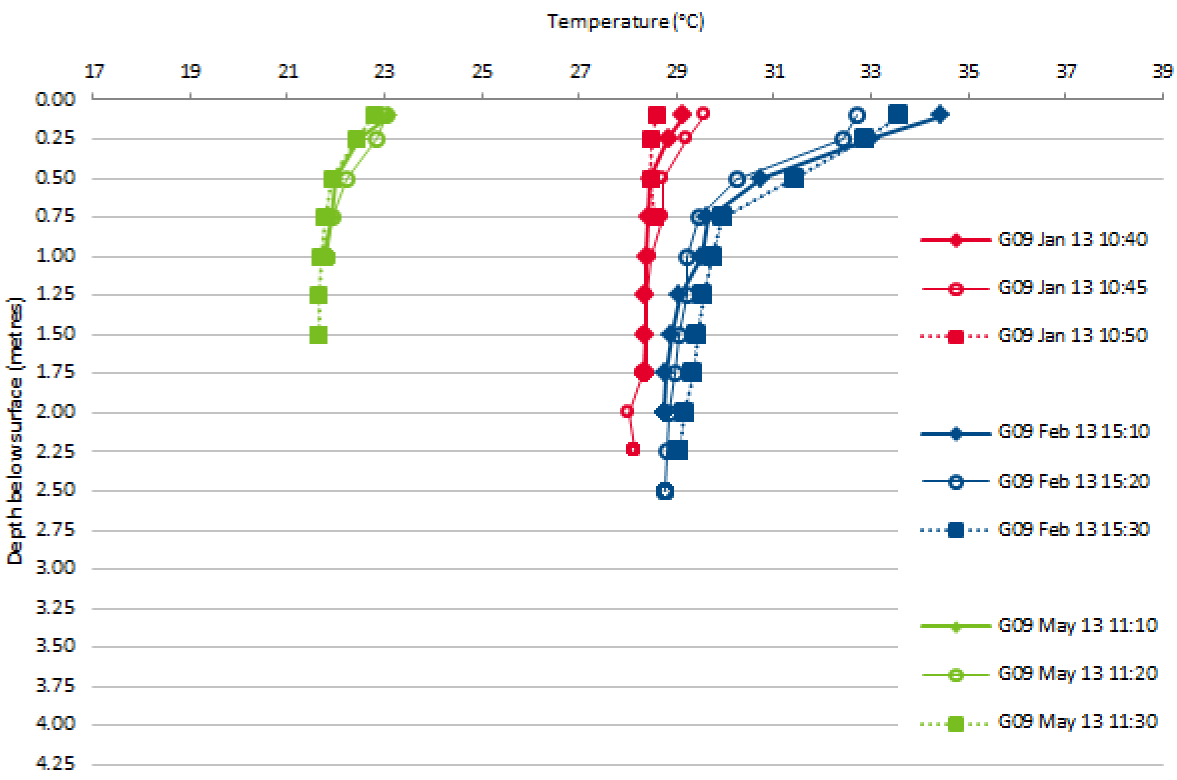
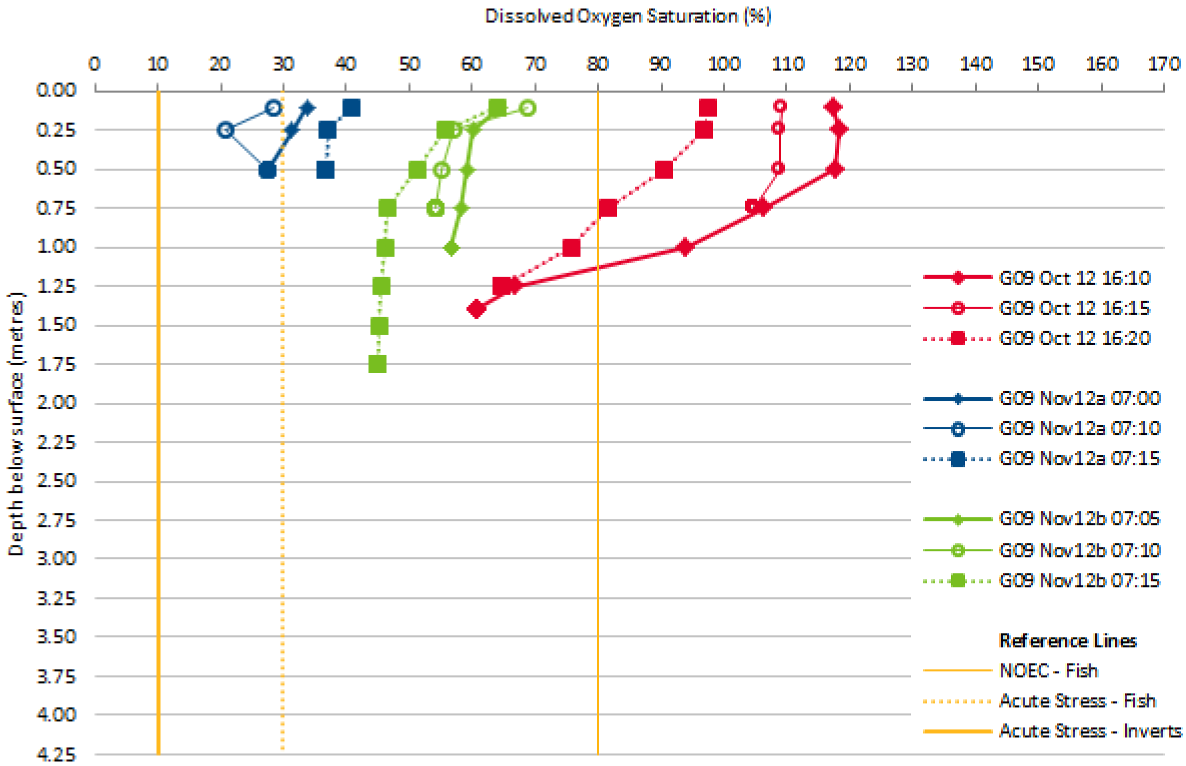


Figure 84 Temperature vertical water column profiles at waterhole G09. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



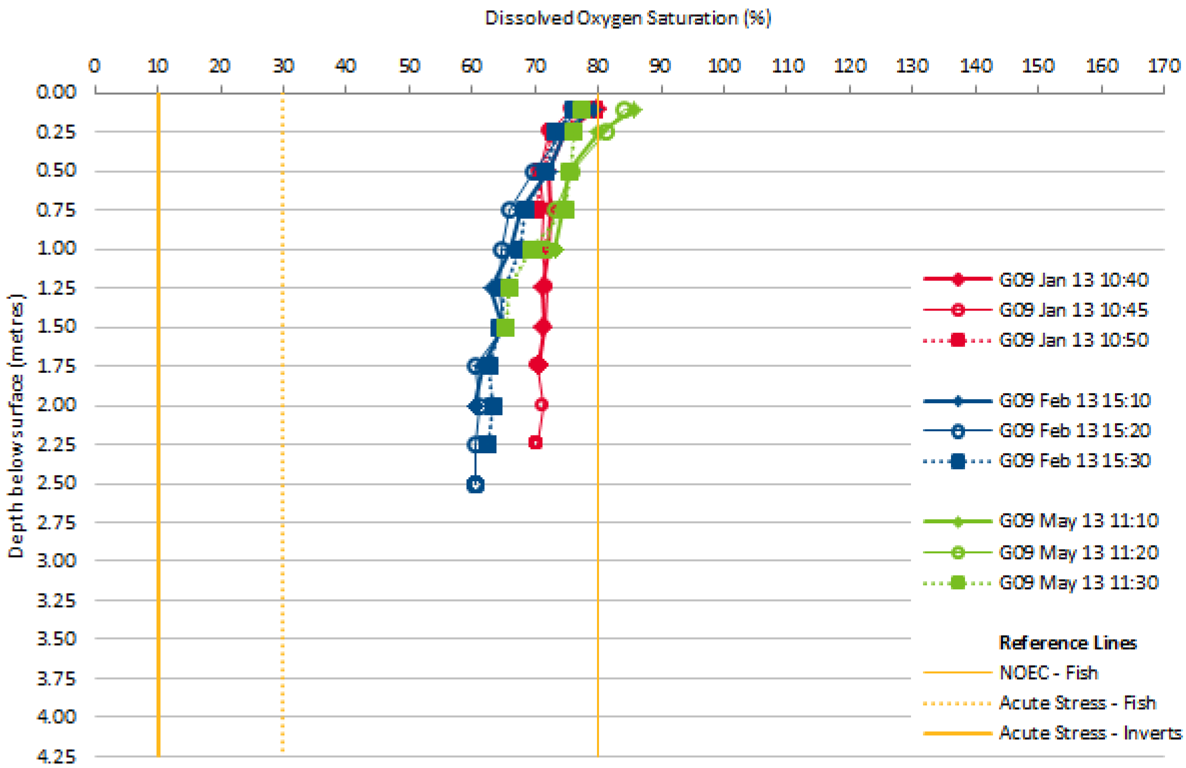
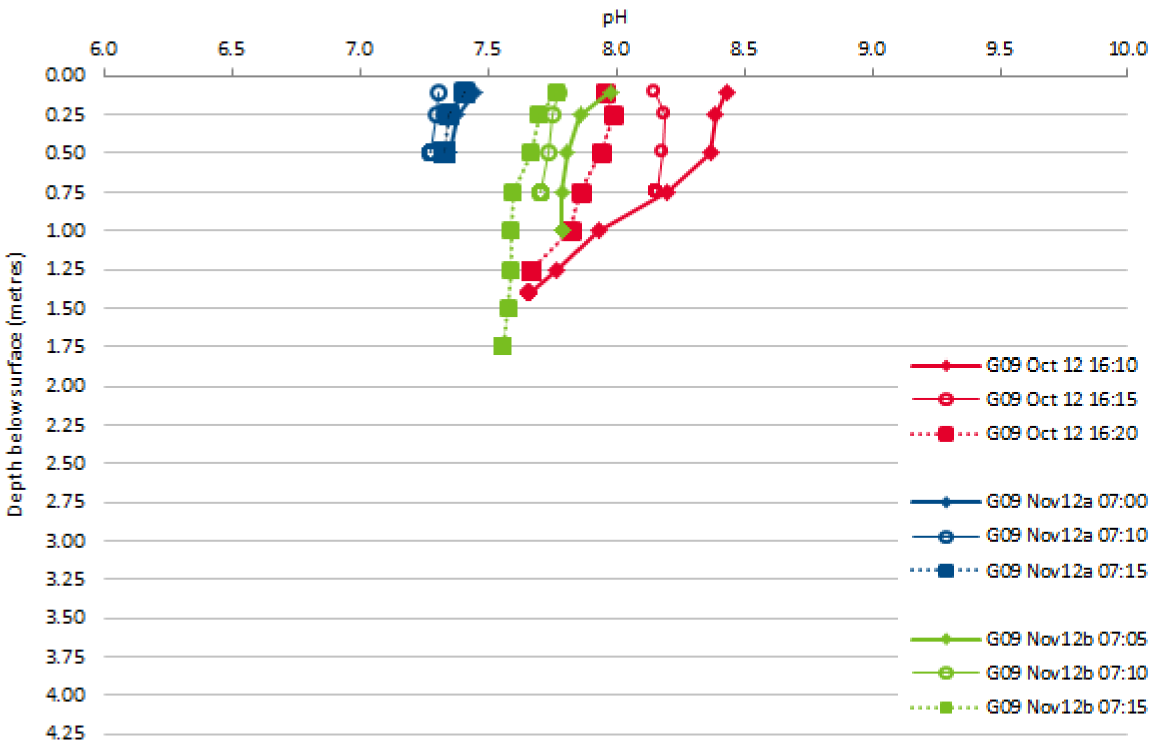


Figure 85 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G09. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



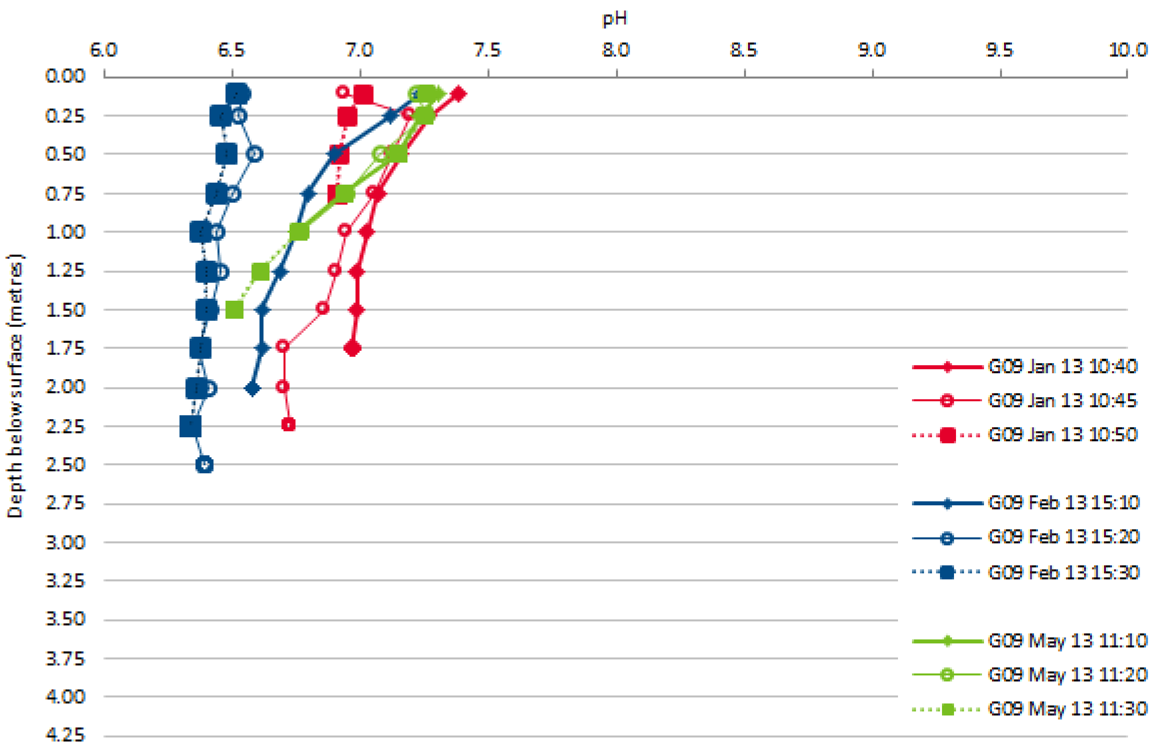
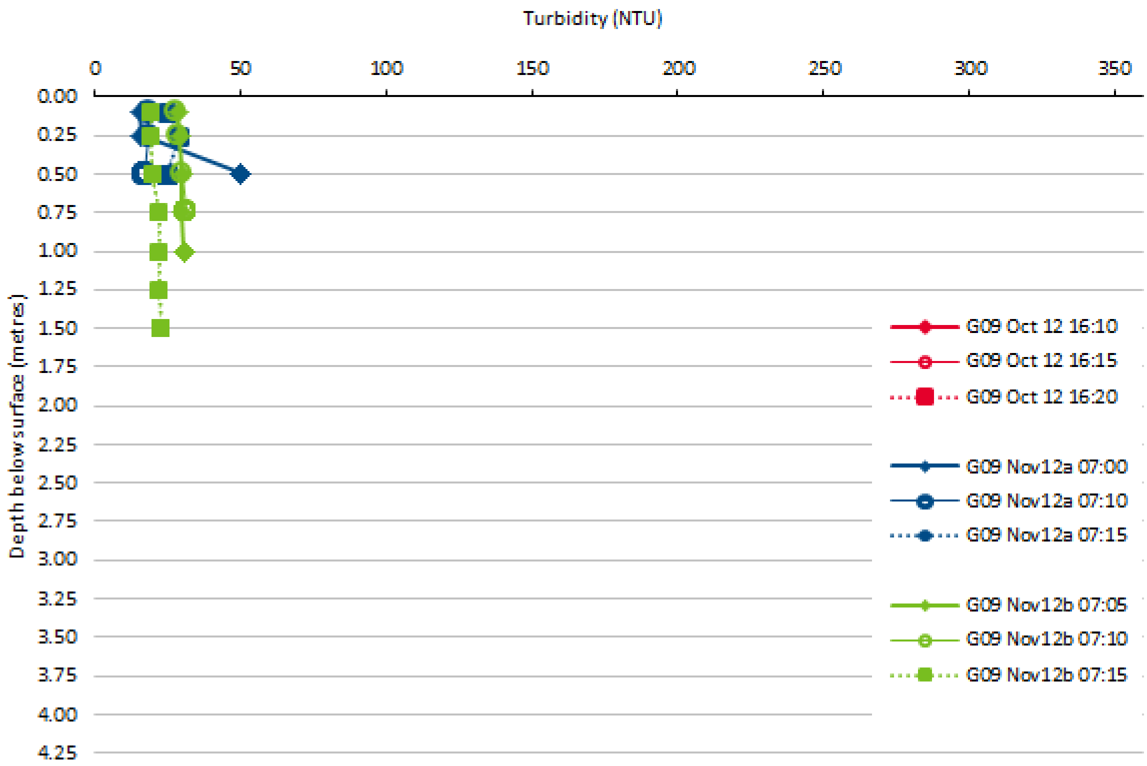


Figure 86 pH vertical water column profiles at waterhole G09. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



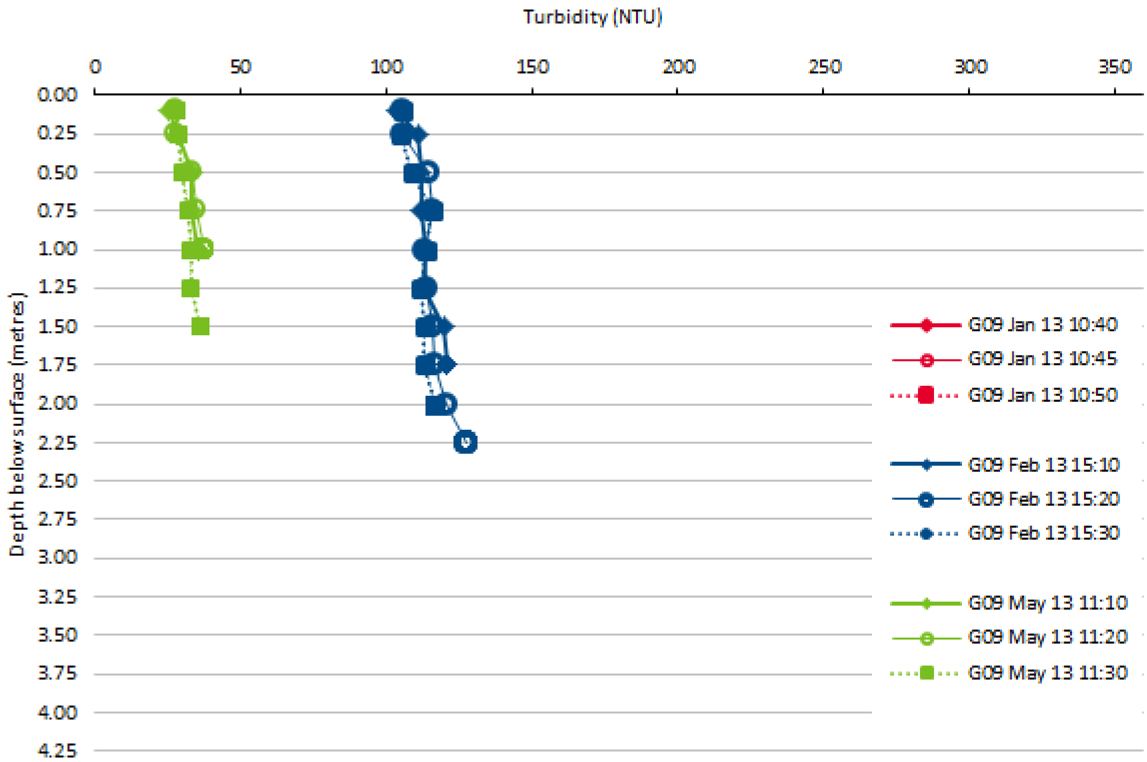
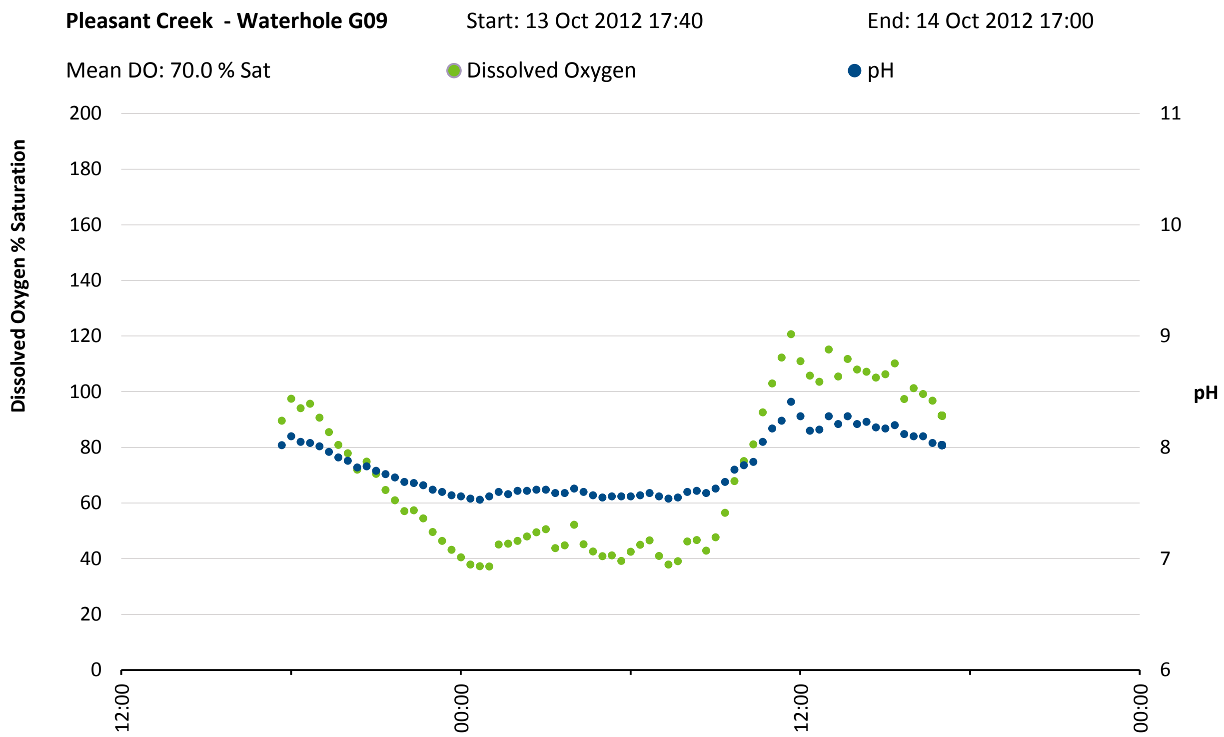


Figure 87 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G09. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



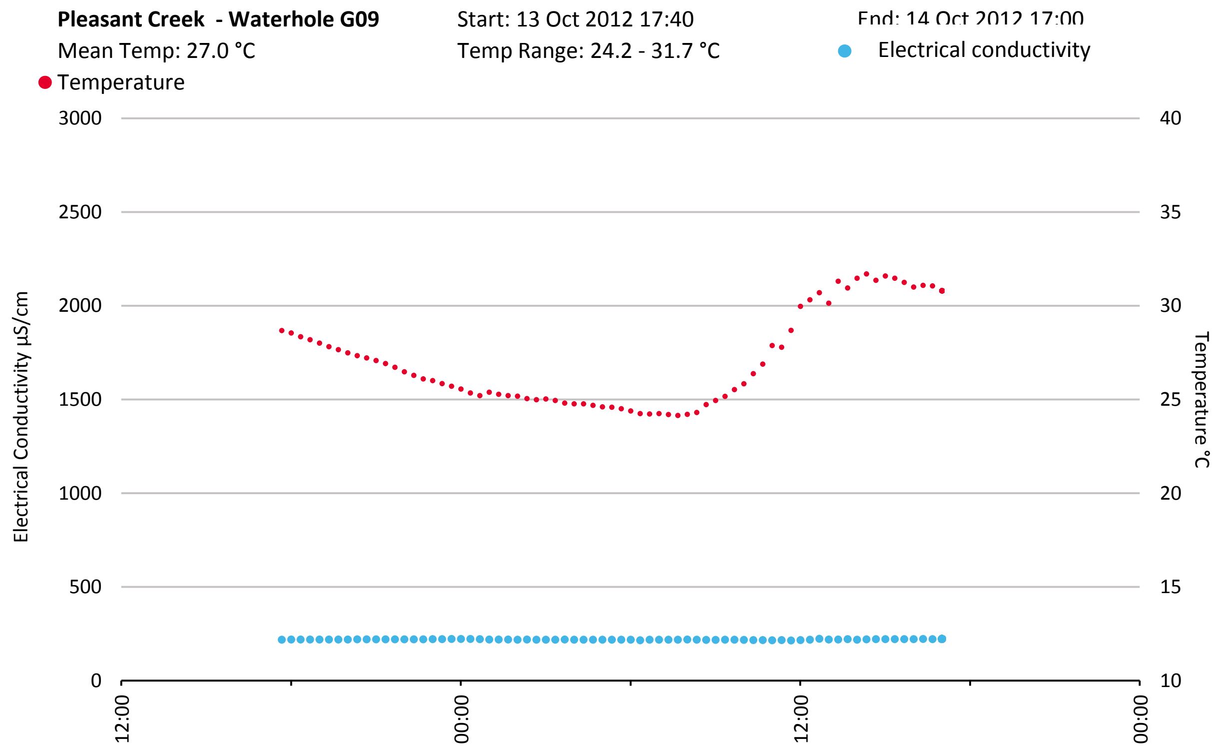
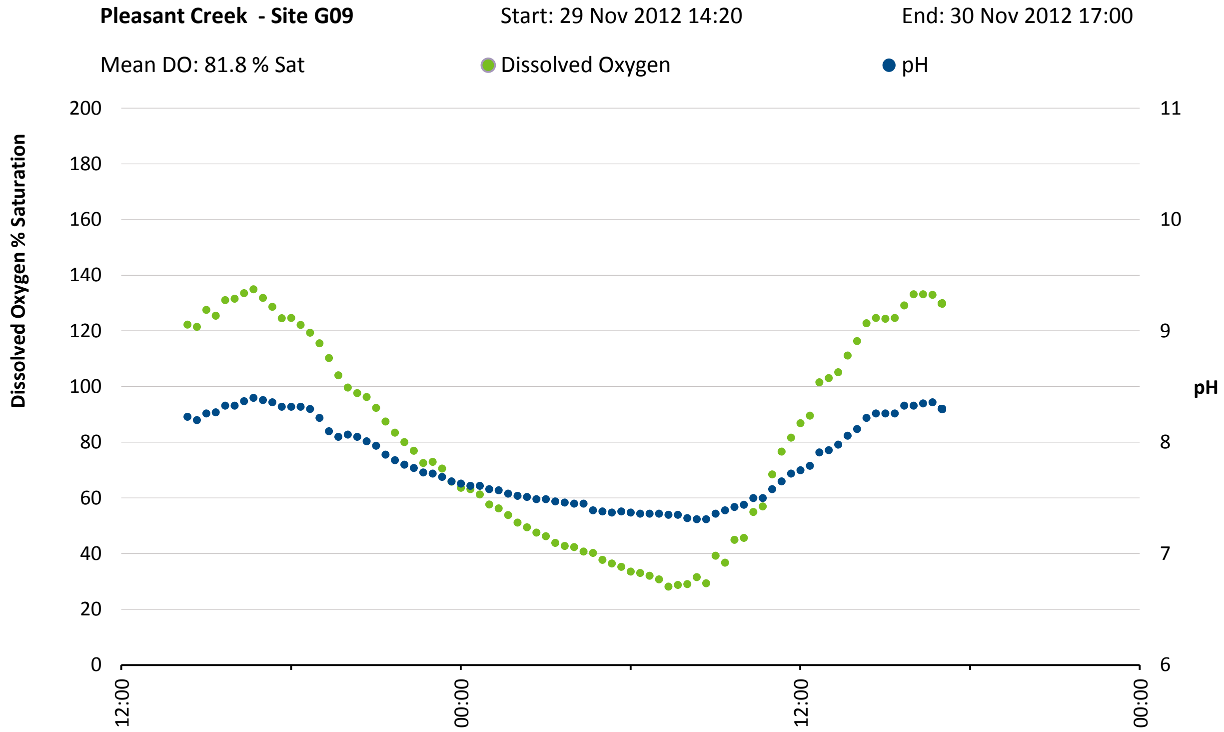


Figure 88 Diel physico-chemical data for waterhole G09, Oct 2012



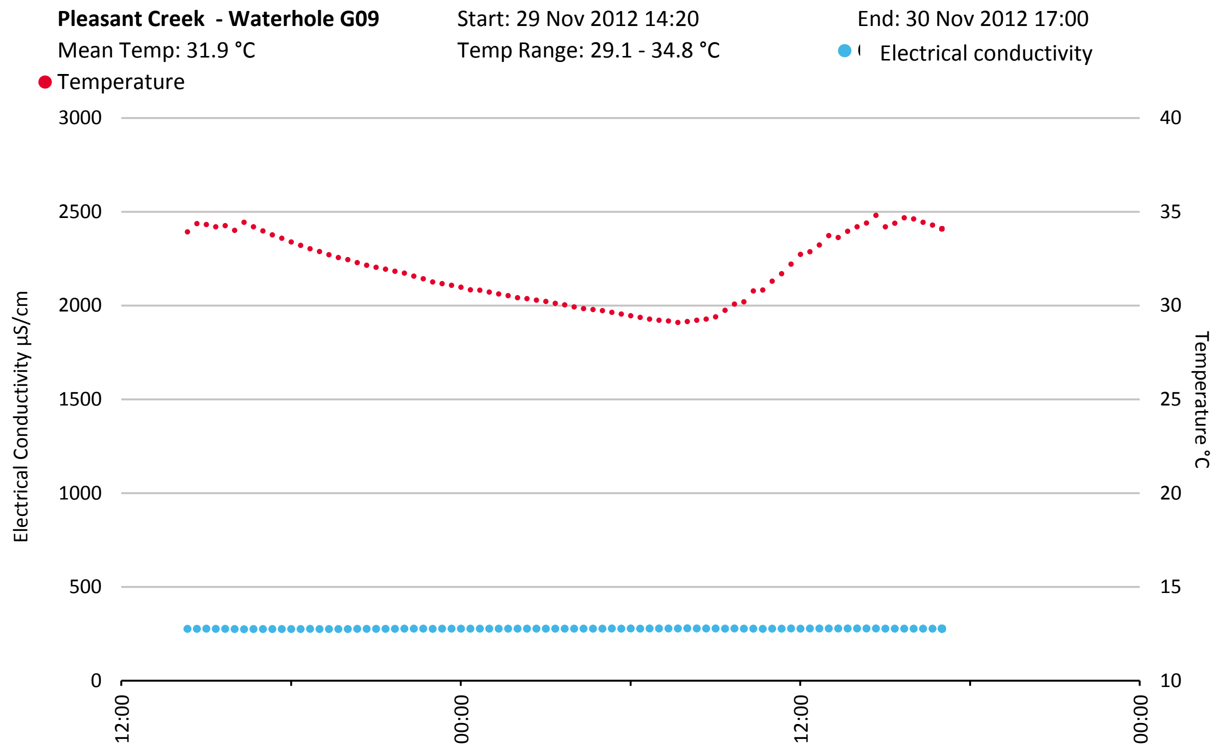
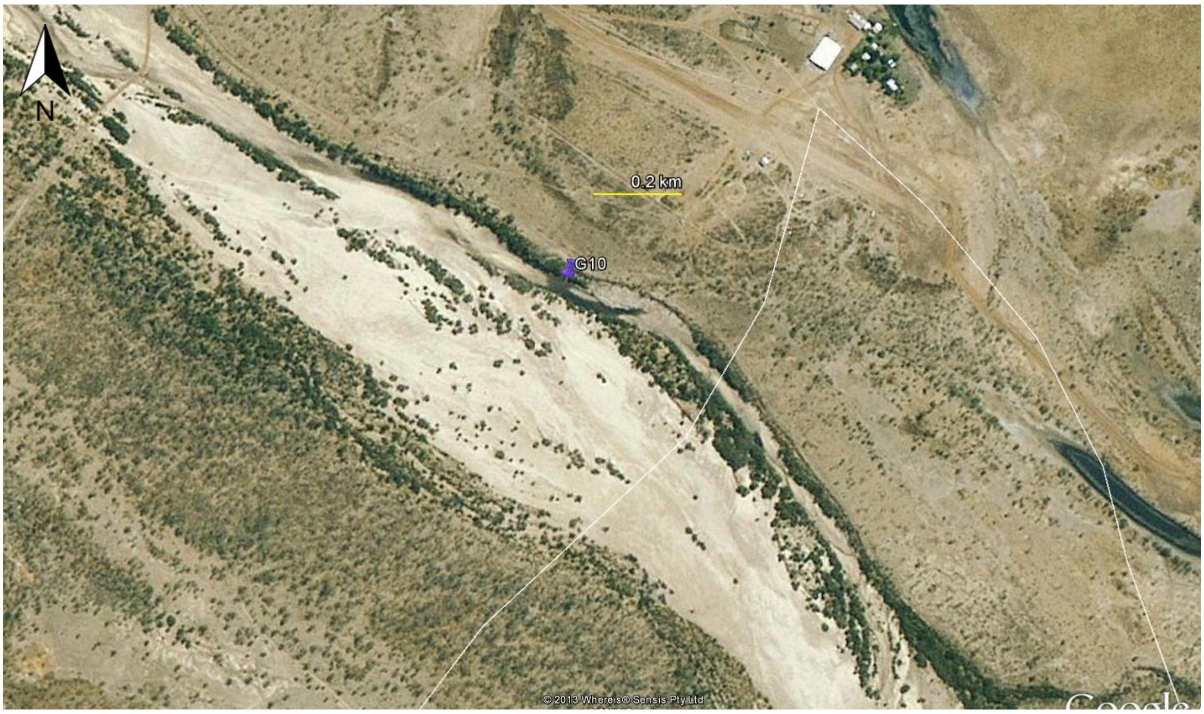


Figure 89 Diel physico-chemical data for waterhole G09, 4 Nov 2012

WATERHOLE G10

FEATURE	DESCRIPTION
Waterhole	G10
Catchment	Gilbert River
Waterhole location	-17.865903°, 142.799004°. Adjacent to Strathmore Station homestead.
Waterhole elevation	~120 m (GoogleEarth elevation data, ± 30 m accuracy)
Survey dates	Survey 2: 13-Oct-12
	Survey 3: 11-Nov-12
	Survey 5: 29-Nov-12
	Survey 7: 19-Jan-13
	Survey 8: 20-Feb-13
	Survey 9: 29-May-13
Waterhole characteristics	Surface area: ~7400 m^2
(measured Oct 2012)	Waterhole volume: ~6400 m^3
	Wetted perimeter: ~ 630 m
	Maximum depth: 1.8 m
	Average depth: 0.8 m
	Waterhole length: 300 m
Instream habitats	This waterhole has a substrate of sand and gravel, along with 50% of the waterhole bottom being bedrock. Aquatic macrophytes ere very rare, with only one species identified, *Potamogeton crispus*. Epilithic algae were fairly dense, particularly in the downstream end of the waterhole (~40% coverage). Some steep banks with overhanging roots provide habitat. Limited snags and woody debris are available.
Riparian zone	The riparian zone is very sparse, and very little shade is offered across the water due the width of the river at this waterhole. The sandy substrate appears to limit plant growth, and banks are generally bare from groundcover. Some *Melaleuca* trees line the banks.
Waterhole depth changes	Waterhole depth fell slightly between September and December 2012. During January 2013 the depth increased by around three meters then declined rapidly to May 2013.
Other notes	Minor impacts from cattle access are evident.

a)



b)

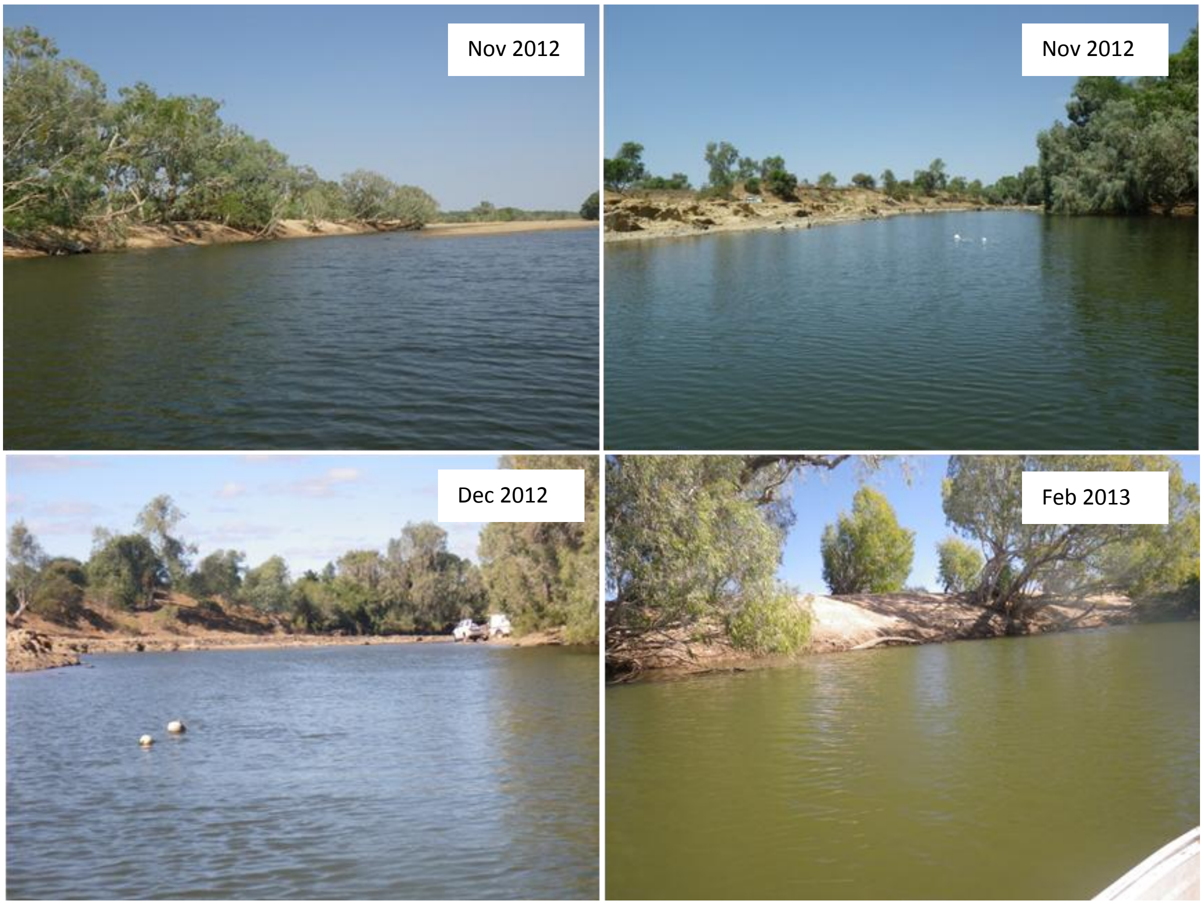


Figure 90 a) GoogleEarth 2004 aerial view of G10. b) Left to right: 1) Looking downstream from mid channel. 2) Looking upstream from mid channel. 3) Looking upstream from mid channel. 4) Towards left bank from mid channel

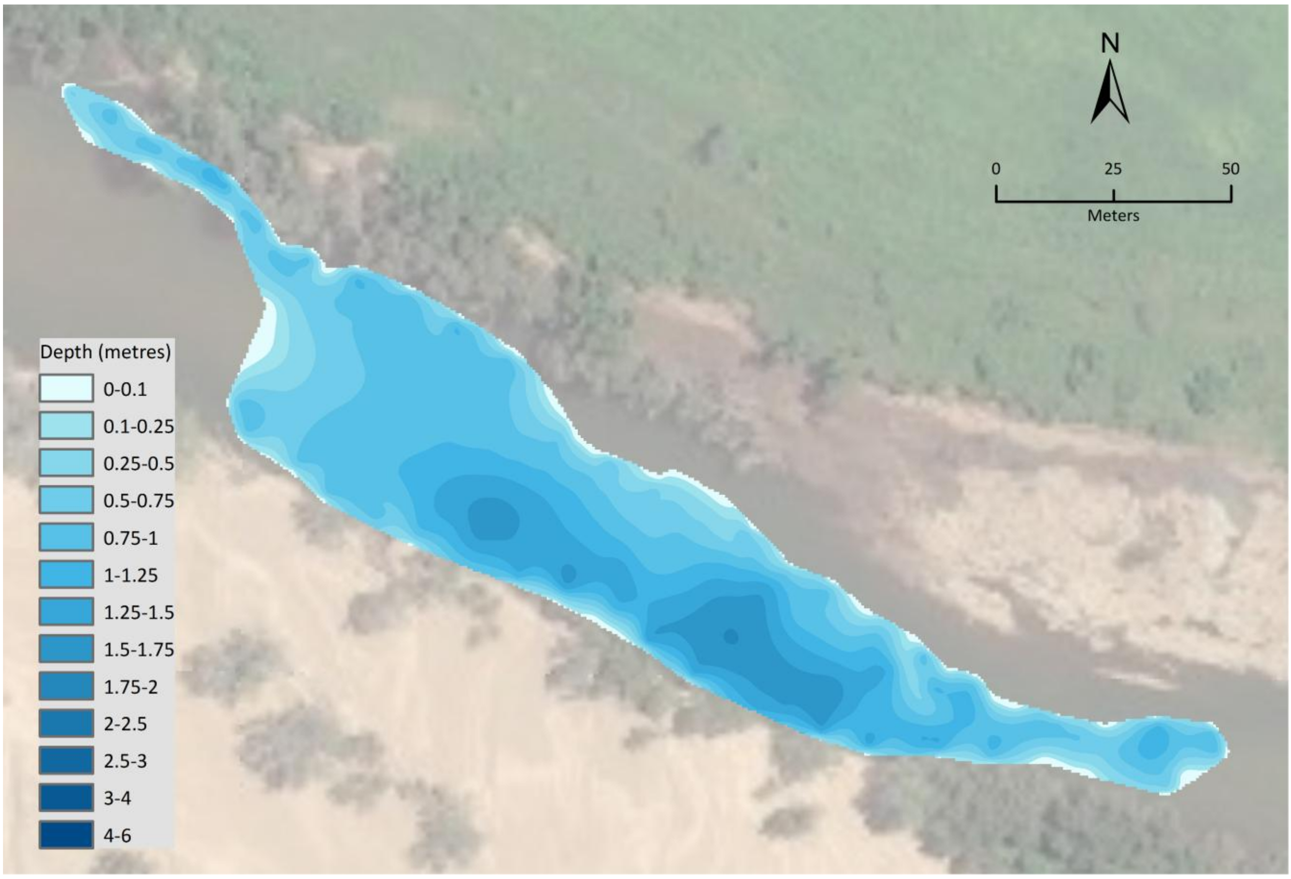


Figure 91 Bathymetry map of waterhole G10. Depth and waterhole perimeter data generated from data collected Oct 2012

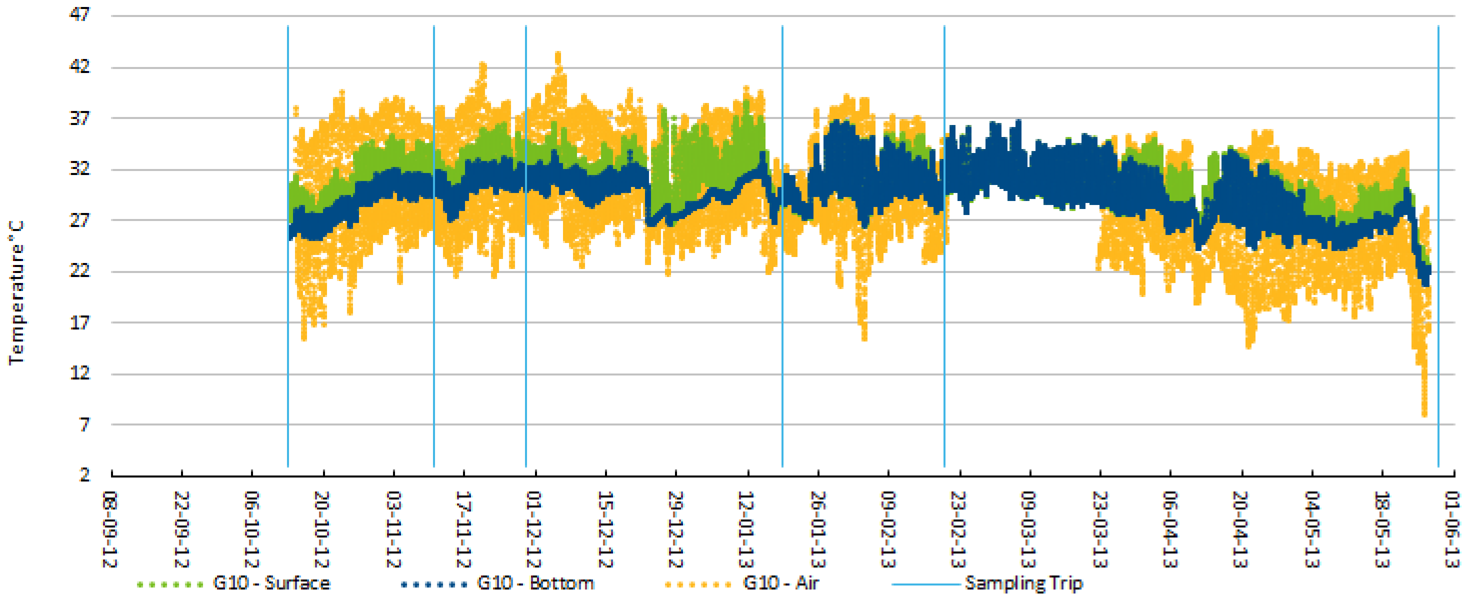
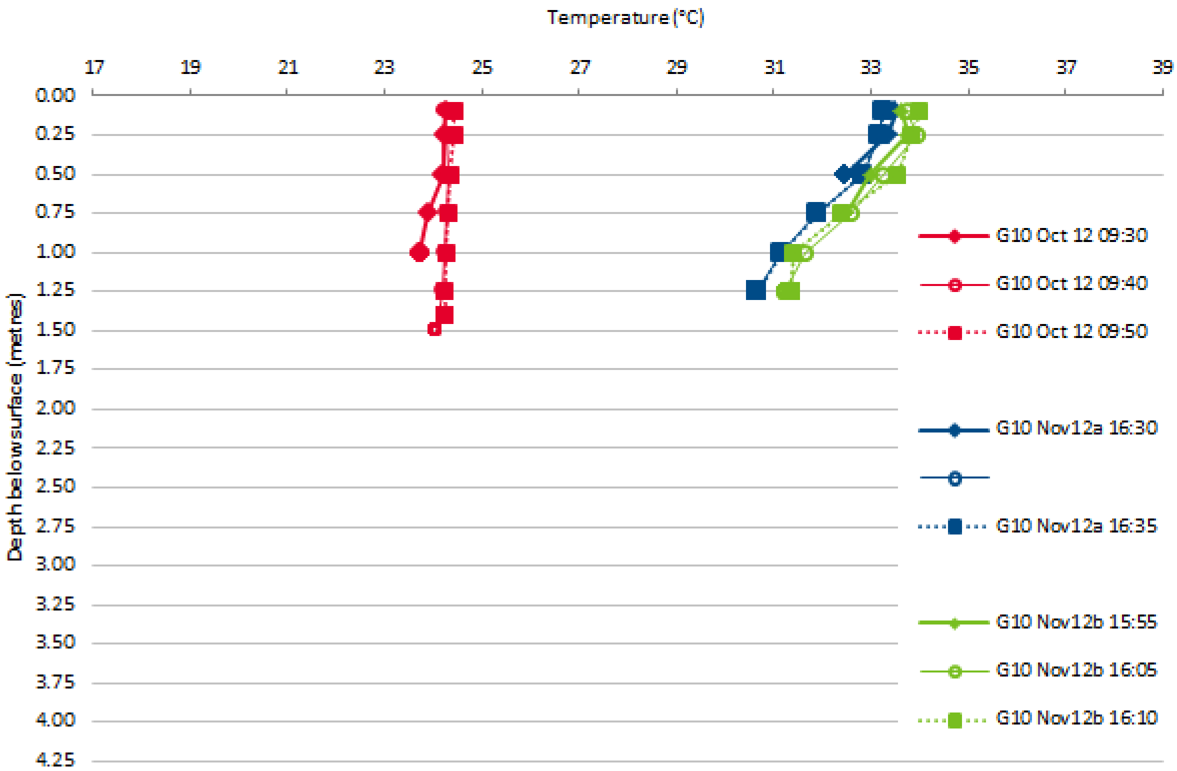


Figure 92 Long term temperature logger data for waterhole G10

Table 10 Continuous water and air temperature logger summary statistics for each survey at waterhole G10.[1] Minimum, mean and maximum temperatures experienced during the period of days (24 h) prior to a survey where the waterhole thermal characteristics were stable. [2]Minimum, mean and maximum recorded difference between surface and bottom temperatures for the time period prior to each survey. Note that minimum surface and bottom temperatures may not have occurred at the same time of day. [3]Percentage of the time period where the difference between surface and bottom temperatures exceeded 0.4, 1.0 and 1.5 °C. All temperatures in °C

TIME PERIOD				AIR TEMPERATURE[1]			WATER SURFACE TEMPERATURE[1]			WATER BOTTOM TEMPERATURE[1]			TEMPERATURE DIFFERENCE (SURFACE - BOTTOM)[2]			PERCENT TIME THAT DIFFERENCE EXCEEDED 0.4, 1.0 or 1.5 °C[3]		
Survey	**From**	**To**	**Days**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**>0.4 °C**	**>1.0 °C**	**>1.5 °C**
Oct 12	14-10-12 00:15	19-10-12 00:15	5	15.6	27.2	37.9	25.6	27.5	31.4	25.3	26.8	28.2	-0.1	0.7	3.5	53.2	23.3	16.3
Nov12a	06-11-12 00:15	10-11-12 00:15	4	24.4	30.3	37.9	29.4	31.5	34.6	29.1	30.5	31.6	-0.1	1.0	3.8	58.1	37.7	28.0
Nov12b	28-11-12 00:15	02-12-12 00:15	4	25.7	31.4	39.3	30.4	32.2	34.7	30.1	31.4	32.7	-0.1	0.8	3.1	51.9	33.9	22.5
Feb 13	18-01-13 00:15	20-01-13 00:15	2	24.2	27.7	32.4	28.5	29.5	31.3	28.6	29.6	31.3	-0.1	0.0	0.1	0.0	0.0	0.0
Feb 13	19-02-13 00:15	22-02-13 00:15	3	24.0	29.0	35.3	28.3	31.7	36.1	28.3	31.8	36.1	-0.1	0.0	0.0	0.0	0.0	0.0



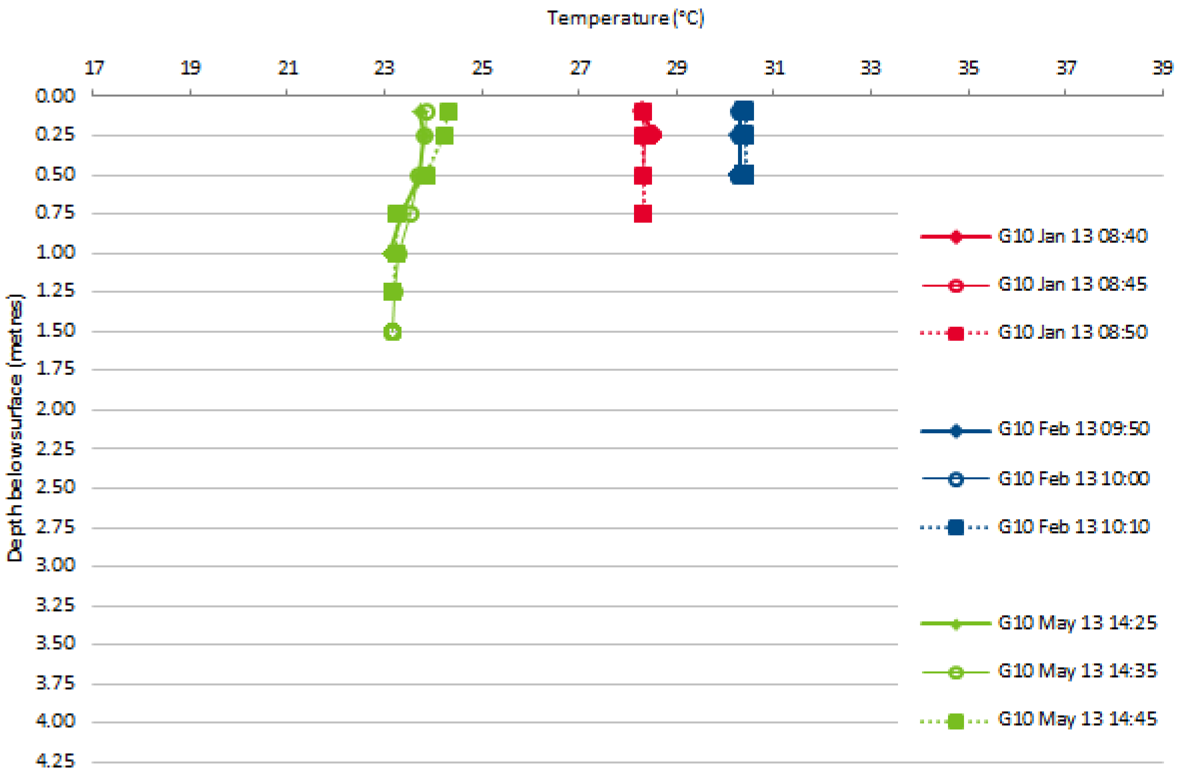


Figure 93 Temperature vertical water column profiles at waterhole G10. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)

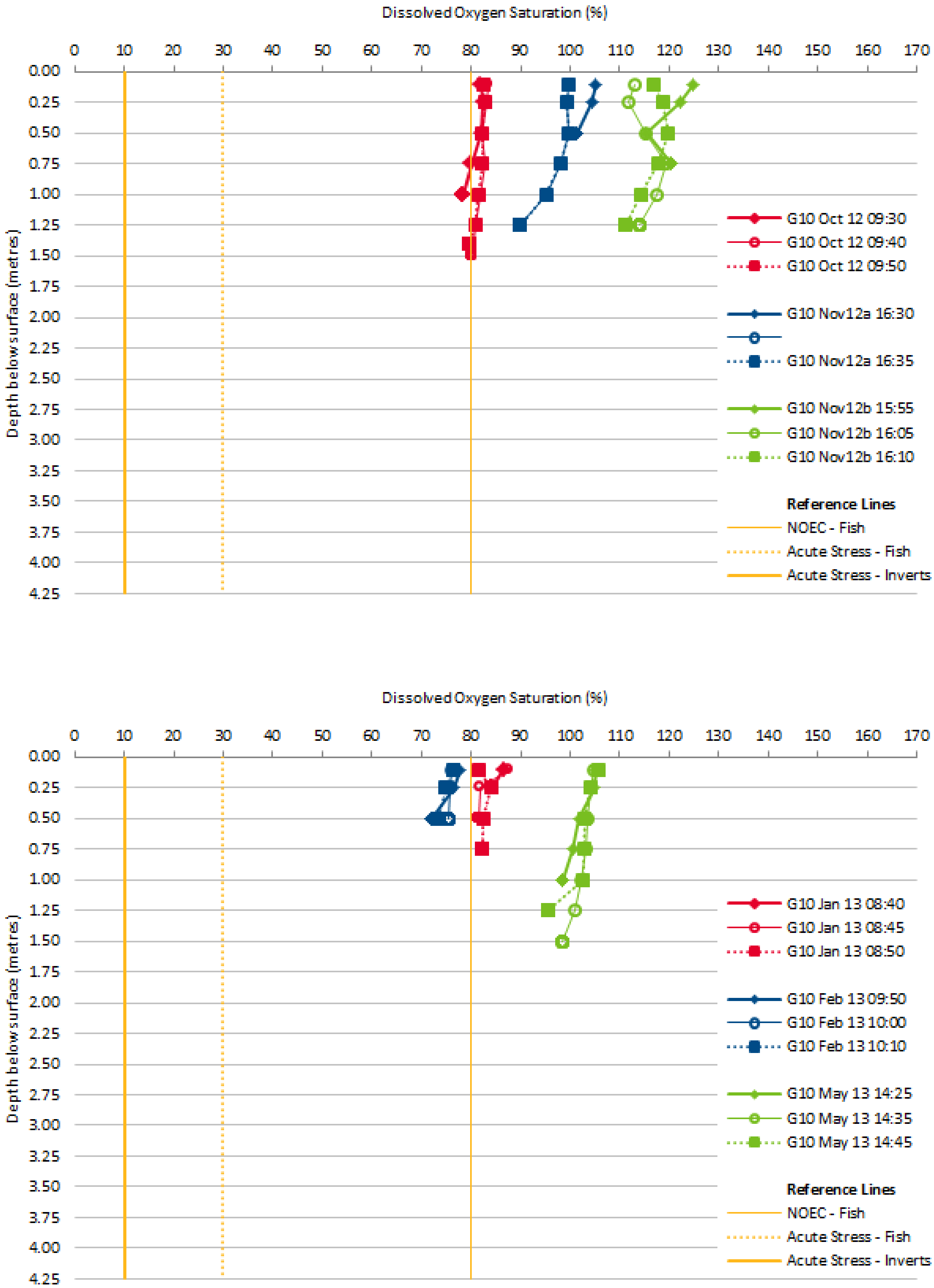
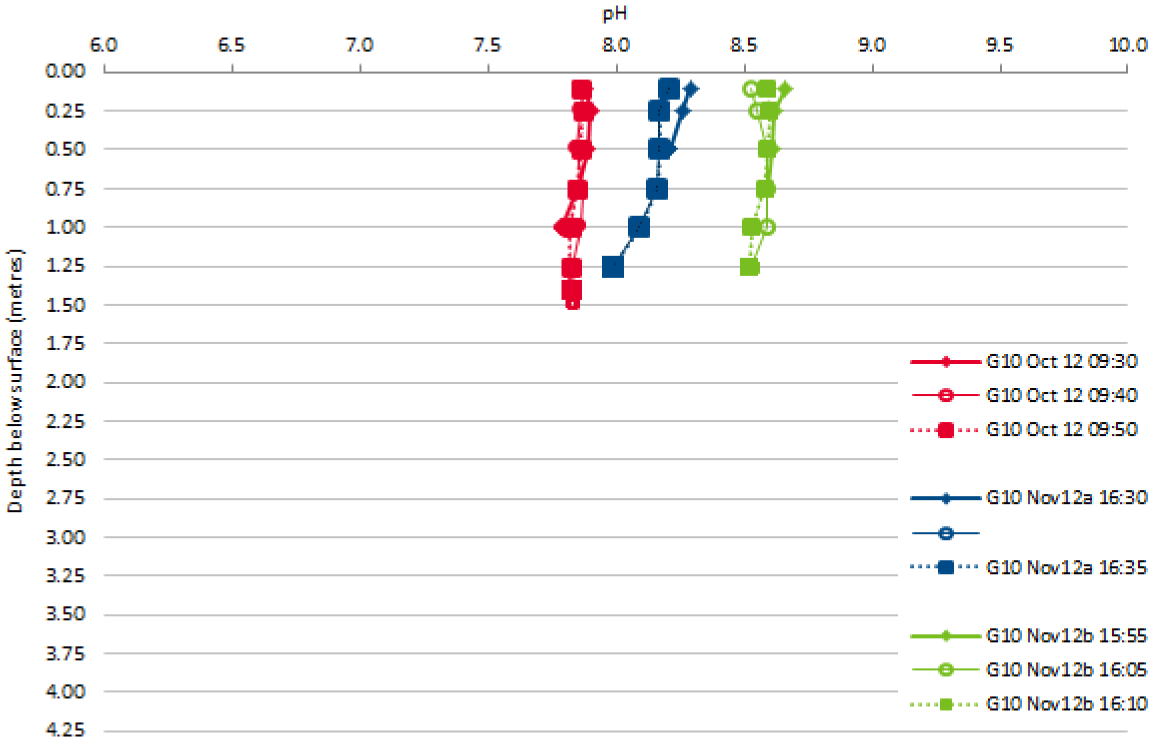


Figure 94 Dissolved oxygen saturation (%) vertical water column profiles at waterhole G10. NOEC = no observed effect concentration. Reference lines from Butler & Burrows (2007). Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



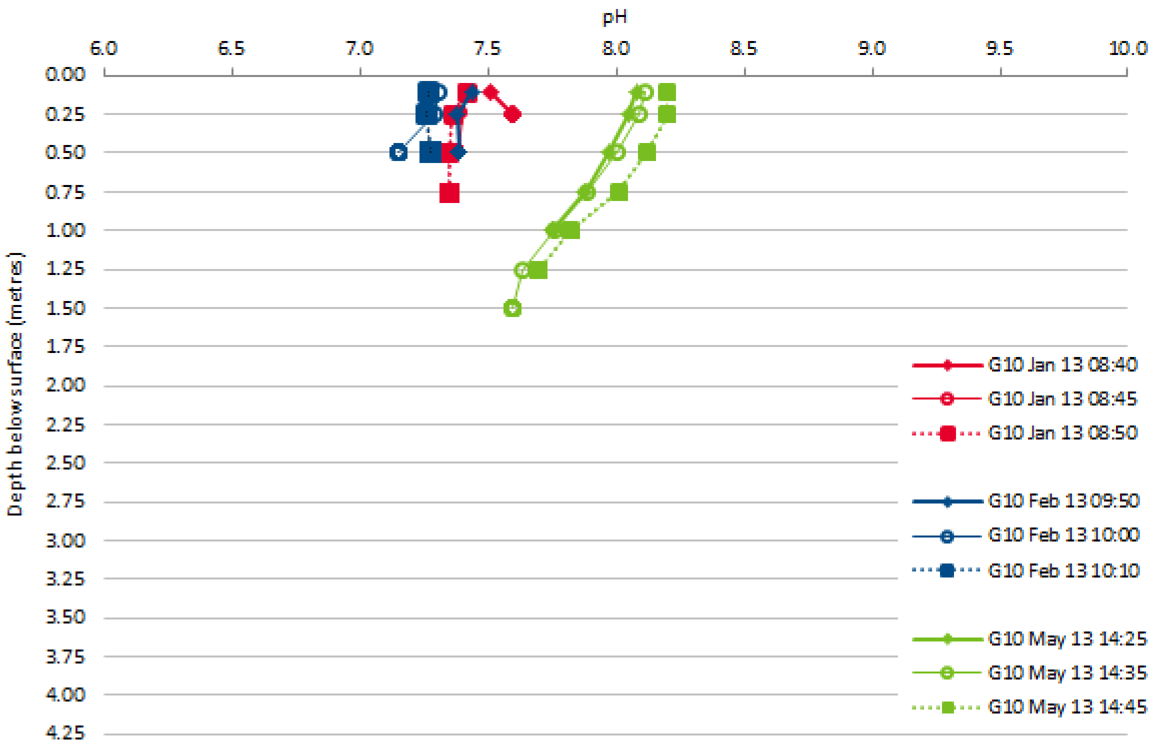
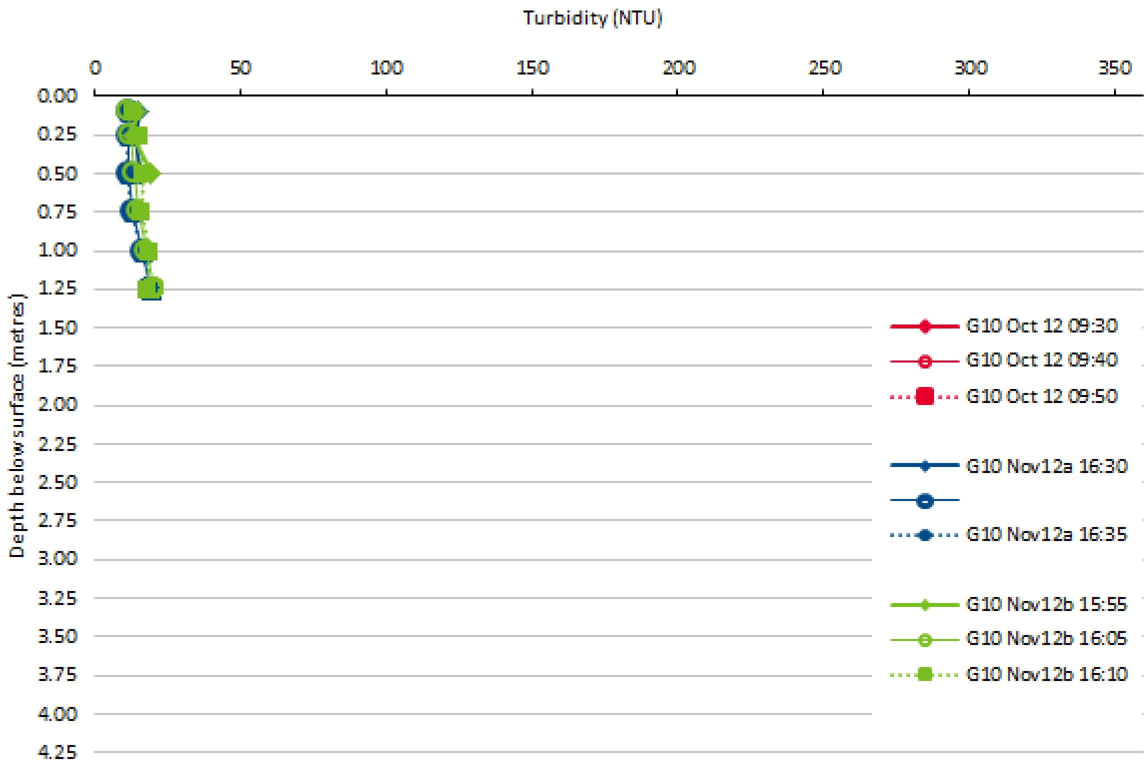


Figure 95 pH vertical water column profiles at waterhole G10. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



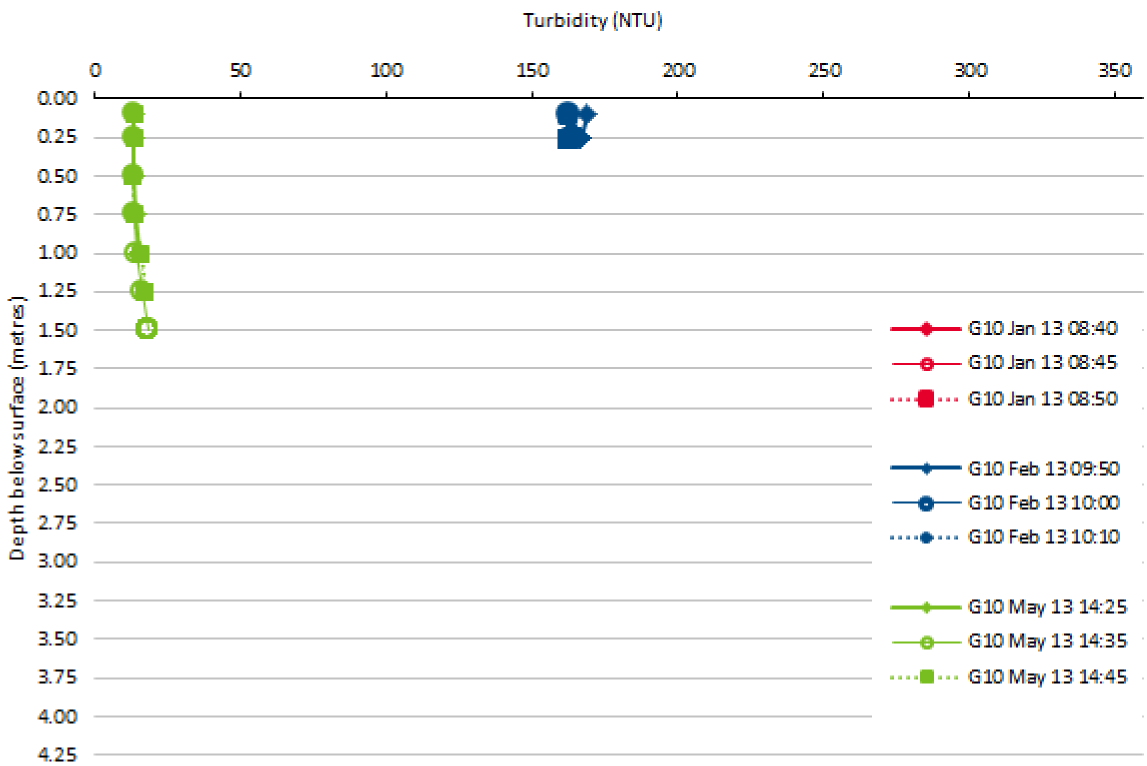
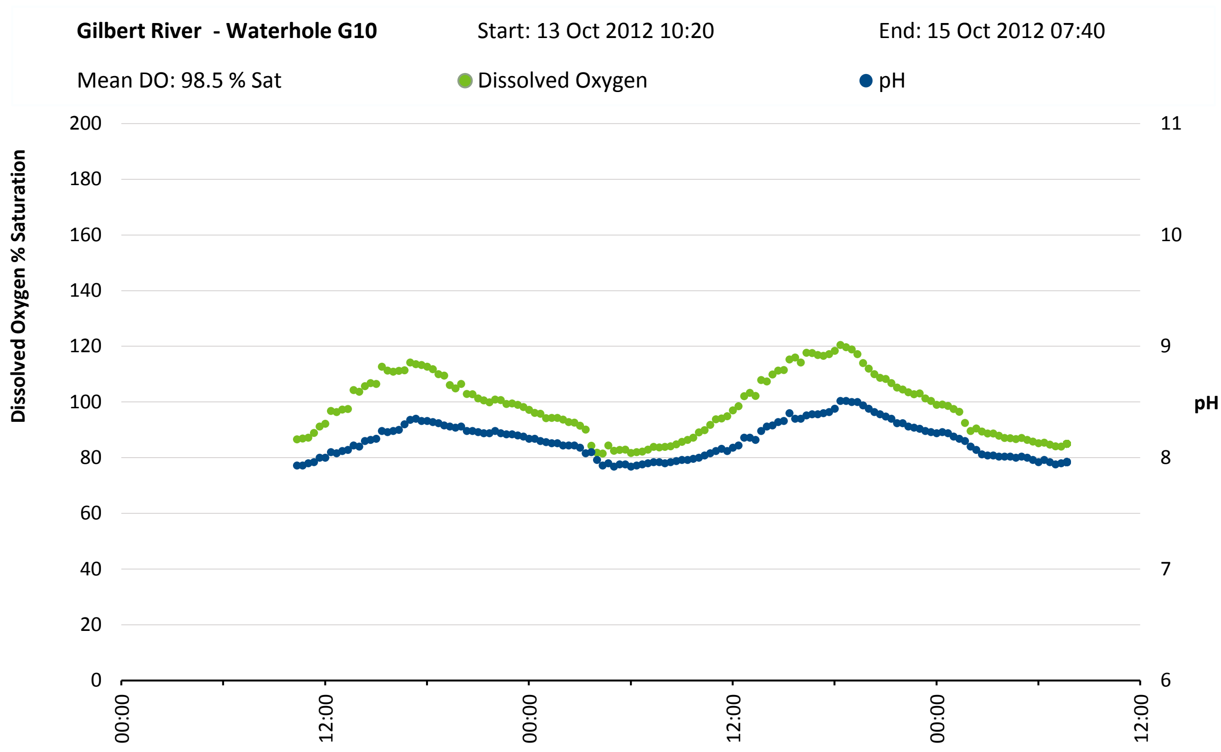


Figure 96 Turbidity (nephelometric turbidity units) vertical water column profiles at waterhole G10. Vertical water column data was collected from three separate locations within the waterhole on each survey trip, separated in the figure by time (hh:mm)



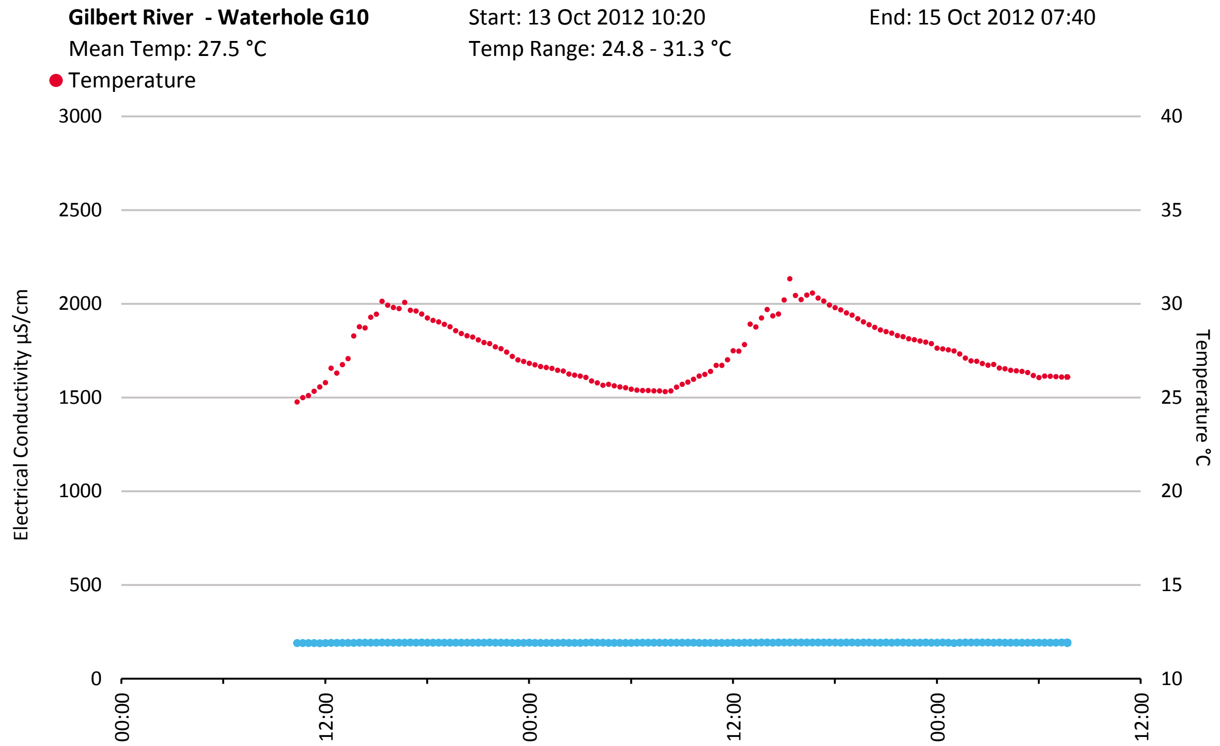
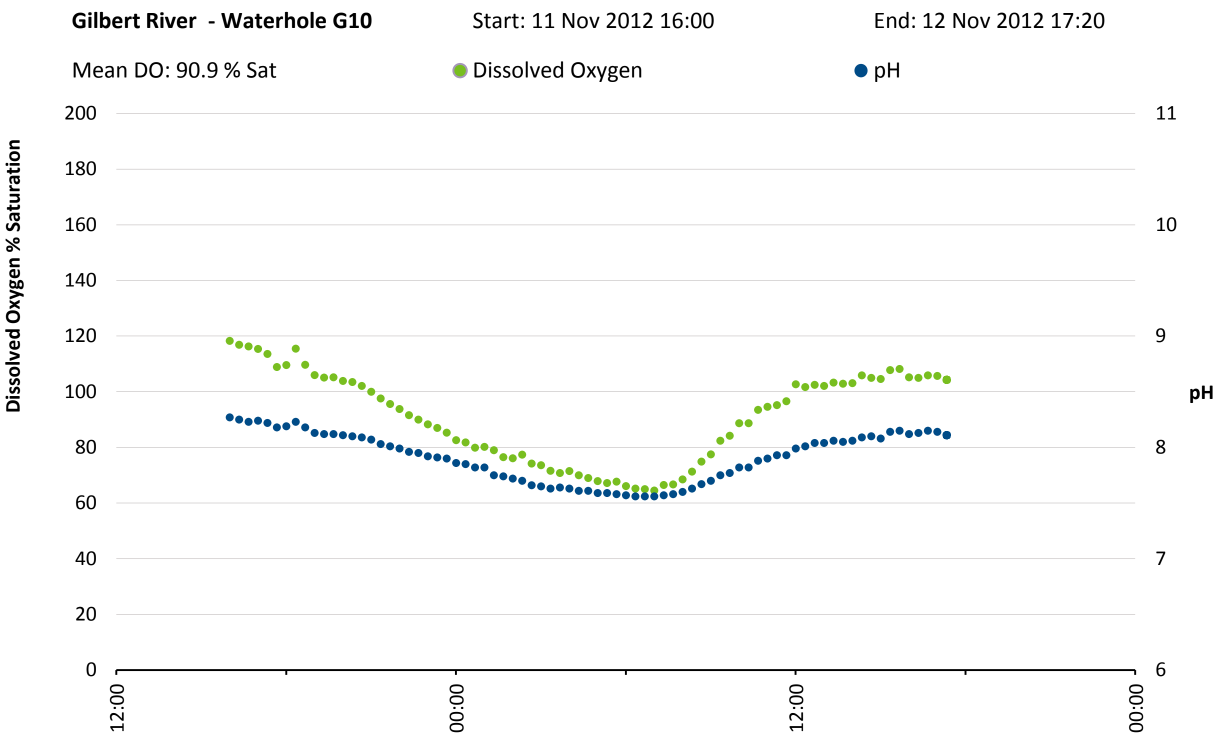


Figure 97 Diel physico-chemical data for waterhole G10, Oct 2012



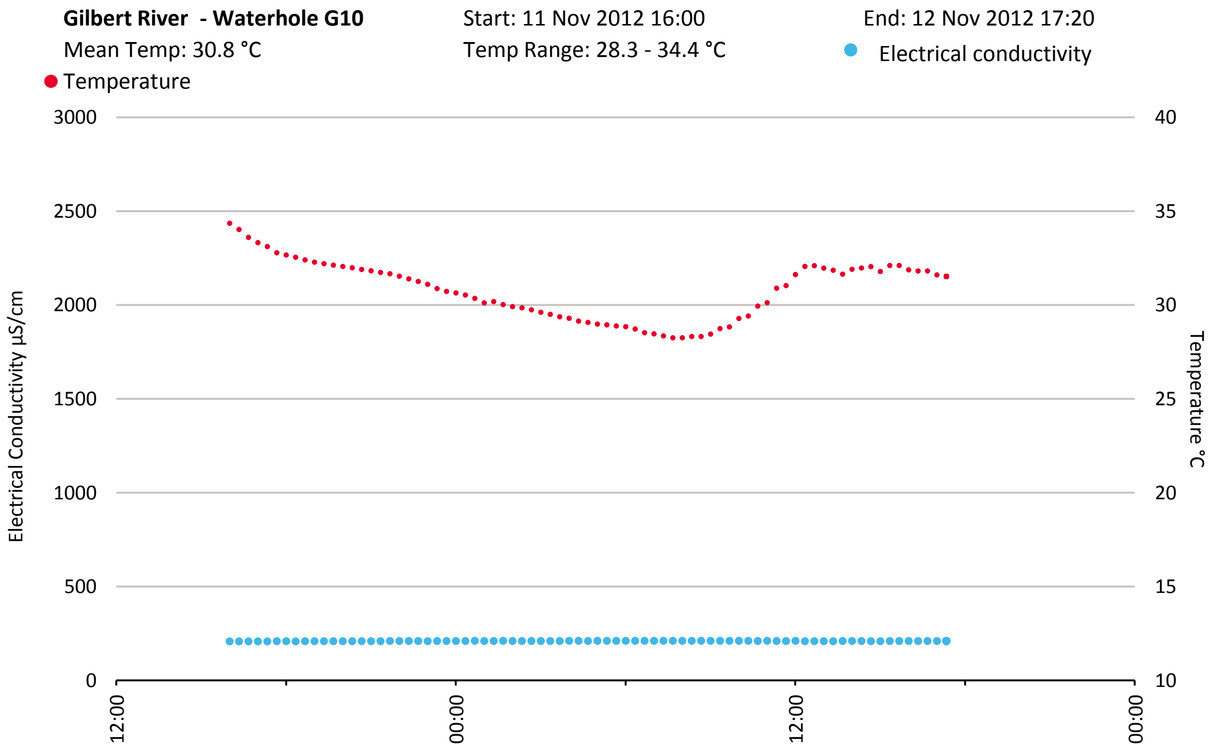
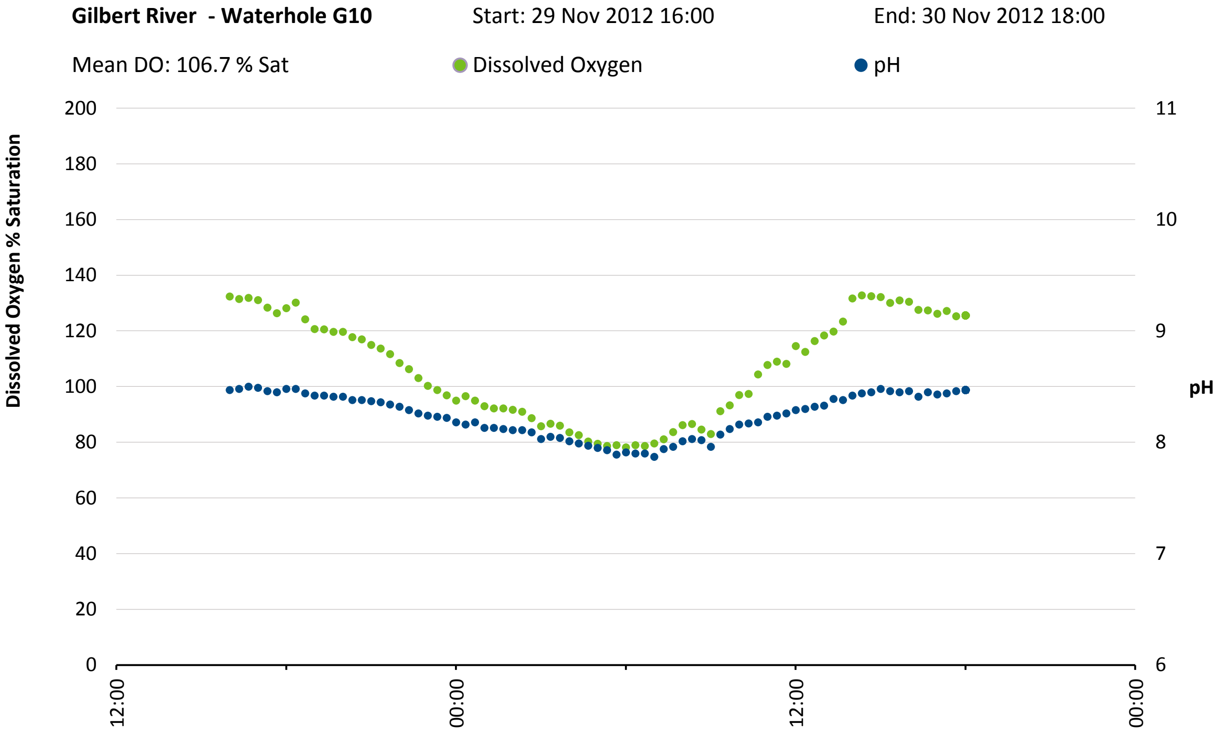


Figure 98 Diel physico-chemical data for waterhole G10, Nov 2012



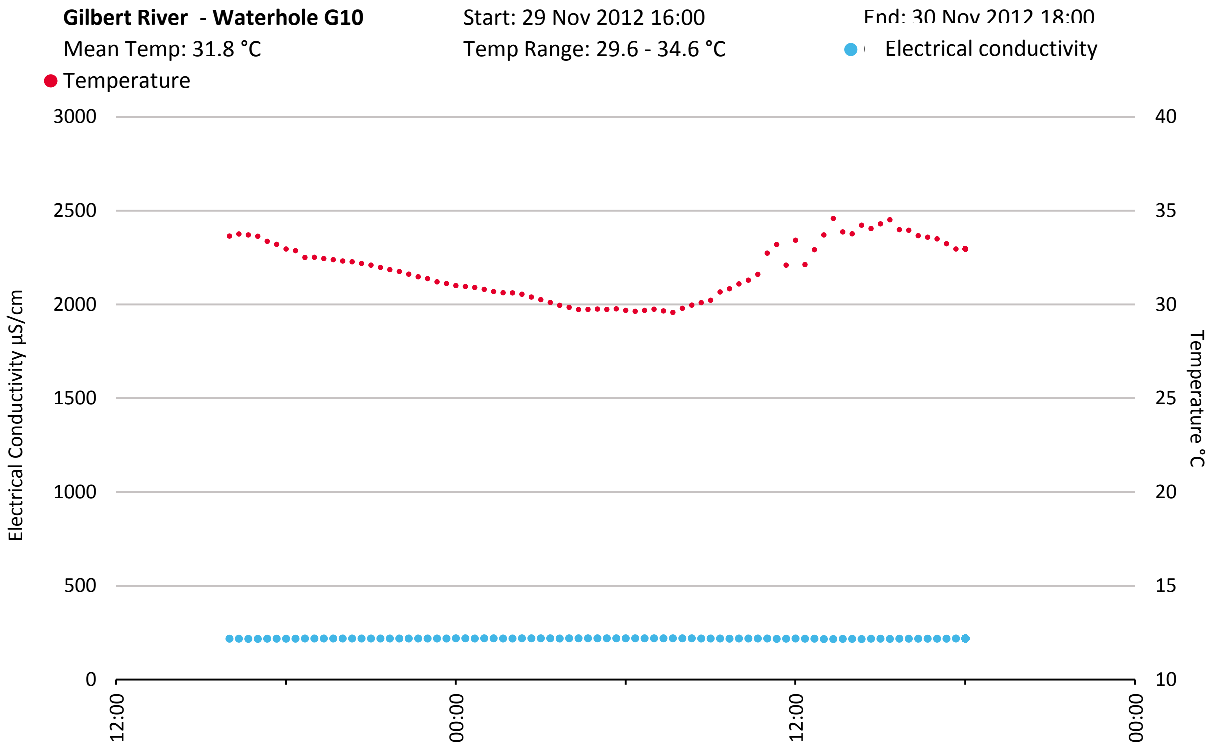


Figure 99 Diel physico-chemical data for waterhole G10, Nov 2012

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