Australian Government
Department of Infrastructure, Transport, Regional Development and Communications

Norfolk Island Water Resource Assessment

Summary report

CSIRO Australia's National Science Agency

Norfolk Island Water Resource Assessment

In light of the water-related challenges facing the Norfolk Island community and the lack of baseline hydrological information, CSIRO was commissioned by the Department of Infrastructure, Transport, Regional Development and Communications to:

- Quantify key components of the water balance of Norfolk Island and understand the drivers of change of hydrological behaviour.
- Investigate options to further improve the resilience of Norfolk Island to extended dry spells.

The Assessment assumed that all sections of the island were within its scope, and that resource use was unconstrained by current legislation, regulations, social norms, values or political considerations, thereby allowing the results to be applied to the widest possible range of uses, over the longest time frame possible.

While the Assessment provides independent biophysical information on the water resources of Norfolk Island and options for providing water during critical periods, it does not seek to advocate or enable any particular development. This is because such a decision ultimately needs to be made by the community, the Norfolk Island Regional Council and the Commonwealth of Australia, in light of their respective values, needs and obligations.

Looking out to Creswell Bay from Bumboras Reserve. One of many scenic reserves on Norfolk Island. Nepean Island in the background.

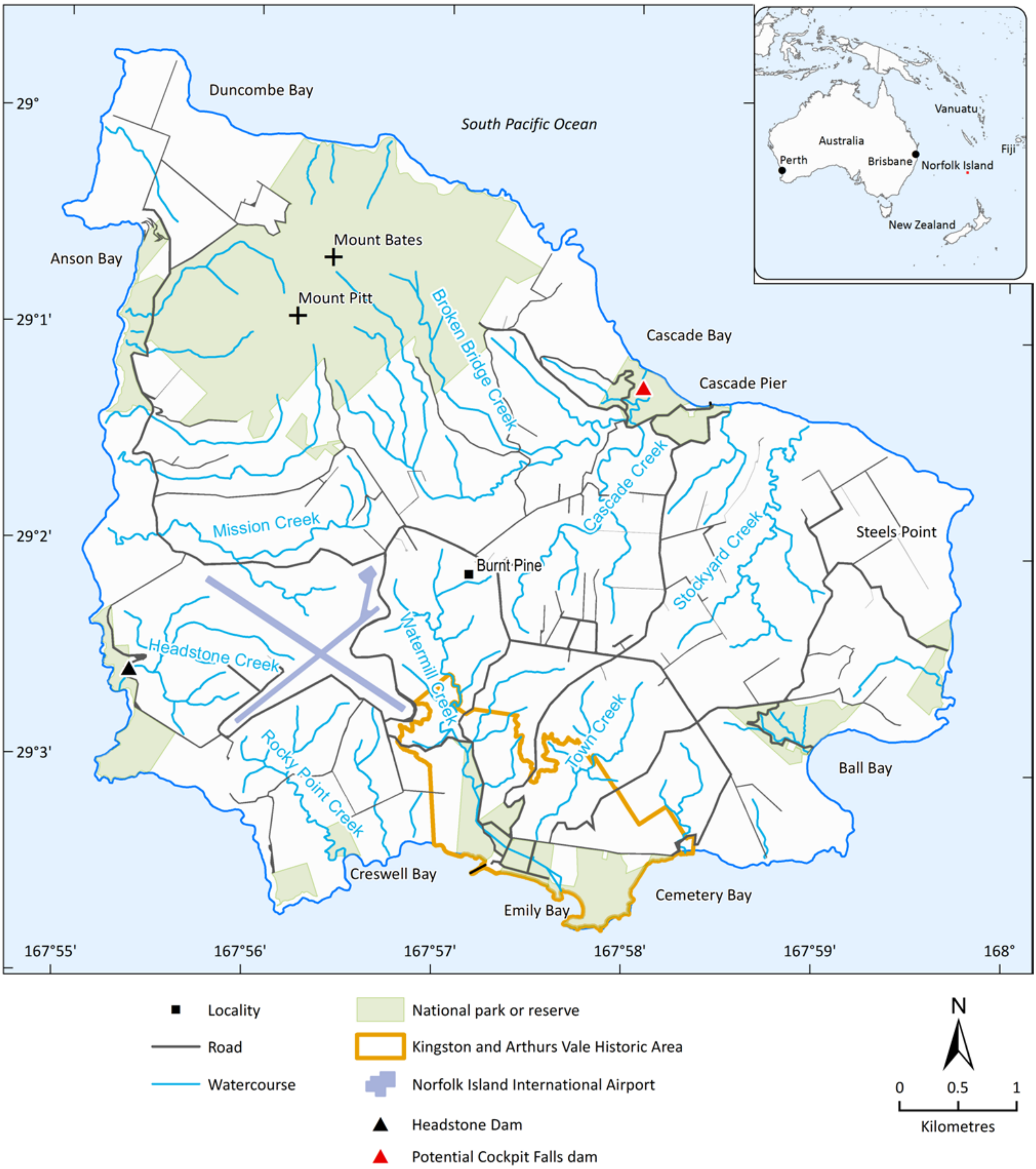

Figure 1 Norfolk Island

Norfolk Island is a subtropical island in the Pacific Ocean approximately 1500 km south-east of Brisbane. The island, a remnant volcano, has an area of 35.7 km² (Figure 1) and is largely comprised of basaltic rocks and tuffs that are weathered deeply, with rich and highly permeable soil.

Like south-eastern and south-western Australia and many other Pacific islands and communities, Norfolk Island is experiencing changing weather patterns, including reductions in rainfall, altered rainfall patterns and rising temperatures. While the island has experienced numerous dry periods in the past and Norfolk Islanders understand the need to conserve water, there is strong evidence that the frequency and severity of dry periods have increased in recent decades.

Key messages

The risk that a significant proportion of the Norfolk Island community may run out of potable water and be unable to replenish their supplies was identified by the Emergency Management Norfolk Island Committee in early 2019. Remoteness and isolation of the island make it important that arrangements are in place to support the community to effectively prevent, prepare for, respond to and recover from a ‘water emergency’.

The mean annual rainfall on Norfolk Island was 11% lower between 1970 and 2020 (1184 mm/year) relative to between 1915 and 1969 (1334 mm/year). Rainfall decline has occurred in all seasons except summer, with the largest decreases in autumn and winter. These observations are consistent with broader patterns of global change.

Long-term changes in rainfall have resulted in a profound change to the hydrology of Norfolk Island. Models show percentage reductions in long-term groundwater recharge and streamflow to be about two and five times the percentage reductions in long-term rainfall over the same time period.

Modelling based on available data indicates that the volume of rock saturated by water has decreased by about 45,000 ML (±50%) or about one-fifth of the stored volume since the mid-1970s. Three-dimensional geological modelling indicates that of ~500 known wells and bores, the number of ‘dry’ wells and bores increased from about 70 to 210 in late 2019. If groundwater levels fell uniformly by a further 10 m and 20 m across the island, the number of dry wells and bores would increase to about 325 and 400 respectively. There is strong agreement among the 21 global climate models assessed that the mean annual rainfall over Norfolk Island will decrease in the future and that potential evaporation will increase.

Fortunately, there are a number of options available to the Norfolk Island community to mitigate the risk and impacts of ‘water emergency’. The suite of risk mitigation options will depend upon the community’s appetite for (or aversion to) risk, available resources to construct and maintain infrastructure, community values, and certainty in yield and cost estimates of each of the options.

Utilising multiple existing groundwater bores within the deep fractured volcanic rock system and above sea level, and constructing water storage and water treatment infrastructure near each bore is likely to be one of the cheaper options (<$100,000 per bore) of providing potable water during critical periods, with a high certainty in cost and yield. For this option to proceed, however, relies on multiple landholders being willing to make their deep bore available for this purpose. This option is likely to remain viable in the medium term (i.e. 10 to 30 years), but sustainability of this option over the long term (>30 years) would require further investigation.

Desalination is the other option capable of supplying large quantities of water with 100% reliability, irrespective of the future climate. While the capital costs are modest (~$515,000) it has large on-going energy requirements.

View to the north from Point Hunter. Emily Bay a popular swimming spot in the foreground. Cemetery Bay to the right.

Cluster-scale roof rainwater harvested rainwater systems are considered to have the next best certainty in yield. The capture of rainwater in tanks is well understood and quantified on Norfolk Island. In addition, the largest cost items, the tanks, are prefabricated and only need to be erected on-site, minimising potential for cost overruns. Tank farms, while yielding less water than other options, may be palatable to the community because they can be sited at a wide range of locations.

The construction of new groundwater bores must be in deeper fractured volcanic rocks and is likely to be one of the more expensive options (i.e. >$1.1 million) due to the depth of drilling and need to import a drilling rig. The cost is also uncertain because multiple exploration holes are often required before a successful bore can be sited. Once a production bore has been established, however, it is likely to reliably yield water for at least the medium term.

An 8.3-m high gully dam at Cockpit Falls had a high capital cost ($1.36 million) but was the cheapest option in terms of cost per litre of water supply. The quantity of water supplied by the reservoir is likely to be far in excess of that required by the community during critical periods. However, the lack of streamflow measurements and uncertainty in the response of Cascade Creek to long-term changes in rainfall mean the yield estimates are uncertain. There is also a reasonably high uncertainty in cost as the construction of a gully dam requires subsurface excavation.

Solely seeking to minimise the community's risk of a water emergency by increasing household rainwater tank capacity is expensive relative to other options (>$10 million).

However, for many households, investing in guttering to connect unused roof catchments to storage tanks and enhancing the efficiency of existing gutters would be a low-cost option for improving the reliability of their roof harvested rainwater system and reducing their dependence on groundwater extraction. Neither of these options individually, however, would prevent a 'water emergency'.

Similarly, managed aquifer recharge, such as swales and recharge weirs, have limited capacity for increasing groundwater recharge at the scale of Norfolk Island. However, they can have considerable local utility where they can capture and infiltrate runoff from impermeable surfaces such as roads, roofs and overflowing rainwater tanks, potentially providing local benefits in terms of increasing soil water and localised recharge, preventing soil erosion, improving the quality of water, and potentially helping keep acid peat soils saturated.

The removal of deep-rooted woody weeds could help slow the rate of groundwater decline, while providing broader environmental benefits, but would not prevent a water emergency on its own.

Ultimately it is likely that a robust emergency water supply strategy would encompass multiple options that could be implemented across a variety of timeframes, thereby providing redundancy and cost-effectiveness. However, all options are entirely contingent upon there being appropriate institutional arrangements and an ongoing commitment to maintain infrastructure and the operational plan. A major limitation to undertaking the Assessment was the lack of long-term monitoring data. Ongoing monitoring of Norfolk Island's resources will enable better management into the future.

Climate

- Norfolk Island had a mean annual rainfall of 1263 mm between 1915 and 2019.
- There is a modest range of rainfall over the seasons, but historically the totals are highest during the cooler months (i.e. between April and August).

Reductions in annual rainfall and changes to the seasonal patterns on Norfolk Island are consistent with broader patterns of observed global change.

- A notable feature of Norfolk Island's historical rainfall has been a decline in annual rainfall since about 1970, which manifested as long runs of dry years in recent decades.
- Relative to the period 1915 to 1969 (1334 mm/year), mean annual rainfall was 11% lower between 1970 and 2020 (1184 mm/year).
- Relative to 1945 to 1969 (1386 mm/year), mean annual rainfall was 12% lower between 1970 and 1994 (1223 mm/year) and 17% lower between 1995 and 2019 (1145 mm/year).
- The decline in rainfall has occurred in all seasons except summer, with the largest decreases in autumn and winter.
- There has been an increase in modelled crop/plant water demand since about 1990, in part due to an increase in temperature but more notably from an increase in wind speed over Norfolk Island.

There is strong agreement among 21 global climate models (~80%) that mean annual rainfall over Norfolk Island will decrease in future and that potential evaporation will increase (~90%).

- All models agree on a decrease in Norfolk Island's spring rainfall and 90% agree on a decrease in winter rainfall. About 40% and 25% of models project decreases of greater than 20% in spring and winter respectively. There is a lack of agreement between models on the direction of rainfall change for summer and autumn.
- There is a substantial warming trend in air temperature and sea surface temperature at Norfolk Island and strong agreement among the global climate models that this will continue into the future.
- Modelled increases in evaporative demand on Norfolk Island have arisen due to slight increases in temperature but more notably to an increase in wind speed since 1990. The increase in wind speed is consistent with other studies, which found surface wind speed to have increased over the ocean but decreased over large continental land masses over the past three decades.
- Coupled with lower rainfall, change in wind speed results in a higher crop irrigation water requirement.

View to the southwest from Steels Point. Steels Point has some of the most suitable land for irrigated agriculture. Phillip Island in the background.

Landscape and soils

- Norfolk Island and its neighbouring Phillip Island are remnants of a weathered and eroded volcanic complex that began forming after volcanic activity approximately 2 to 3 million years ago.
- The island has an area of 35.7 km² and is largely comprised of basaltic rocks and tuffs that are weathered deeply, with rich and highly permeable soil, suitable for a wide range of cropping.
- Six types of soil occupy the majority of the island and are formed from late Tertiary basalt flows with interbedded ash and tuff. These soils all have firm strongly structured surfaces with rapid surface infiltration, and no impeding subsurface layers.
- These volcanic clay soils have a high water holding capacity (~120 mm/m).
- Erosion is evident on Norfolk Island from three processes, soil creep, slumping (land slips) and sheet erosion, contributing to infill in lower parts of the landscape and drainage lines.
- Soils have clay textures (>35% clay) throughout the profile, and with compaction would be suitable for earth embankment gully dams.
- Rock and sand suitable for construction are in short supply on Norfolk Island and concrete, which has to be imported to the island, is expensive.

Soil sampling near the Kingston and Arthur's Vale Historic Area. Profile descriptions to determine key soil and landscape attributes were investigated at 106 locations across the island.

Norfolk Island has numerous small areas of some of the most acidic soils in the world.

- Acid sulfate soils are naturally occurring soils, unconsolidated sediments or organic accumulations (peat) in which sulfuric acid may be produced or has been produced. They are formed under waterlogged (anaerobic) conditions in peaty wetlands across Norfolk Island.
- Although the mapped areas of acid peat sulfate soils on Norfolk Island are small, they occur in many drainage lines and consequently are of significance to the hydrology and may affect options for providing good quality water in wetlands, streams and dams during critical dry periods.

Acid sulfate soils are considered the most benign soils in the world, if left undisturbed. Disturbed and aerated they are the 'nastiest' soils in the world.

- Under the current dry climate conditions and in areas of anthropogenic activity (draining, excavation, dam building) where acid sulfate materials with sulfide containing minerals (pH >4) have become exposed to air, they have oxidised and are producing sulfuric acid to form Sulfuric organic soils (pH <4). Treatment is required to halt the ongoing impacts.
- This has resulted in localised environmental degradation in drying wetlands and in long-term degradation of infrastructures such as dam walls and bridges in the Kingston and Arthurs Vale Historic Area.
- Under a projected drier future climate, acid sulfate material with sulfide containing minerals will increasingly become exposed to air, raising the potential for localised environmental degradation and reducing the pH to < 4.5 in adjacent water bodies (e.g. dams) upon rewetting.

Hydrogeology

Subaerial eruptions of lava flowing down from the volcanic vent and subsequent successive lava flows with interbedded tuff layers have created a complex hydrogeological environment exhibiting high heterogeneity.

- The major aquifer systems on the island occur in the weathered volcanics and the agglomerate and fractured unweathered basalt bedrock sequences deposited above present-day sea level. The majority of the >500 bores and wells on the island are within these systems.
- A small number of bores are found in the minor aquifers in the shallow alluvium, fractured unweathered basalt rock below present-day sea level and carbonate calcarenite aquifer along the Kingston lowland. These aquifers have limited spatial extent and, the latter two aquifers are vulnerable to seawater intrusion.

Interbedded basalt flows and ash layers behind Cascade Pier. An example of the high heterogeneity below the ground surface.

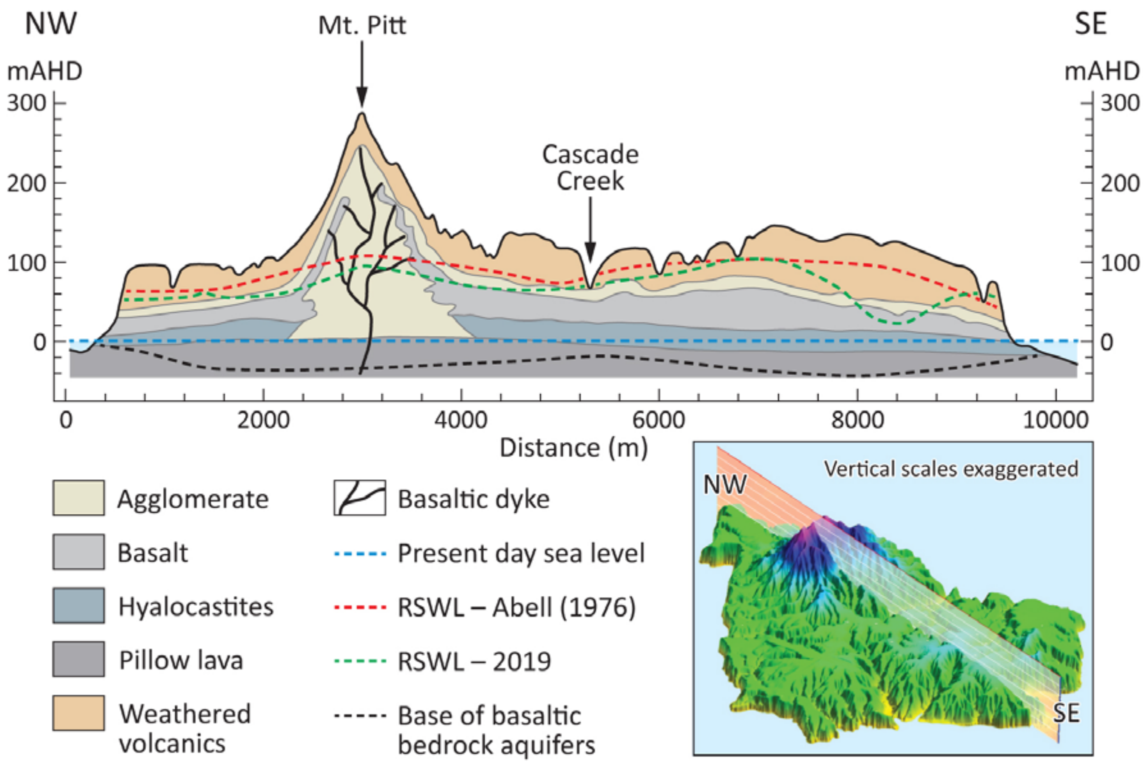

Figure 2 Hydrogeological cross-section including a comparison of reduced standing water level (RSWL) surfaces from 1976 and 2019

Bottom right inset is the location of the northwest–southeast slice through the geological model. Diagram based on data extracted from the geological model.

- Groundwater flow systems on Norfolk Island are localised, broadly following the major drainage basins and aquifers are generally hydraulically interconnected with vertical leakage from the weathered volcanics recharging the underlying agglomerate and basalt aquifers.
- Recharge to the weathered volcanics occurs predominantly across the elevated parts of the island on the southern and northern plateaux and the upper reaches of surface drainage basins, though little is known about recharge and groundwater flow beneath and at the break of slope around Mount Pitt and Mount Bates.
- A dominant feature is a high-level watertable under the southern plateau with a height of over 100 m above sea level and hence high hydraulic potential. This watertable mound is maintained by a combination of high groundwater recharge, bedrock topography and low permeability of the weathered volcanic rock.
- On the southern side of the island Rocky Point Creek, Watermill Creek and Town Creek extend into the watertable mound under the southern plateau and are effective discharge features because, unlike other creek lines on Norfolk Island, they drain down to sea level.
- The time scales for groundwater flow ranges from a few years to tens of years in the elevated recharge areas, increasing to tens of years to a few hundred years in the lower lying discharge areas, though in some places faster flow may occur preferentially through fractures in the unweathered basalt rock.
- The northern part of the island, north to north-west of a line running along Mission Creek and Broken Bridge Creek, is a geomorphic boundary that aligns with a volcano structural boundary separating the main volcanic vent on Mount Pitt and Mount Bates from the volcanic apron/southern plateau. Conceptually this boundary splits the island into two hydrological units.
- The northern part of the island differs from the south in that discharge features are sparse. All creek lines north of this boundary have been mapped as only intermittent, and according to residents are unknown to (or rarely) flow.

Anson Bay and its northern escarpment. The Norfolk Island Pines pictured here are likely to be sourcing some of their water from groundwater.

Demographics, land and water use

- The island was first settled by East Polynesian seafarers whose artefacts have been dated to ~800 to 1400 AD. However, when Captain Cook discovered the island in 1774 it was uninhabited.
- Following two attempts by the British Government to use the island, first as a colonial settlement from 1788 to 1814 and secondly as a penal settlement from 1825 to 1855, the island was settled in 1856, with the permission of the British Government, by Pitcairn Islanders whose islands had become too small for their growing population.
- As a consequence of its rich history, Norfolk Island has experienced complicated and alternating cycles of clearing and regrowth, which would have impacted on the island's water balance. A large proportion of the island is now covered in deep-rooted woody weeds.
- The 2016 Australian Government Census showed there were 1748 people on Norfolk Island and 1080 private dwellings, of which 748 (75%) were occupied.
- Tourism is the largest industry, with approximately 30,000 tourists visiting annually. This is roughly equivalent to an additional 575 permanent residents.

Quality Row and Government House within the Kingston and Arthur's Vale Historic Area.

Norfolk Island has no large dams or reticulated water supply. Individual households and businesses are responsible for their own supply of potable water.

- Due to the dispersed nature of the residential population and tourist accommodation, a reticulated water supply system servicing the whole island would be prohibitively expensive.
- Over 95% of households source their water primarily from roof harvested rainwater tanks. During extended dry periods many households replenish their supplies using groundwater.
- The weathered basalts of Norfolk Island allowed construction of hand-dug wells with relative ease. Groundwater bores were not constructed until the 1960s with the arrival of drilling rigs. In 1996 there was a moratorium on new bores.
- Today there are over 500 known wells and bores, and many more abandoned and unregistered bores.
- Prior to World War II and the availability of Southern Cross piston pumps, residents only extracted enough groundwater to meet their needs due to the laborious effort involved. With electrification of the island in 1969 significant increases in groundwater extraction are likely to have occurred.
- Groundwater use on Norfolk Island is not regulated or measured. Mean annual groundwater extraction is estimated to be approximately 120 ML, about three times that estimated prior to World War II.

Water balance of Norfolk Island

An important part of assessing options for improving Norfolk Island's resilience to extended dry periods is to understand the islands baseline climate and hydrology.

- Rainfall inputs can be broadly broken into evaporated (from soil and plants) and non-evaporated components. The non-evaporated component of rainfall, also referred to as 'excess water', can be broadly broken into overland flow and groundwater recharge.
- Recharge replenishes groundwater systems, which in turn discharges into creeks, cliff lines and the ocean, and can be transpired by vegetation in areas where the groundwater is shallow. Overland flow and groundwater discharge into rivers and combine to become streamflow.

Evapotranspiration

Deep-rooted vegetation (e.g. trees) transpire more water than shallow-rooted vegetation (e.g. pasture, shrubs).

- Evaporation or evapotranspiration is the process by which water is lost from open water, plants and soils to the atmosphere. It is a 'drying' process and is a function of the quantity and timing of available energy (sunlight, wind) and water.
- Remotely sensed imagery indicated that native hardwood forests, eucalypt (*Eucalyptus* spp.) plantations and deep-rooted woody weeds transpired similar quantities of water, and slightly higher quantities than stands of native Norfolk Island pine (*Araucaria heterophylla*). Evapotranspiration was lowest from areas of pasture.

A convict built well and dwelling within the Kingston and Arthur's Vale Historic Area. The water level in 63 wells and bores were measured as part of the Assessment.

Modelled percentage reductions in evapotranspiration for Norfolk Island were three to four times less than the percentage reductions in mean annual rainfall over the same time periods.

- Relative to the period 1945 to 1969, rainfall and modelled evapotranspiration between 1970 and 1994 declined by 12% and 3% respectively. Between 1995 and 2019 rainfall and modelled evapotranspiration declined by 17% and 5% respectively, relative to the period between 1945 and 1969.
- This is because in low rainfall years, vegetation requiring higher rainfall will seek to transpire quantities of water required for optimal growth, and hence reductions in evapotranspiration tend to be less than reductions in rainfall.

Groundwater recharge

Potential recharge was modelled to be higher under shallow-rooted vegetation than deep-rooted vegetation because deep roots can access soil water lower in the soil profile.

- Estimates of groundwater recharge were highly variable, ranging from 116 mm/year to 330 mm/year. Potential recharge is likely to be highest on the southern plateau and slopes of Mount Pitt and Mount Bates.
- Spatially averaged across the island, potential recharge was estimated to be about 220 mm/year (i.e. 20% of rainfall) between 2010 and 2019.

Percentage reductions in modelled potential recharge are about twice the percentage reductions in rainfall over the same time periods.

- Relative to the period 1945 to 1969 (487 mm/year), modelled potential recharge declined by 26% (363 mm/year) between 1970 and 1994 and 40% (295 mm/year) between 1995 and 2019.
- Of these reductions in modelled potential recharge, about 85% of the reduction arose from differences in climate (i.e. predominantly a reduction in rainfall) and 15% due to a change in vegetation (i.e. increases in deep rooted woody vegetation), averaged across the island.

Groundwater levels

Groundwater levels on Norfolk Island are declining, which indicates groundwater discharge exceeds groundwater recharge.

- Groundwater levels on Norfolk Island fell between about 5 m and 20 m between the mid-1970s and late 2019. This was modelled to be equivalent to a reduction of about 45,000 ML (±50%) of groundwater, or averaged over the last 45 years, discharge has exceeded recharge by about 1000 ML/year (±50%).
- There appears to have been an unusually large reduction in groundwater level between Town Creek and Ball Bay.
- During the mid-1970s it is estimated that of the ~500 registered wells and bores on Norfolk Island, 70 were dry. During late 2019, the base of 210 known bores and wells were modelled as being above the groundwater level. If groundwater levels uniformly fell by a further 10 m and 20 m across the island the number would increase to about 325 and 400 respectively. It should be noted, however, that groundwater levels generally exhibit smaller decreases in areas of groundwater discharge relative to areas of groundwater recharge.
- Groundwater discharge can occur by a variety of processes including groundwater extraction (~1 to 2% recharge between 2010 and 2019), discharge to seeps/creeks (~15% recharge), transpiration of shallow groundwater by vegetation (~1% recharge), and seepage through cliffs and submarine discharge (i.e. discharge into the ocean) (~80 to 85% recharge).
- Spatially averaged across Norfolk Island, anthropogenic groundwater extraction (120 ML/year) is estimated to be approximately 3.4 mm rainfall depth equivalent. Although this may only be equivalent to 1 to 2% of groundwater recharge, it is between 6% and 18% of the difference between groundwater recharge and groundwater discharge over the last 45 years.

Runoff and streamflow

Small percentage reductions in long-term rainfall can result in five-fold percentage reductions in long-term runoff.

- Overland flow on Norfolk Island only occurs during severe rainfall events when rainfall intensity is greater than surface infiltration rates, or if soils are saturated, or where there is concentrated flow from hard impermeable surfaces.
- Runoff on Norfolk Island is a small component of the water balance, modelled as being approximately 4% of rainfall (i.e. ~40 mm/year) between 2010 and 2019, down from 7% of rainfall between 1967 and 1976.
- Modelled runoff exhibits a steadily declining trend over the last 50 years. Between 1970 to 1994 and 1995 to 2019 rainfall decreased by 6% and modelled runoff decreased by 33%.

Headstone Dam, one of three community watering point on Norfolk Island. Acidic peat soils can be seen along the base of the creek.

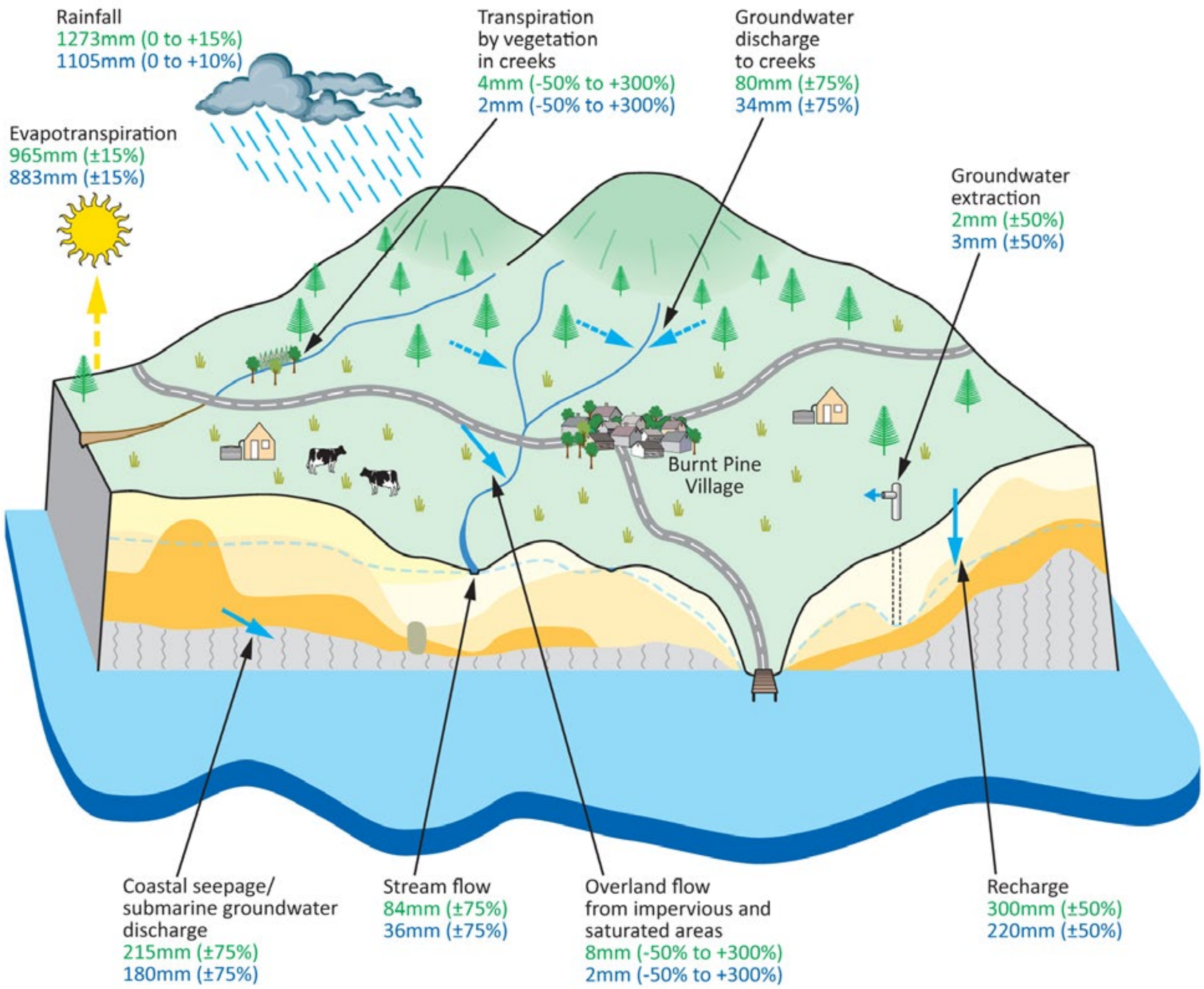

Figure 3 Modelled water balance of Norfolk Island in the mid-1970's and 2019

The dominant hydrological processes on Norfolk Island have changed.

- The reductions in streamflow are particularly pronounced on Norfolk Island because as groundwater levels in discharge zones fall below creek lines, groundwater no longer discharges into the creeks and surface runoff events become less prevalent because without shallow groundwater the highly permeable soils do not saturate easily (Figure 4).
- The reason it can take years for a change in the streamflow characteristics to become evident is that it often takes many years of sustained reduction in rainfall and hence recharge to manifest as a change in water levels in low-lying discharge areas.

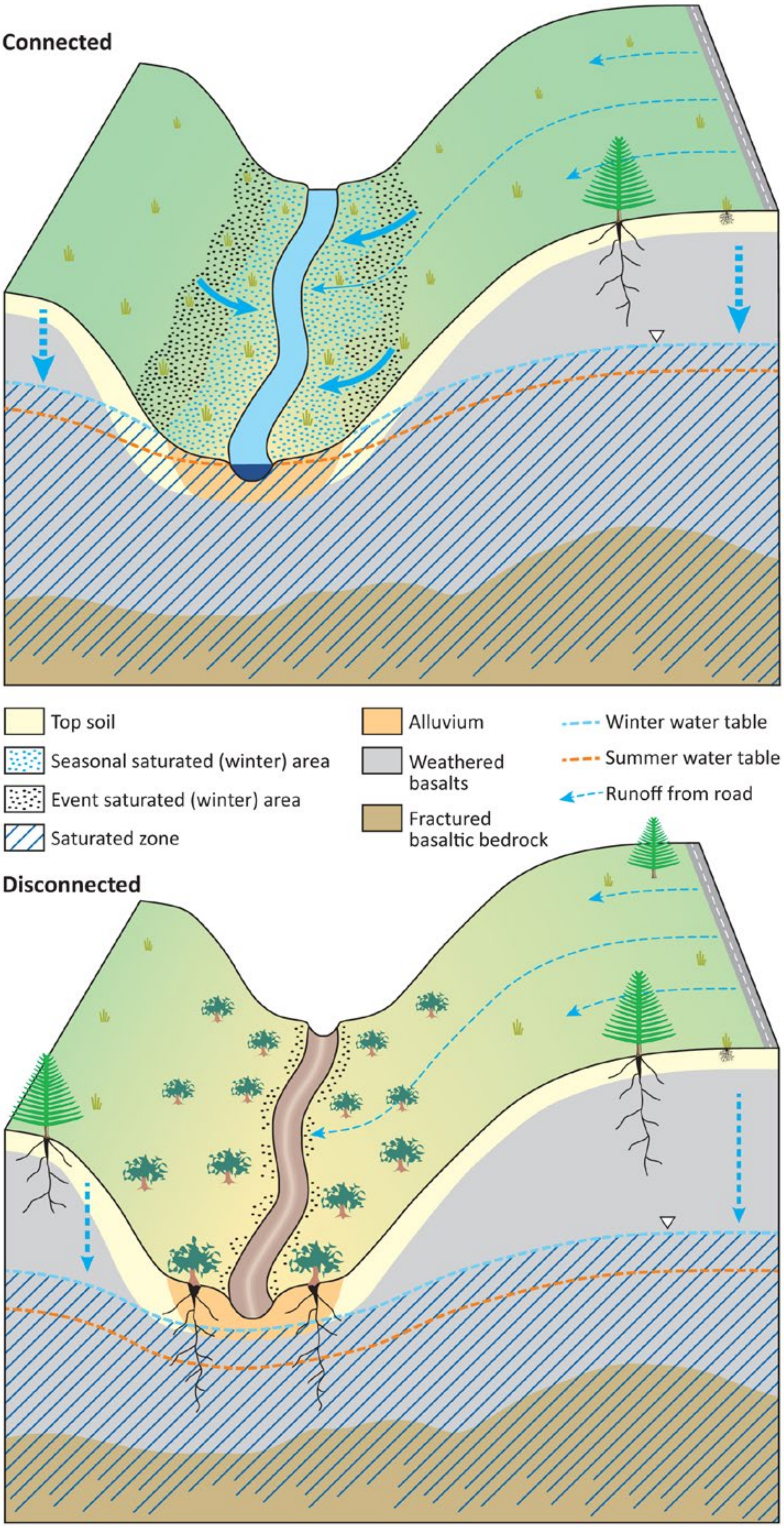

Figure 4 Conceptual model of the change in dominant hydrological processes on Norfolk Island as creeks become disconnected from the underlying groundwater system.

Household roof harvested rainwater systems

Roof harvested rainwater systems on Norfolk Island can supply water with higher reliability than in most parts of Australia. Nonetheless it is challenging for roof harvested rainwater systems to supply water with 100% reliability.

- The cost of installing rainwater tanks on Norfolk Island is considerably higher than on mainland Australia (i.e. 40 to 100% greater), largely due to the high cost of shipping, which is dependent upon both the volume and weight of an item.
- The most cost-effective way of increasing the reliability of water supply for many households will be to connect existing unutilised roofs to existing rainwater tanks and to maintain and enhance existing rainwater collection gutters.
- The total household rainwater tank storage capacity on Norfolk Island is estimated to be about 70 ML, of which about one-third is estimated to be concrete underground tanks. The median household storage capacity is estimated to be about 54,000 L.
- Historically, the highest daily modelled roof harvested rainwater storage stress occurs between the end of January and the end of March. This also coincides with the time that groundwater levels are typically lowest.

Rainwater tank storage capacity, reliability and water usage are interlinked. Increasing water usage will decrease the reliability of supply. Increasing storage capacity will increase the reliability of supply or enable an increase in water use at the same reliability.

- At 100% daily reliability there is no difference in the quantity of water that could be supplied by the household rainwater tank system between 1915 to 1969 and 1970 to 2019. This is because the most critical rainfall period for roof harvested rainwater systems was similar in both periods.
- However, based on Norfolk Island's rainfall between 1915 and 1969, a household with a roof area of 200 m^2 and storage capacity of 50,000 L could supply 525 and 575 L of water in 95% and 90% of days respectively. Based on rainfall records from between 1970 and 2019, the same roof rainwater harvesting system could supply 400 and 450 L of water in 95% and 90% of days respectively.
- This is equivalent to a reduction in water supply of about 20%, approximately twice the reduction in rainfall over the same period. This is because changes have also occurred to the patterns of rainfall important for roof rainwater harvesting.
- It was found that households with surplus rainwater in storage could theoretically meet the needs of other households with insufficient storage capacity in most years. However, households with surplus capacity could not meet the needs of the entire residential population during the most critical periods.
- Community education campaigns on water conservation were considered likely to result in a small to moderate decrease in 'failed' households in many years, but campaigns would have had little impact during the most critical periods on record.
- Increasing the resilience of the residential population to extended dry periods through increasing household rainwater tank storage capacity was found to be expensive relative to other options. Achieving 100% daily reliability for all households was modelled to cost about 12.5% higher than when achieving 95% reliability.

Rainwater tank storage capacity can only usefully increase to the point where the system becomes limited by the amount of water the roof can generate.

- It is not possible to achieve water security for the entire island by increasing rainwater tank capacity alone. For some households, roof area limits an increase in the reliability of water supply.

The Burnt Pine commercial area looking west from The Village.


MAX'S

Cluster-scale roof harvested rainwater systems

Cluster-scale roof harvested rainwater systems collect rainwater from multiple roofs and convey the water to one or more communal rainwater storage tanks.

- Small-scale examples of cluster-scale roof harvested rainwater systems already exist on Norfolk Island, where neighbouring businesses share roof and storage capacity and residents own neighbouring portions of land.
- One of the most promising cluster-scale roof harvested rainwater systems could utilise the unused roofs of Rawson Hall, council chambers and the Norfolk Island Liquor Bond Store (3006 m^2), with water storage infrastructure sited adjacent to the Bicentennial Oval.
- It would be possible to site 15 × 0.5 ML rainwater tanks adjacent to Bicentennial Oval with minimal disruption to existing use. This system would cost about $1.95 million and could supply 35 kL/day and 40 kL/day for 90 days in each of the driest 50% and 20% of years respectively.
- The major physical limitation to cluster-scale roof harvested rainwater systems in the Burnt Pine district is the limited availability of unused, level land suitable for large rainwater storage tanks. Underground concrete tanks are expensive, and excavations cannot be close to existing buildings.

An alternative method of capturing rainwater is using 'rainwater tank farms' – where a group of tanks stands alone and consequently the potential rainwater supply is limited by the area of the roof of the tanks.

- Rainwater tank farms are attractive in that they are standalone structures, highly modular and do not require much infrastructure, which means they can be situated at a wide range of level/slightly sloping locations and assembled relatively quickly and with minimal risk.
- A group of 9 × 0.5 ML tanks could supply 19 kL/day and 27.5 kL/day for 90 days in the driest 50% and 20% of years at a cost of about $1.05 million.
- Rainwater tank farms could be sited at multiple unutilised locations across the island, each servicing a different area, thus minimising the distance water needs to be carted.

Burnt Pine commercial area looking south. Bicentennial Oval is in the foreground behind which are Rawson Hall (green roof), council chambers (silver roof) and the Norfolk Island Liquor Bond Store (yellow roof).

Pumping groundwater from fractured unweathered basalt

Further development of groundwater to supply potable water during critical dry periods could target aquifers in the deeper fractured unweathered basalt, where seasonal and inter-annual reductions in groundwater levels exhibit smaller changes.

- Yields from bores in the deeper fractured rock system are low and are estimated to vary from 0.1 to 3.8 L/s (median of 0.7 L/s), though no proper pump tests have been conducted on the island. Furthermore, it is likely that bores sited in these fractured rocks may only be pumped for about an hour, several times a week.
- This means multiple bores would be required and they would need to be strategically operated to fill large storages in advance of a critical period. The bores would have limited capacity to be used reactively during a critical period.
- Pragmatically, to drill new bores would require a drill rig to be transported to Norfolk Island via a military C-17 aircraft (~$160,00 each way). The highly heterogeneous nature of the deep fractured volcanic rock would make it challenging to confidently site new bores capable of yielding sufficient quantities of water, and it is likely that multiple exploration holes would need to be drilled before a successful production bore is established.
- Areas considered likely to have potential for further development of groundwater within the deep fractured volcanic rocks/agglomerate material are near the break of slope on the southern side of Mount Pitt, where it is likely that recharge to bedrock aquifers is expected to be high. Other areas with potential include the upper reaches of Watermill Creek, Town Creek, Rocky Point and Mission Creek.
- It is estimated that the cost of drilling 14 exploratory holes, constructing and installing 6 new production bores, labour cost, accommodation and flights, and water tank storage would be about $2.5 million (including C-17 transport).

A cheaper and lower risk option than drilling new holes would be to utilise existing bores sited within the deeper fractured unweathered basalt on Norfolk Island.

- This would require long-term cooperation and agreement from owners, including permission to construct large water storage tanks and water treatment infrastructure and to permit access for water carters.
- Provided the bores were only used to fill large tanks for use during irregular critical dry periods, the use of deep groundwater bores for this purpose is unlikely to have a large impact on the groundwater balance, as the volume of water extracted would be small relative to current annual groundwater extraction (<5%).
- New or existing bores used for this purpose should be sited above sea level to avoid the risk of sea water intrusion.

Field chemistry on Norfolk Island.

Earth embankment gully dams

- Gully dams are usually constructed from earth, rock or concrete materials to form a barrier across a creek to store water in the reservoir created.
- The island has an abundance of good quality clay that could be used in construction of earth embankments. However, to avoid excessive leakage, reservoirs would need to be lined, adding considerable expense.

The existing Headstone Dam has a number of defects including water seeping through the embankment foundation.

- Its reservoir retains water, despite not being lined, because it is situated on acid peat soils, which unlike much of the surrounding landscape are only moderately permeable.
- The development of a new dam at Headstone offers the opportunity of ensuring sound foundations. However, if the reservoir were to extend beyond the extent of the acid peat within the drainage line, the base of the reservoir would need to be lined. This would require the acid peat material to be excavated because it would not be able to hold the weight of the water above the lining.
- Excavated acid peat on Norfolk Island would need to be carefully transported, treated and continually managed to avoid potential impacts on human and animal health, agriculture and the environment. The excavation of acid peat from Headstone would be a very costly and logistically complex operation.

A potential dam at Cockpit Falls within Cascade Reserve has several advantages over other potential dam sites investigated on Norfolk Island.

- These include the location of the site on Norfolk Island Council and Commonwealth land, greater certainty in yield estimation at Cockpit Falls because there is now a stream gauge at the site, the apparent absence of acid peats in the reservoir area and it has the largest catchment area on the island (6.3 km^2).
- An 8.3-m high earth embankment dam would provide a storage capacity of 28.1 ML. The reservoir, which would be entirely contained within the reserve, would occupy an area of 1.38 ha and would need to be lined. The whole project is estimated to cost $1.36 million. The reservoir could potentially supply 290 kL/day for 90 days in each of the driest 50% and 20% of years.
- However, Cascade Reserve is on the Norfolk Island Heritage Register and protected under the *Heritage Act 2002* (NI). It has national environmental significance and other values protected under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act).

Cascade Reserve and Cascade Creek. Looking downstream towards Cockpit Falls and a potential dam site.

Managed aquifer recharge

- Managed aquifer recharge is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit.
- The key requirements for managed aquifer recharge are the presence of a suitable aquifer with available storage capacity, water available for 'recharging' the aquifer and local demand for water.

Three types of managed aquifer recharge already in use on some properties on Norfolk Island are infiltration swales, infiltration ponds or basins, and recharge weirs (locally called leaky weirs).

- At the island scale, managed aquifer recharge in the form of swales, infiltration ponds and recharge weirs are likely to have a limited effect in mitigating falling groundwater levels because only small and irregular volumes of overland flow are generated in those positions of the landscape with sufficient groundwater storage capacity.
- Most overland flow on Norfolk Island is generated in areas where the watertable is close to the ground surface or in close proximity to impervious infrastructure. These locations are generally unsuitable for managed aquifer recharge because there is limited storage capacity in the unsaturated zone and they are generally situated at low locations in the landscape, long distances down gradient of where the majority of groundwater extraction occurs.
- Under a drier future climate, reductions in long-term rainfall are further amplified in reductions of surface runoff, resulting in smaller quantities of water available for managed aquifer recharge. Managed aquifer recharge may have local utility, however.
- Swales can capture and infiltrate locally produced runoff from impermeable surfaces such as roads, roofs and overflowing rainwater tanks. In addition to providing local benefits in terms of increasing soil water and localised recharge, they can arrest flow to protect against soil erosion, be used to convey water and treat the quality of water.
- Placing recharge weirs to capture runoff from impermeable surfaces (e.g. airport tarmac) and immediately upstream of acid peat soils may be one strategy for helping to keep these soils saturated under a drying climate.
- The relatively low cost of managed aquifer recharge (typically $1000 to $2000 per site), the need to site weirs close to the water source and the localised nature of the benefits, suggest these options are likely to be pursued by individual landholders where local circumstances warrant.
- Reductions in runoff from impervious surfaces arising from long-term reductions in rainfall will be considerably smaller than reductions in runoff from non-impervious surfaces.

An infiltration swale flooded via tank overflow during an intense rainfall event.

Managing vegetation for water security

- Prior to European settlement, Norfolk Island was dominated by subtropical rainforest and a native flora of which over 30% is endemic. About 15 plant species native to Norfolk Island are listed as threatened under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act).
- Today Norfolk Island has a flora of 523 vascular plant species of which 387 species have been introduced and are naturalised.
- Woody weeds, which were once grazed by cattle, started to proliferate across the island with the fencing of properties during the 1950s. Today they can be found in large patches across the island. Even the 'intact' forests are significantly invaded by a variety of non-native plant species.
- The most pervasive and troublesome woody weeds are Red Guava (*Psidium cattleianum*), African Olive (*Olea europaea cuspidata)* and the so-called Hawaiian Holly (*Schinus terebinthifolius*). Cotoneaster (*Cotoneaster frigidus*) and Umbrella Tree (*Schefflera actinophylla*) are among more recent arrivals, now starting to rapidly expand in extent.
- Parks Australia have an ongoing program of weed eradication and enrichment planting in the Norfolk Island National Park and Phillip Island.

Woody weed species use water deeper in the soil profile compared with short-lived and herbaceous species.

- Outside of Norfolk Island National Park and on slopes less than 35% (a recommended cut-off for the operation of machinery and minimising erosional processes on stable well-drained soils) it is estimated that there are about 167 ha of large contiguous patches of red guava, African Olive, Hawaiian Holly and Eucalypt plantation.
- It is estimated that removing woody weeds in these large contiguous patches and replacing them with appropriate pasture species would cost in the order of $2 million (including spreading grass seed and follow-up slashing in the first year) with an annual maintenance of about $125,000.

- Replacing woody weeds with suitable pasture species increased modelled groundwater recharge by the equivalent of 10 to 20% of the reduction in groundwater recharge between 1970 to 1994 and 1995 to 2019, or an estimated 20 to 30% of the imbalance between groundwater recharge and discharge. While this potential increase in groundwater recharge alone would not arrest further falls in groundwater levels it would slow further decline.

Weeds are a significant issue on Norfolk Island for a number of reasons in addition to any hydrological impacts that they have.

- Weeds threaten the broader environmental values of the island, notably by competing with native and endemic species, ornamentals, pastures and horticultural activities.
- Protection of native forests, and their flora and fauna, would be facilitated by reduced abundance of weeds on the island in general.
- Weed management does, however, come with an opportunity cost. Investment in weed control competes with other demands for limited resources.

Weed management can have other undesirable side effects.

- For example, mechanical treatment of weeds inevitably involves soil disturbance and use of herbicides may result in non-target impacts and some level of chemical contamination of the environment. Weed management can also spread pathogens, for example when machinery is used in weed control the spores of root rot fungi can be spread from one site to another.
- These opportunity costs and off-target effects must be considered when deciding whether to undertake a weed management program and which methods, tactics and strategies to apply when doing so, taking into consideration local experiences.

**Forested slopes of the National Park looking west from Cascade.
A – Mixed native hardwood and woody weeds; B – Mixed native hardwood;
C – Moist Palm/Tree Fern/mixed hardwood valley; D – Monoculture of Red Guava forest;
E – Mixed native hardwood and woody weeds; F – Mixed native hardwood;
G – Norfolk Island Pine and mixed hardwood.**

Desalination

- Desalination is the process of removing dissolved salts and minerals from saline water (usually seawater) using different forms of energy (e.g. diesel generator or solar panels). The primary purpose of desalination plants is to produce freshwater for drinking, domestic and industrial use and sometimes irrigation.

Cascade Pier was identified as a potentially suitable location for a containerised or skid-mounted reverse osmosis desalinisation system.

- The site offers a level surface for the plant, 3-phase power electrical connection and existing infrastructure upon which a submersible seawater pump could be mounted. A preliminary analysis indicates the seawater is likely to be of suitable quality for the feedwater intake system.
- Freshwater could be pumped up to storage tanks situated on land owned by the Commonwealth immediately adjacent to Youngs Road. An advantage of this arrangement is that water carters would not need to drive their vehicles down to Cascade Pier.
- A skid-mounted 2.3 m^3/hour reverse osmosis unit and associated infrastructure is estimated to cost $515,000 and could produce 45,830 L/day. The cost of energy would be about $300/day. A second plant would increase the cost by about 30% and could provide redundancy in case the first has mechanical problems.
- The primary uncertainty is the cost associated with discharging brine into the marine park environment. While in operation the 2.3 m^3/hour reverse osmosis unit discharges brine at a rate of 1.3 L/s. Elsewhere the impact on the marine environment of brine discharged from large deaslination plants has been found to be minimal, even resulting in a significant increase in fish abundance around the outlet while in operation.

- Desalination plants should run continuously for best efficiency and longevity. However, manufacturers report that the plants can be operated for a reduced period of time each day and that it is possible to only operate a plant for several months per year. However, if the plant ceases operation for an extended period of time the membranes would need to be sealed with protection fluid to prevent bacterial contamination or replaced before it is used next.

With the exception of transporting water to Norfolk Island by ship, desalination is the only option that is capable of supplying large quantities of potable water with 100% reliability.

Cascade Pier was the location of a temporary desalination plant operated by the Australian Defence Force in February 2020.

Summary of options

A range of options were considered for improving Norfolk Island's resilience during critical dry periods.

- Water related infrastructure options that lend themselves to being centrally operated and managed are compared in Table 1 under a scenario where the infrastructure was operated for 90 days/year for the 'driest' 25 of the last 50 years.
- Levelised costs are often used by economists to compare different options. In Table 1 levelised costs are expressed as the present value of the capital and operating cost of an option divided by the amount of water the option can supply or yield at 100% reliability.

Options such as vegetation management and increasing household rainwater tank capacity rely heavily on the engagement and consent of residents and businesses, and consequently are unlikely to be implemented as reliabily as 'centralised' infrastructure options.

- Options of managed aquifer recharge and vegetation management may result in small increases in groundwater recharge, and may partially offset further reductions in groundwater levels, but these strategies would not guarantee a potable supply of groundwater during critical dry periods.
- Increasing household rainwater tank capacity across Norfolk Island is likely to be expensive relative to centralised options for meeting irregular short-term demand (i.e. several months) for water during extended dry periods.
- Options such as managed aquifer recharge, vegetation management and community education are considered 'no regret options', that is they are likely to generate a net social, ecological or economic benefit irrespective of whether Norfolk Island's rainfall continues to decline into the future.
- Although some options may cost more and/or yield less, there may be other social, cultural, political and/or ecological considerations that make options attractive.
- Approximately 50% of the islands population is serviced by a reticulated sewerage system known as the 'Water assurance scheme'. Options for managing this effluent were considered in a parallel study.

It is likely that a robust emergency water supply strategy would encompass multiple options.

- The development of an emergency water supply strategy or risk management framework for managing water security on Norfolk Island was not within the scope of the Assessment. However, the information and tools generated by the Assessment would assist in preparation of such frameworks.
- In developing a risk management framework and/or an emergency water supply strategy the likelihood and consequences of a range of possible outcomes should be considered. Possible outcomes should include a drier future climate and that fewer residents may have access to potable groundwater to replenish their rainwater tank supplies.
- Water (and energy) related infrastructure expenditure needs to be guided by an understanding of both the projected supply of water and projected demand for water into the future.

Table 1 Comparative performance of alternative 'centralised' infrastructure options. Yield estimates assume the infrastructure is required to be operated for 90 days a year, for the 'driest' 25 of the last 50 years. Levelised cost are based on a 7% discount rate the service life of infrastructure.

OPTION	YIELD (L/day)	CAPITAL COST ($)	LEVELISED COST ($/year per ML/year)
Desalination	45,853	515,000	49,300
Cockpit Falls dam	317,000	1,360,000	9,270
Cluster-scale roof harvested rainwater system	50,000	1,950,000	129,760 90,830†
Rainwater tank farm	18,900	1,050,000	120,680
Use of existing deep groundwater bores x6	18,670	515,000	77,930
New deep groundwater bores x6	18,670	2,500,000	317,950

† Including the capture of rainwater that falls on roof of the water storage tanks

Streamflow measurement and rainfall chemistry collection instrumentation above Cockpit Falls on Cascade Creek.

- Options may be staged and/or simultaneously implemented over short, medium and long-term timeframes, and may encompass a broader range of options than discussed here, including less costly and no regret options such as research and monitoring, community education and raising awareness (e.g. encouraging the connection of existing unutilised roofs to existing rainwater tanks), water planning and strategic purchases or rezoning of land.
- The most effective suite of risk mitigation options will depend upon the community's appetite for risk and available resources to construct and maintain infrastructure.

If you don't measure it, you can't manage it.

- The lack of ongoing baseline monitoring and robust data archival are a serious limitation to designing systems to enable Norfolk Island to become sustainable in potable and industrial water supply.
- The current lack of data limits water-related management, scientific study, policy and legalisation development, and community education. It is a major source of uncertainty in the development of a risk management framework and emergency water supply strategy, and in understanding how biophysical systems on Norfolk Island may respond to change.
- The extremely high heterogeneity in aquifers and groundwater responses to rainfall and groundwater extraction makes it challenging to understand the groundwater systems without access to a large number of bores and wells distributed across the entire island. This would require on-going cooperation from landholders.

Units and shortened forms

UNIT	DESCRIPTION
GL	gigalitre
ha	hectare
kL	kilolitre
km	kilometre
L	litre
m	metre
mAHD	metres Australian Height Datum
ML	megalitre
mm	millimetre
RSWL	reduced standing water level
s	second

Unit conversions

UNIT
1 gallon = 4.56 litres
1 foot = 0.3048 metres
1 kilolitre (kL) = 1000 litres
1 megalitre (ML) = 1,000,000 litres
All costs are reported as late 2019.

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