RESEARCH IMPACT EVALUATION

Natural Hazards and Infrastructure Initiative Case Study

March 2019

Contents

List of figures

List of tables

List of boxes

1. Executive summary

The CSIRO Data61 Natural Hazards and Infrastructure (D61-NHI) group are driving a nation-wide all-hazards planning and adaptation initiative which brings together researchers, emergency services, government, and the community to deliver innovative digital solutions to build a more resilient and sustainable society, capable of adapting to the ever growing threats of natural disasters and associated risks.

This case study focuses on Bushfires, Flood Adaptation and Evacuation Modelling capabilities, their underpinning infrastructure, and the social media analysis platform developed by the D61-NHI team. The initiative specializes in modelling and analysis of natural hazards for disaster risk assessment, mitigation, and preparedness, risk resilience, urban planning, adaptation and development of policies and plans. In particular, the group specialises in modelling bushfires, floods, landslides, mudflows, evacuation plans, geospatial data integration, and processing applications.

The challenge

Natural and man-made disasters constitute a major threat to the economy, environment, and communities in Australia and globally. CSIRO's research aims at improving situational awareness and building decisional support for strategic, tactical, and real-time planning and post-recovery efforts. These decisions involve multiple complex infrastructures, multiple agencies, and multiple stakeholders and focus on building environmental and societal resilience.

The NHI's motivation to provide solutions in the areas described in this case study are:

- Australia has a very large coastline with about 85% of its population living along this coastline
- Australia is very bushfire prone and this is affecting more of its population due to the peri-urban sprawl
- Expected increases in both the severity and frequency of both floods and bushfires due to climate change
- Australians like to live among nature and this creates its own challenges when it comes to evacuation during a natural hazard event.

Challenges faced by researchers in addressing these problems include:

- Lack of good quality nationally consistent data and mapping
- Spatial and temporal challenges in modelling and analysis of hazard events, especially in an urban context
- Lack of understanding of climate change and its impacts especially in the context of local infrastructure planning
- Inability to synthesize disparate historical datasets to then produce an evidence base for future infrastructure investment decisions
- Inability to reconcile with apparent conflicts in planning decisions especially in larger complex cities
- The unavailability of digital tools that incorporate the latest knowledge in natural hazard science impairing critical decision making in the event of a natural disaster.

The response

The D61-NHI has worked to improve disaster preparedness through the development of innovative and integrated computer-aided modelling, data analytics and visualization tools for natural disaster management. These digital technologies will also serve as educational platforms for the community at large. The following technologies demonstrate the group's specific response to this national challenge:

Bushfires - Development of flexible and globally scalable bushfire modelling tools Spark and Amicus – vehicles that build upon decades of bushfire research at CSIRO.

Flood adaptation - Creation of an integrated shallow water-based framework called Swift for the study of floods, particularly in an urban context with the inclusion of underground drainage infrastructure in the models.

***Evacuation* modelling** - Development of an intelligent system for integrated evacuation planning. The evacuation tool provides information on when to evacuate, issue messages, and how to evacuate first. For evacuation modelling MATSim, an urban transportation system has been integrated into CSIRO's modelling framework for planning and advanced operational emergency management.

Geostack - The team is also developing a general purpose geospatial analytics infrastructure called Geostack that underpins the different digital tools developed by D61-NHI. It is an open source infrastructure that can be used for a range of applications.

Emergency Situation Awareness platform (ESA) - CSIRO's ESA, an award-winning technology, collects, filters and analyses Twitter streams across Australia and New Zealand in real-time, converting the deluge of data into situation awareness information and enabling effective alerting for unexpected incidents with results accessible via an interactive website for crisis coordinators and the general public.

The flexibility, scalability, transparency, and capabilities to incorporate the impact of climate change in these digital tools provide significant competitive advantage in comparison to the other solutions available in Australia and globally.

The impacts

a) **Educative benefits:** D61-NHI's work has led to significant advantage in terms of **new knowledge generation and transfer** to governments and the community that has originated from D61-NHI's work over several decades. A direct evaluation of the educative benefits to Australian society is difficult. However, the willingness to pay by outside organisations for CSIRO's diagnostic tools – reflected in purchases to date – can provide at least a lower bound estimate.

b) **Early commercial uptake:** Increase in government and industry willingness to pay for newly developed digital tools to replace their traditional assessment methods as they transition to address new challenges such as better disaster risk mitigation and management, the future effects of climate change on their policies and procedures in the natural disaster management space. Against CSIRO's initial investment of 1.1 million in 2017, the project has attracted overall external funding of ~6 million for this program over past 3 years.

c) **Creation of new options:** D61-NHI work is generating new options for the future through enhanced capabilities, improved knowledge, better research infrastructure and clearer understanding in natural hazard space for future research. The capabilities help to inform decisions between those options. This is demonstrated through collaboration with communities and allied industries e.g. banks, infrastructural and involvement in shaping their policies and procedures.

d) **Cost-benefit analysis**: Digital tools and technologies being developed by D61-NHI team are an ongoing activity. Although the work builds on the knowledge from decades of work conducted by CSIRO especially in the bushfire domain, the capabilities and digital tools discussed in this case-study have been developed only in the last 3-5 years Despite the current level of commercial interest, the developed tools and technologies are considered to be in a very preliminary stage of commercial uptake and hence a robust cost-benefit analysis is not possible at this stage. It is recommended that the case-study be revisited in 3-5 years to perform a complete CBA supported by longer-term time frame facts and figures.

A suggestive potential benefits quantification analysis has been included in Appendix B to give a high-level estimation of benefits based on the assumption that the developed tools and technologies are able to prove their effectiveness for the intended purpose in the upcoming years. This section has been included for INDICATIVE purposes ONLY.

Impact pathway

INPUTS

INVESTMENT

- CSIRO BU funding and in-kind support
- External financial Investment by Industry/ Government
- Access to high calibre, multidisciplinary CSIRO, university and global capabilities
- Access to decades old fundamental research and capabilities at CSIRO
- Staff (researchers etc.)
- Industry, government and university partnerships
- Background IP (Geostack, bushfire and flood modelling digital tools, ESA, Evacuation)
- Inputs from public and end users
- High performance computing resources provided by CSIRO
- Commercial Infrastructure: Amazon Web Services (AWS) cloud nodes for commercial tasks

CSIRO D61-NHI team and BD, CSIRO other BUs, Government and industry partners, universities, Science Council

ACTIVITIES

- **Fundamental Research** in the areas of building and improving supporting infrastructure Geostack, Bushfires, Floods and Evacuation Modelling digital tools, ESA platform
- Development and continuous improvement of digital tools and technologies in natural hazard space.

  Bushfires: Spark and Amicus
  Floods: Swift and C-Fast
  Geostack: Underpinning geospatial infrastructure
  Emergency Situation Awareness Platform

- Develop relationships and perform collaboration activities with Government, Industry, International Agencies and Academia for testing, implementation and continuous improvement of the developed tools.
- Recruit PhDs, Postdocs and technical staff for performing work

CSIRO D61-NHI team and BD, CSIRO other BUs, Government and industry partners, universities, Science Council

OUTPUTS

- Digital tools and technologies for – Bushfires, floods and evacuation modelling, underpinning infrastructure and ESA
- Access to highly competitive digital tools and technologies for natural hazard risk assessment, planning and management.
- Access to world class knowledge base in the domain of natural hazard risk assessment, planning and management through IPs, Publications, Awards and Patents
- Engagements (domestic and international) with industry, government bodies and universities resulting in building capabilities, generating funding and helping with uptake and adoption of the developed tools
- Workshops and trainings to build capability and for continuous improvement of the developed tools and technologies

CSIRO D61-NHI team and BD, CSIRO other BUs, patents and comms staff, collaborators: Government and industry

OUTCOMES

- New science that underpins externally funded projects.
- Positioning of CSIRO as an international leader/ influencer in the domain of natural hazard risk assessment, planning, management and adaptation space.
- New partnerships with national and international industries, government and research bodies.
- Domestic and international uptake of the digital tools and technologies
- New commercial products or services to provide revenue, equity for CSIRO
- Better forecasting and management of Bushfires and flood events across Australia and globally (not focus of this case-study).
- Availability of platforms to facilitate community engagement and awareness in the event of natural hazards
- Collaboration with allied industries like banks, infrastructural managers etc to assist with improvement of tools (to incorporate uncertainty, climate change etc) for devising new decisional support systems, policies and programs

CSIRO D61-NHI team and BD, CSIRO other BUs, commercialization and patent staff, distributors and retailers, sales and marketing teams, general public, collaborators: Government (all 3 levels), and industry collaborators, allied industries, universities

IMPACT

ECONOMIC IMPACT

- Lower the economic damages to property and infrastructure from bushfire, floods and other related hazards. Better preparedness. Smarter allocation of available resources.
- Develop smarter new resilient infrastructure

ENVIRONMENTAL IMPACT

- Reduce ecological and habitat impacts from bushfires, floods and other related hazards.
- Contribute to the development of green and sustainable infrastructure

SOCIAL IMPACT

- Reduce the risk to life, personal property and memorabilia. Enhanced community confidence and resilience.

Consumers, Government (all 3 levels), Collaborators, Emergency Managers, Allied Industries, General Public, Environmental Groups

Years 2017-2019 (Activities)

Years 2017-2018 to 2028-2029 and onwards (Outputs, Outcomes, Impact)

2. Purpose of the case study and audience

Australia is frequently affected by the high occurrence and widespread scale of bushfires, heatwaves, and floods which cause considerable damage and danger to societies, infrastructure, and the environment. Hundreds of lives have been lost while costing the economy billions of dollars in infrastructure replacement and environmental restoration costs[1].

The purpose of this case study is to discuss the spectrum of economic, environmental and social benefits arising for a range of stakeholders from the bushfires, flood adaptation and evacuation modelling work conducted by CSIRO's Data61 Natural Hazard & Infrastructure (D61-NHI) team. It will assess the key outcomes and impacts arising from R&D outputs, incorporation of the effects of climate change in digital tools, the application of the developed technologies, and their prospective commercialisation for improved emergency response management, strategy planning, and building sustainability and resilience against natural hazards. The analysis provides an estimate of the benefit-cost ratio and assesses the economic viability of the investment in D61-NHI projects through examining the quantitative and qualitative impacts of the research. The case study also discusses the key limitations associated with the work.

This report can be read as a stand-alone item or alongside other D61-NHI evaluations to substantiate the impact and value of CSIRO's activities against funds and resources invested in these projects. The information is provided for accountability, communication, engagement, continuous improvement and commercialisation (where relevant) purposes. The intended audience includes Business Unit Review Panels, government at all three levels, state emergency management departments in Australia, fire agencies, rural fire authorities, land management agencies with responsibility of managing fire on public land, coastal councils, emergency managers and infrastructural planning authorities, project collaborators, Commonwealth Departments, allied industries like insurance/ asset management/ banks, CSIRO, universities and the general public.

3. Background

Bushfires and floods are two types of natural disasters which have significant and long-lasting social, environmental, and economic impacts both in Australia and across the globe. As Australia is one of the most fire-prone countries, bushfires are characterised by their widespread scale, and high frequency, resulting in significant damage and danger to societies, infrastructure, and the environment. The 'disaster-level' bushfires (with total insurance cost > $10 million ONLY) cost Australia an average of A$77 million per year. 173 people lost their lives during the Black Saturday Bushfires in 2009. These fires also injured hundreds, burnt 4,500 km^2 land, and destroyed 2,000 homes[2], underscoring the magnitude of disruption bushfires can cause. This event alone cost the economy around A$4.4 billion according to the Bushfires Royal Commission[3]. The study also indicates that 80% of the people impacted by the calamity were underinsured. The current policies for bushfire mitigation in Australia are focussed on suppression activities, prevention of fire ignition, and improving disaster management[2].

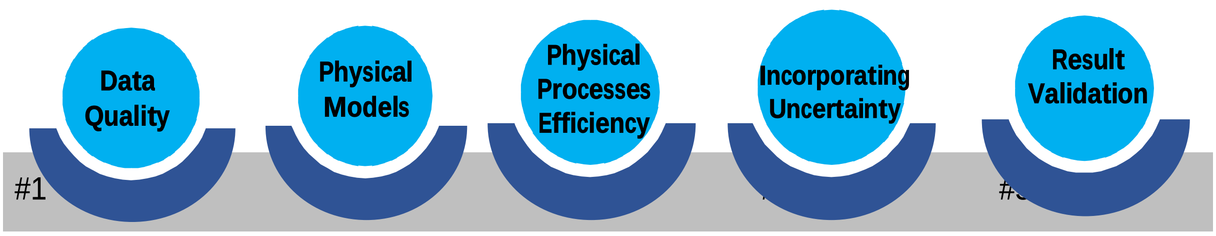
With 85% of the Australian cities being coastal, Australia is also highly susceptible to the threat of flood events. The effects of flooding events are set to get substantially larger in the next decades, owing to global climate change, which is expected to exacerbate and accelerate their occurrence, presenting an area of significant global concern. Flood costs have reached 29% of Australia's natural disaster data damage, costing around $314 million each year, which makes it the most expensive natural disaster in the country[2]. The losses are associated with human life, crops, rail lines, livestock, roads, and property.

Given the scale and increased frequency of such disasters in Australia and globally, with complexity and severity being heightened by climate change, there is a very strong push and need to improve the understanding of natural hazards behaviour, and their interaction with the ecosystem, to assist in developing improved emergency management systems for better prevention, preparedness, and management. With growing application of computational models and data analytics to deploy solutions across all the industries, their utilisation to have a better grip on bushfires and floods calls for creation of scientifically sound, time-sensitive, cost-effective, and evidence-based methods to develop (a) risk prevention practices and policies; (b) decision support systems; (c) improved understanding of natural hazards like fire and flood behaviours for prevention and better preparedness; (d) develop reliable evacuation methods; and (e) develop reliable awareness methods. The digital tools have the capability of combining scientific capabilities with public inputs to address uncertainties and complexities associated with multi-dimensional natural hazard phenomena.

CSIRO's Data61 Natural Hazards and Infrastructure (D61-NHI) team is an innovation hub with digital innovation, software and data integration at the heart of its mission to address natural disaster challenges. D61-NHI, in collaboration with the fire science team in the Land & Water Business Unit in CSIRO, has been at the forefront of fire science research in Australia and has been undertaking fundamental science and applications work in bushfire domain for decades. The team has been working on expanding capabilities in the areas of flood adaptation and evacuation improvement in the recent past to build safeguards for improved disaster response. The team is also working to further improve the capabilities and enhance application of the underpinning infrastructure – Geostack, a framework that supports the different digital tools. D61-NHI has developed Emergency Situation Awareness (ESA), a technology to perform social media analysis for all hazards. The focus of the team is to utilise the potential of computational simulation and data analytics combined with wealth of fundamental knowledge and multidisciplinary talents to build highly differentiated decision support systems that are central to understanding and addressing these natural hazards and their interaction with cities, the landscape, and infrastructure. The case study also provides details on evacuation modelling work done by the D61-NHI team, which underlines a crucial aspect of disaster management, and is generally the first prevention measure to ensure the safety of the community. This multi-dimensional utilisation of data science helps improving disaster preparedness and provides educational platforms to serve the community at large and build their confidence.

Scientific challenges

Key scientific challenges and capability gaps associated with the existing digital technologies currently being used in Australia and globally in the space of natural hazard understanding, prediction and management include:



i) ***Data Quality:*** Availability of quality of input data is critical to the success of any data analysis. This remains a challenge in the case of natural hazards due to heterogeneous data sources.

ii) ***Improving physical models:*** Modelling physical processes for natural hazards remains a hurdle due to their complexity and various associated unknowns. Application, veracity, and scaling models to the often extreme conditions presents a significant opportunity. Applying model-data fusion techniques to improve the spatio-temporal resolution of natural hazards-related modelling is a key step towards enhancing the applicability of physical models in real world scenarios.

iii) ***Representing the dominant physical processes in a computationally efficient manner:*** The intractability of the time involved in computing of the natural hazard processes, limited application of the developed models, and the challenge of its assimilation with latest computer hardware technology requires further work. In this context applying a combination of data driven (Machine Learning/Deep Learning) and physical modelling-based approaches provides another way forward to deal with the challenges of applying modelling for better than real time applications.

iv) ***Incorporating uncertainty:*** Capability to incorporate uncertainty associated with natural hazard input data (much of which is based on probabilistic distributions) and visualizing it in an easily understandable way presents a scientific opportunity and challenge.

v) ***Validation of results*****:** The validation of natural hazard models against real-world conditions remains a challenge due to the difficulties of accurately determining the temporal characteristics of floods or fire. Integration of remote sensing (long overpass time) and IR line scans (infrequent) remain ineffective in the current models. The use of IoT based sensors for validation and/or calibration of natural hazard models has so far been very limited in its application especially by way of use of edge computing based video analytics.

D61-NHI team has conducted some groundbreaking work and developed digital tools for natural hazard disaster management in collaboration with different partners that include researchers, emergency services, government, and the community while addressing many of the key challenges identified above. The tools developed incorporate allied scientific impact areas like the integration of downscaled climate models with bushfire and flood models, evacuation modelling while utilising more sophisticated underpinning infrastructure and social media platforms to develop decision support systems, and surrogate models to build efficient simulations for improved disaster preparedness and awareness.

Bushfires

In the domain of bushfires, the team has built fire propagation and data assimilation techniques into the predictive computational simulation system Spark and software Amicus, vehicles that help implementation of decades of bushfire knowledge wealth at CSIRO. The tools combine quantitative and qualitative information based on scientific principles and personal experience for improved fire prediction under a range of weather, fuel, and topographical conditions. These capabilities are being accessed and assessed by trained fire behaviour analysts and emergency management services for the timely determination of the potential threats and impacts of a fire, and to assist with sound fire-management decision-making. The work has led to the development and testing of new fire propagation models, fire propagation behaviour with terrain, fire interaction with local winds, integration of remote sensing data in the simulations, and validation of fire risk reduction strategies. The work also clarifies the role of fire caused by electrical faults. Spark has recently been used to perform hundreds of thousands to millions of simulations to assess the risk of bushfires under various environmental conditions to infrastructure such as powerlines as well as critical rail infrastructure in New South Wales (NSW).

Floods

In the flood adaptation domain, the D61-NHI team has developed the Shallow Water Integrated Flood Tool (*Swift*) primarily for flood risk assessment and evaluation of flood adaptation strategies in a city context. Swift is shallow water based integrated flood tool for end to end processing, simulation, and analysis, particularly for urban flood inundation and adaptation with the integration of underground infrastructure in the model. The tool incorporates the effects of saltwater inundation and other factors on freshwater ecosystems; and has been used to evaluate future management options in a flood context. This tool has led to the successful development of the first tidally driven hydrodynamic model of the Kakadu region which provides critical insights into the potential loss of freshwater floodplains in the region. Recently Swift has been integrated with a range of modular adaption options so that it can be used to evaluate the effectiveness of various soft and hard adaptation measures, such as the inclusion of sea walls, upgrades to drainage infrastructure, addition of flood retention/detention systems and placement of man-made coastal wetland ecosystems to prevent current and future (climate change related) flooding. The newly developed tool is called City Flood Adaptation Solutions Tool (C-Fast) and is currently being deployed on a large study evaluating inundation effects due to coastal and catchment flooding in the Port Phillip Bay region in Victoria, Australia.

Evacuation modelling

In the evacuation modelling space, Data61 scientists are designing evacuation plans while incorporating multiple complex factors to limit congestion and ensure all evacuees reach safety in time. This highlights a crucial area to enhance safety that assists local emergency services make evidenced-based decisions in their infrastructure planning, as well as in emergency situations.

Geostack

The D61-NHI team has developed a general purpose geospatial analytics infrastructure called Geostack that underpins the different digital tools developed by the team. It incorporates the entire set of processing modules, dynamic models, and data interfaces. The dynamic solver (for e.g. Spark and Swift) modules consist of physical models tailored to natural hazards as well as sub-solvers for modelling additional physical aspects. It is an open source infrastructure that can be used for a range of applications. This system provides a platform that allows modules to be seamlessly connected into a processing pipeline. D61-NHI is currently working on Geostack's transition from its original modular workflow composer and execution management system called Workspace to API for making it an open-source component and improving the flexibility of the infrastructure for the wider application.

Emergency Situation Awareness (ESA) platform

D61-NHI's ESA is an award winning technology that uses natural language processing and data mining techniques to provide early detection of events and to provide enhanced situational awareness information as a disaster unfolds to restore safety and essential services. It has notable features like burst detection, real-time alert monitoring, topic clustering, and tweet search (among others) to allow for enhanced situation awareness for emergency managers to restore safety and essential services. The technology also has application in non-emergency services through developing alerts on any unusually high frequency words.

CSIRO's work in all of the domains discussed above is gaining traction from domestic as well as international organisations working in the area of emergency management, as well as local councils, and state government agencies (such as road authorities) with the goals of assessment, adoption, and collaboration. Owing to the ever-evolving global needs, growing concerns due to the heightened effects of climate change, potential unsustainable effects on the economy, society and environment and paucity of research and data around relative costs and benefits of alternative approaches for disaster management, there is a critical need as well as considerable governmental emphasis to drive development of innovative solutions and capabilities in this space. This impact evaluation case study provides an overview of how inputs into the D61-NHI team's research are used to conduct activities and deliver outputs, which in turn lead to outcomes for stakeholders and beneficial impacts for Australia. However, for this case study, it should be noted that the impact evaluation is going to be an evolving process over time with the continuous improvement of digital tools and changing trends and challenges in the technology and natural hazard space.

This impact case study uses the evaluation framework outlined in the CSIRO Impact Evaluation Guide. The results of applying that framework to the D61-NHI team's bushfire, flooding, evacuation modelling, Geostack infrastructure, and ESA work are summarised below in Figure 1.

4. Impact pathway

INPUTS ► ACTIVITIES ► OUTPUTS ► OUTCOMES ► IMPACT

INPUTS

INVESTMENT

- CSIRO BU funding and in-kind support
- External financial Investment by Industry/ Government
- Access to high calibre, multidisciplinary CSIRO, university and global capabilities
- Access to decades old fundamental research and capabilities at CSIRO
- Staff (researchers etc.)
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    Bushfires: Spark and Amicus
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- Digital tools and technologies for – Bushfires, floods and evacuation modelling, underpinning infrastructure and ESA
- Access to highly competitive digital tools and technologies for natural hazard risk assessment, planning and management.
- Access to world class knowledge base in the domain of natural hazard risk assessment, planning and management through IPs, Publications, Awards and Patents
- Engagements (domestic and international) with industry, government bodies and universities resulting in building capabilities, generating funding and helping with uptake and adoption of the developed tools
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CSIRO D61-NHI team and BD, CSIRO other BUs, patents and comms staff, collaborators: Government and industry

OUTCOMES

- New science that underpins externally funded projects.
- Positioning of CSIRO as an international leader/ influencer in the domain of natural hazard risk assessment, planning, management and adaptation space.
- New partnerships with national and international industries, government and research bodies.
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- New commercial products or services to provide revenue, equity for CSIRO
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- Availability of platforms to facilitate community engagement and awareness in the event of natural hazards
- Collaboration with allied industries like banks, infrastructural managers etc to assist with improvement of tools (to incorporate uncertainty, climate change etc) for devising new decisional support systems, policies and programs

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IMPACT

ECONOMIC IMPACT

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ENVIRONMENTAL IMPACT

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SOCIAL IMPACT

- Reduce the risk to life, personal property and memorabilia. Enhanced community confidence and resilience.

Consumers, Government (all 3 levels), Collaborators, Emergency Managers, Allied Industries, General Public, Environmental Groups

Years 2017-2019 (Activities)

Years 2017-2018 to 2028-2029 and onwards (Outputs, Outcomes, Impact)

Figure 1: Impact pathway for D61-NHI Initiative case study

Project inputs

Background IP

Geostack: Geospatial Analytics and Modelling Infrastructure

Spark: Bushfire/Wildfire Spread Modelling and Analytics Toolkit (https://research.csiro.au/spark)

Amicus: Local bushfire/wildfire danger related calculator (https://research.csiro.au/amicus)

ESA: Social media based emergency situational awareness tool (https://esa.csiro.au/aus/index.html)

Swift/C-Fast: Flood and Flood Adaptation Modelling and Analytics Toolkit (https://research.csiro.au/swift)

Evacuation Modelling capability developed using the open source and generic MATSim (https://matsim.org/) multi agent transport modelling toolkit.

Investment

Table **1:** Cash and in-kind support for D61-NHI Program**

	FY17	FY18	FY19
External	376,443	2,713,033	2,940,944
Appropriation	1,101,319	-	- 103,766
Total cost	1,477,762	2,128,249	2,837,178
External	25%	127%	104%
Appropriation	75%	0%	-4%

**Data from D61-NHI Team

The Total Cost and the External Earnings for FY 18 and 19 have minimal appropriation from CSIRO which means that this activity has become self-sustaining (i.e. a fully externally funded project). CSIRO being a not for profit organisation if external funding for any project is exceeded, CSIRO's appropriation is taken out and ploughed back into other projects within the organization, which is the case in this program as well. For D61-NHI projects, the total cost numbers also show that the project has increased in size from around 1.5 million per year in FY17 to almost 3 million per year this FY18 thereby indicating significant external collaboration interest.

Resources

Core Data61 members

Dr Mahesh Prakash, Senior Principal Research Scientist, Senior Project Manager and Group Leader
Dr Vincent Lemiale, Senior Research Scientist, Project Manager and Team Leader
Dr Simon Dunstall, Program Director, Decision Sciences Program
Dr James Hilton, Principal Research Scientist and Project Manager
Dr Leorey Marquez, Senior Research Scientist
Dr Raymond Cohen, Senior Research Scientist and Project Manager
Mr William Swedosh, Project Officer
Dr Nikhil Garg, Post-Doctoral Research Fellow
Dr Yang Chen, Post-Doctoral Research Fellow
Mr Rajesh Subramanian, Software Engineer

In-deployed from CSIRO Land & Water

Dr Andrew Sullivan, Principal Research Scientist, Project Manager and Team Leader

Dr Miguel Gomez Da Cruz, Principal Research Scientist and Project Manager
Dr Matthew Plucinski, Senior Research Scientist
Mr Richard Hurley, Experimental Scientist

In-deployed from CSIRO Oceans & Atmospheres

Dr Kathleen McInnes, Senior Principal Research Scientist, Project Manager and Group Leader
Dr Marcus Thatcher, Principal Research Scientist and Team Leader
Dr Julian O'Grady, Senior Research Scientist
Dr Ron Hoeke, Principal Research Scientist

In addition to the above resources, the team consists of eight contributed research professionals (CRPs) amounting to around 4 EFT from RMIT University, Swinburne University, Monash University and University of New South Wales. The team also has eight PhD students working on various aspects of research through these universities.

For further information visit: https://research.csiro.au/nhi

Research infrastructure

The NHI team heavily relies on high performance computing resources provided by CSIRO, especially the Bracewell GPU Accelerator cluster with the following specifications:

- *Dual Xeon 14-core E5-2690 v4 Compute Nodes (i.e. a total of 3,192 compute cores) with 256 GB of RAM, 1TB local SSD, and FDR10 InfiniBand interconnect*
- *456 NVidia Tesla P100 (SXM2)*

The team also uses high end desktops and laptops for testing the implementation of algorithms as well as for visualisation requirements. Discussions are also ongoing with the National Computational Infrastructure (NCI) based in Canberra to evaluate the possibility of utilising their GPU nodes for some computations.

Commercial Infrastructure

The team uses the Amazon Web Services (AWS) cloud nodes for commercial tasks on a user pay basis. This method of delivering services to clients is expected to become more common moving forward service offering is migrated on the cloud and on the web using a pay per use model.

Activities

CSIRO has been on the forefront of bushfire research in Australia from decades and this work is used by several domestic as well as global organisations. The NHI team has also been conducting substantial work in the domains of flood adaptation, evacuation modelling, capability enhancement of underpinning infrastructure Geostack and social media analysis platform ESA for the last 3-4 years which has very quickly developed into a significant activity within Data61. The work has been focussed on improving fundamental scientific understanding of multi-faceted aspects of natural hazard events and capability building of digital technologies while addressing the current gaps to build robust digital tools and technologies.

Fundamental Research & Technology development and continuous improvement of digital tools

Bushfire

Digital Tools: Spark and Amicus

Fire and environmental impacts: Understanding fundamental systems in the landscape, including vegetation response, biodiversity, air quality, carbon, and water.

Real-time response during fire: Determining likely spread and behaviour of fire, identification of most effective and efficient deployment of suppression relative threat of electricity distribution system fire ignitions and other sources of bushfire.

Understanding bushfire behaviour essential for global community, especially countries that are prone to bushfire/wildfire activity.

Floods

Digital Tools: Swift and C-Fast

Working with variety of local councils (Port Phillip, Greater Geelong, Bunbury) to explore potential combined effects of sea-level rise, extreme rainfall and storm surges while incorporating variabilities caused by climate change.

Development of computational models that make use of big data (on bathometry, terrain, climate, meteorology, structures) for city planning, mitigation design and community engagement purposes.

Onshore and offshore mitigations such as urban pipe networks, seawalls, retention/detention systems and wetland ecosystems

Evacuation

Building a Decision Support System (DSS) for evacuation modelling, which includes

Planning:

- Identifying current weak points in the infrastructure
- Resource allocation
- Testing current policies and strategies
- Educating society (risk awareness)

Response:

- When to evacuate
- When to issue messages
- Which areas should be evacuated first

Geostack

Infrastructure: Geostack

Open Source Infrastructure: Capabilities to be flexibly used as open source infrastructure for a range of geospatial applications.

Cumulates national scale information, attaches uncertainty metrics and provides output on quantifiable indicators

ESA Platform

Social Media Analysis Platform: ESA

Continuous improvement to collect, filter and analyse tweets through working on:

Burst Detection, Real-time alert monitoring, Topic clustering, Tweet Search, Alert Search, Past Event Replay, Incident Monitoring, Text Classifiers, Location Mapping

Core areas of focus for D61-NHI research activities for addressing capability gaps

The research team is creating innovative digital solutions to manage the threats of natural disasters and associated risks through working on the following main verticals of capability building:

i) **Physical/biological systems and data:** Building digital tools that allow modelling, analysis and prediction of natural hazards based on the understanding of physical systems through the interpretation and integration of data of various forms including that produced from sensors (ground, airborne and satellite based) and through physics and statistical models.

ii) **Analysing, representing and modelling data:** Developing model data fusion techniques to (a) provide real time predictions of natural hazard events especially fires and floods in an urban and peri-urban context with flexibility around usage of models for different geographical areas; (b) inform infrastructure planning decisions to mitigate the impact of current and future hazards;(c) provide an understanding of the spatio-temporal risk for mitigation as well as risk pricing; and (d) incorporating variabilities and concerns caused by climate change.

iii) **Quantification of and reasoning with risk and uncertainty:** Digital tools capable of addressing: (a) the uncertainty associated with input data and how it impacts prediction confidence; and (b) its representation and visualisation in the context of ensemble based outputs emanating from natural hazard simulations.

iv) **Shaping data-driven society:** Effectively communicate the outcomes of the applied research to the community especially the underlying uncertainty. Providing ESA platform for capacitating social media analysis of natural hazards. CSIRO's work also includes elements of citizen science led voluntary initiatives focussed on collecting data for validation of our models. The goal is to educate the community while engaging them to collect data to be inputted into models and analytics for validation and calibration purposes. The key result is shaping a data-driven society that understands the value of evidence (data) based approaches to resolve key societal

Key research collaborations

Data61

- Decision Sciences Optimisation and Risk Analytics Group (data analytics and optimisation)
- CMS CSEV Team (software engineering and visualization) Engineering and Design through the Terria Team (mapping, visualisation)
- S&CS Program Urban Monitor Team (remote sensing, GIS)
- Decision Sciences Knowledge Discovery and Management Group (NLP and software engineering support)

Internal

- CSIRO Global
- CSIRO Chile

Land & Water

- Fire Science Team led by Dr Andrew Sullivan
- Environmental Informatics Group led by David Lemon
- Climate Adaptation Group led by Dr. Veronica Doerr

Oceans & Atmosphere

- Downscaled Climatic Modeling Team led by Dr Marcus Thatcher
- Sea Level Rise and Storm Surge Team led by Dr Kathleen McInnes
- Climate Science Centre led by Dr Helen Cleugh

External

- UNSW Fire Science Group led by Dr Jason Sharples
- Monash University, Disaster Risk Group led by Prof Jeff Walker
- RMIT, Intelligent Agents team led by Prof Lin Padgham
- La Trobe University, Applied Mathematics
- Bureau of Meteorology, Australia
- Swinburne University
- National University of Singapore
- AStar Singapore
- Radiant Earth Foundation, US
- Ecole des Mines d'Ales, France, student exchange program
- IIT, Mumbai, India, PhD student program
- Chinese Academy of Sciences

Outputs

D61-NHI's work has significantly contributed towards the fundamental and applied understanding of natural hazard events and their behaviour for better response and emergency management, smart resource allocation and policy structuring through the application of developed computer-aided modelling and data analytics and visualization tools. This section gives a snapshot of the tools and technologies developed by D61-NHI team, their key features, scientific achievements, the competitive advantage of digital tools in comparison to other scientific solutions available in the market, publications and patents, capacity building and new collaborations that stemmed because of this work.

Emerging digital platforms

Bushfires

Spark-a simulation system and **Amicus**-a local bushfire danger predictive software are the two vehicles that have been developed by the NHI team that leverage CSIRO's decades of knowledge and multidisciplinary expertise to improve prediction of bushfire behaviour for effective fire management. The capabilities are not only used to safeguard against fires but also to provide better preparedness for the fire season, improve community confidence and help with shaping government policies and programs.

The tools represent state of the art capabilities in fire disaster management. The digital innovation solutions provide information that is critical for emergency management services for predicting risk, deploying firefighting resources appropriately, and determining evacuation routes, thereby providing the basis for sound fire-management decision-making. Fire behaviour prediction combines quantitative and qualitative information sources that are based on scientific principles and personal experience describing the combustion and behaviour of fire in a range of weather, fuel and topographical conditions. Key capabilities of the tools include:

Spark	*CSIRO's fire simulation system, faster-than-real-time computational modelling, and analytics capability for bushfires carried out using GPU based code*
01	**Fire Front Capture Capability and Spot-fire Modelling Framework** Spark employs a modified level set method able to accurately capture the fire front curvature and includes the effect of ember attacks through a sophisticated spot-fire modelling framework
02	**Simulation system efficiency** Ensemble runs exceeding 10^5 individual simulations can be run in minutes using Spark in the cloud, to derive probabilistic estimates of the fire front, fire intensity, and effect of spot-fire behaviour which is very essential for use as a risk analysis engine in a bushfire context.
03	**Open Framework, Fully configurable fire propagation system** Spark is an open framework that facilitates simplicity for the fire agencies to incorporate the software into their existing systems and the fire science community to collaborate and keep adding new fire behaviour knowledge. Spark allows rate-of-spreads for any fuel type based on the latest fire science research. The system includes a range of plug-in packages including real-time topographic correction for wind fields, road/transmission line crossing and spotting behaviour models. Any bushfire spread model can be added to Spark which means, as new fire models come along, the older parts of the system be replaced.

04	**Incorporation of weather and geospatial data in fire models** Spark allows flexibility to easily incorporate weather conditions (like wind, temperature etc.) and geospatial information (like land slope, vegetation etc) to determine fire spread based on specific location and current environmental conditions. This reflects dominant capability of the model as these parameters are dynamic, complex and contribute significantly to fire behaviour including fire spread.
05	**Transparent view of fire behaviour** Spark provides a more transparent view of fire behaviour thereby providing the necessary insights to improve modelling approaches as required to then be able to be deployed in a real-world context.
06	**Predict Future Bushfire Events** Incorporates the latest knowledge of fire behaviour with state-of-the-art simulation to predict future bushfire spread through utilization of data and modelling tools thereby empowering the emergency management services to make decisions in real bushfire scenarios. See Figure 2 below.
07	***Integration with Climate Models*** Emerging strength in the integration of high resolution downscaled climate model outputs with bushfire spread models, to understand and evaluate the role of Australia's local weather on bushfire behaviour; representing a significant capability in comparison to other available models.
Amicus	*National fire behaviour knowledge base, a new fire predictor software that endeavors to provide a unique centralised framework in which qualitative and quantitative information based upon personal experience and scientific principles is accessible and utilizable in a consistent and comprehensive manner for the sole purpose of operational prediction of the behaviour of bushfires by trained fire behaviour analysts.*
01	**Predicting Fire Danger** Helps merging current knowledge of predicting bushfire behaviour and the danger emanating from its spread for a range of vegetation types and provides a simple calculator for fire danger (as a point source).
02	**Predicting Fire characteristics using 4 components** The Amicus system comprises four primary components: fuel description, fuel moisture models, wind models, and fire behaviour models, and uses these to predict fire characteristics for burning conditions.
03	**Integration of a suite of fire behaviour models covering the main Australian fuel types** Models to include fuels like eucalyptus forests, exotic pine plantations, grasslands, and shrub-lands.
04	**Compatibility with digital gadgets** Amicus is compatible with a variety of platforms – PC, Tablet, Smartphones etc and can be used offline (no internet connectivity required) so can be used by on the ground fire fighters to evaluate bushfire risk.

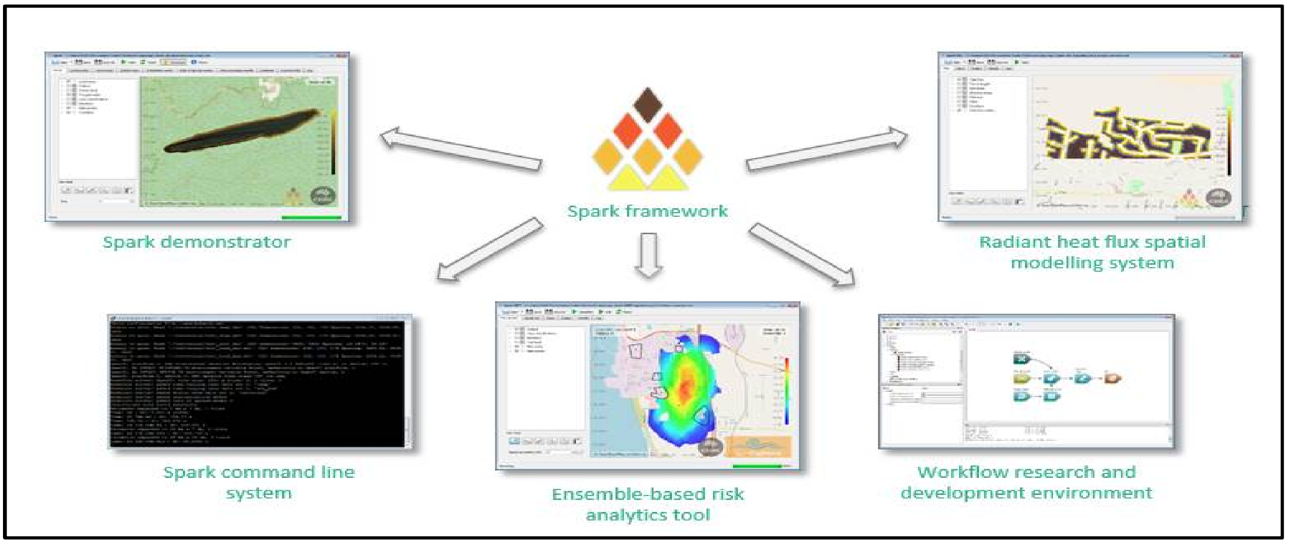


Figure 2: Spark fire spread simulator. Framework comprises modules for fire prediction and multiple tools for research, operations, and planning.

Flood Adaptation

The D61-NHI team has developed and distributed two tools, Swift and C-Fast**.**

Swift	*A flexible software system for modelling coastal and catchment flooding from heavy rainfall, dam breaks and storm surge events, through a modified finite-volume based shallow-water implementation on GPUs.*
01	Swift is capable of modelling different timescales of coastal and catchment flooding, through simplified boundary conditions, reducing reliance on deep ocean modelling.
02	Incorporating uncertainties and variabilities triggered by climate change, this tool offers capability to impose extreme water level predictions as a boundary condition for the entire Australian coastline to correctly predict coastal inundation for a range of scenarios. Ongoing effort is being undertaken to extend its application to other relevant coastlines around the world.
03	Includes a range of plug-in packages including a coupled hydraulic model for drainage networks, and models for rainfall, evapotranspiration, and infiltration for flexibility and scalability of application.
04	Ability to perform joint probability analysis to compare the significance of coastal vs catchment flooding
05	The tool is used for City-Flood Adaptation Solutions Tool (C-Fast), currently being developed for coastal councils within Australia.
C-Fast	*An integrated adaptation framework for cities at risk from coastal inundation and flooding events. C-Fast is built on top of the Swift hydrodynamic and hydraulic solver framework.*
01	Application in urban flood emergency management, identification of community flood risk and for improving infrastructure investment decisions. It allows dealing with climate adaptation pathway by enabling trial and evaluation to determine various future "before" and "after" complex adaptation scenarios through an evidence-based approach before investing into longer-term infrastructural projects
02	Hydrodynamic and coupled hydraulic modelling capability with analysis tools for adaptation option evaluation. Both hard (such as sea walls, retention/detention systems) and soft (such as coastal wetlands) can be evaluated.
03	Application in both catchment and coastal flood modelling, including sea level rise, for present and future flooding.

Evacuation Modelling

CSIRO has been working on developing agent-based models that can mimic potential human behaviours, and are capable of interacting with local features such as roads and other infrastructure and respond to immediate environmental threats (such as an evolving fire front or fast moving flood calculated from separate simulations). The key objectives of the work include:

- understand probable human evacuation behaviour. Seamless integration with Spark and Swift
- identify potential modifications to roads and other infrastructure and communications
- improve the likelihood of successful evacuations for people. Potential application in emergencies like terrorist threats, building fires etc.

Evacuation Modelling

An intelligent system for integrated evacuation planning that has capability to pull information from raw databases (for e.g. detailed road network, population census, threat scenarios etc.) and pre-processes the data to display it to the planners via the web interface.

01

The evacuation tool provides the following response options:

- When to evacuate
- When to issue messages
- Which area should be evacuated first

02

Key features:

Provides capability to planners to manipulate the data and define the evacuation network (a simplified or reduced version of the road network)

⬇

Planners can then specify the areas that need to be evacuated, as well as the safe areas and shelters.

⬇

Information added remains saved in database and can be utilised to produce an evacuation instance which is then used as input to the evacuation optimisation module

⬇

The resulting evacuation plans are then presented to the planner who can then iterate the process, refine the selection of residential zones, evacuation roads, and threat scenarios thereby assisting the local emergency services in making evidenced based decisions in their infrastructure planning as well as in emergency situations.

Geostack

An underpinning infrastructure that supports existing and upcoming D61-NHI digital tools (such as Spark, Amicus, Swift, C-Fast, Evacuation etc.) and combines the different data streams. Figure 3 shows Geostack engine.

Geostack	*A general purpose geospatial analytics infrastructure that underpins the different digital tools developed by D61-NHI and can be configured in any user-defined manner for geospatial applications or data generation.*
01	**Geospatial data processing** The infrastructure helps with common steps involved with the processing for any geospatial application or generation of geospatial data like reading data, remodelling and filtering vector and raster data and running arbitrary GPU-accelerated scripts on this data.
02	The dynamic solver modules consist of physical models tailored to natural hazards as well as sub-solvers for modelling additional physical aspects.
03	Geostack is being transitioned to API workflow composer and emergency management system to provide • capability of open source infrastructure • binding with Python to allow interaction with other scientific tools • usability in complex systems and multi-platform application • close integration with web deployment and mapping technology for scalable delivery on systems ranging from local machines to servers to cloud systems.

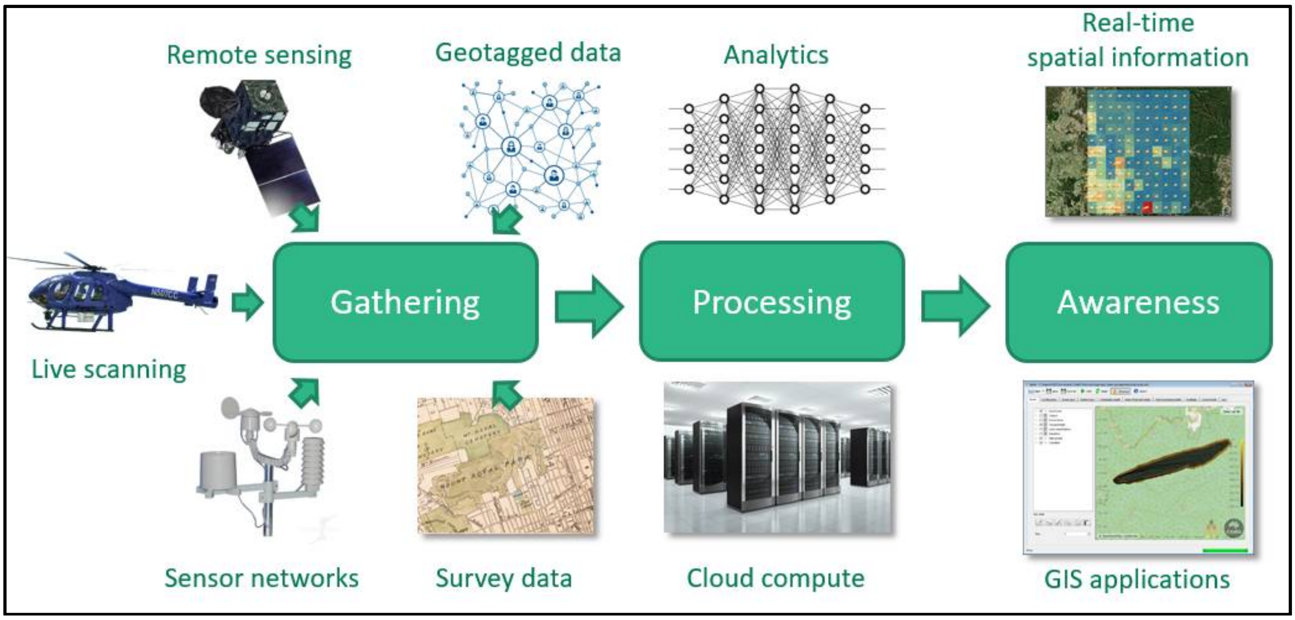


Figure 3: Geospatial processing pipeline

Emergency Situation Awareness platform

ESA	*A platform that leverages social media for improved disaster management. It performs social media analysis for all hazards and utilises natural language processing and data mining techniques for early detection of events and to extract situation awareness information as a disaster unfolds (https://esa.csiro.au/aus/index.html)*
01	**Effective Alerting through Tweet Stream Analysis** • Monitors the Tweet stream in real-time across Australia and New Zealand; converts the deluge of data into situation awareness information, thereby enabling effective alerting for unexpected incidents with results accessible via an interactive website. • Makes sense out of Twitter data using language models to identify discussion topics, trends, and hot topics. • Collects, filters and analyses tweets from specific regions of interest in near-real-time, stores Twitter stream information and allows post-event analysis.

	Features		
02	Burst Detection	Real-time Alert Monitoring	Topic Clustering
	Tweet Search	Alert Search	Past Event Replay
	Incident Monitoring	Text Classifiers	Location Mapping

03	**Application Landscape** Potential technology application in new domains such as marketing, financial services, brand management, customer engagement

Key scientific achievements

i) CSIRO's D61-NHI team has demonstrated the capability of closely replicating fire shapes found in small scale experimental fires, allowing development of small scale fire propagation models.

ii) The team has established that the shape of fire is strongly dependent on the fluctuations in wind conditions and the speed of fire is dependent on fuel variation.

iii) Development of first-of-its-kind model in collaboration with UNSW for the interaction of fires with local wind conditions with the capability of allowing dominant feedback mechanism in fires for fast predictive models.

iv) In collaboration with Monash University, the work actualized integration of remote sensed data directly into fire simulations. Developed a fuel recovery index representing the spatial availability of fuel. This index can be directly generated and used in fire simulations from freely available multispectral remote sensed data, avoiding costly pre-processing steps currently carried out for operational fire predictions

v) Successfully validated fire risk reduction strategies. D61-NHI team utilized Spark to gauge the effectiveness of mechanical fuel reduction strategies to reduce fires in eucalypt woodlands.

vi) Provided a data-driven confirmation that fires caused by electrical faults are indeed more prevalent during elevated fire danger conditions and burn larger areas than fires ignited by most other causes.

vii) Developed a methodology to create fuel map layers directly from Landsat-based remotely sensed satellite data sets that are available globally. This ability will significantly improve the ability of our bushfire models to be applied in a global context (Massetti et al. 2017).

viii) Developed algorithms to reconstruct rivers, estuaries and other inland water bodies for catchment scale inundation modelling as well as for the accurate “stitching” of terrain with bathymetry for coastal inundation (Cohen et al. 2017 and Hilton et al. 2017a).

ix) Created a photogrammetry-based workflow to cheaply yet accurately capture high-resolution 3D digital terrain data that can be directly used as input into natural hazard models utilizing standard digital cameras (Mead et al. 2015, 2017). This approach is most useful for localised event analysis, especially in underdeveloped and developing countries where sophisticated data gathering techniques prove too expensive.

x) Developed a methodology to integrate modular flood adaptation solutions with shallow water-based flood modelling solutions for engineers and planners to be able to evaluate effectiveness of soft and hard adaptation solutions for current and future years (including the effect of climate change; Prakash et al., 2015).

xi) Development of Geostack- an open source infrastructure that underpins multi-faceted digital tools. The engine can be easily repurposed for different applications, allow application for complex scenarios and provides opportunities to scale up the utilisation of Australian innovation on the global landscape.

xii) Development of ESA, an award winning technology for social media analysis of natural disasters and is finding a lot of traction for wider application, continuous improvement and co-creation by diverse stakeholders (government, industry, and the general public). The social media insight capabilities of tools are also being used for non-emergency event detection purposes.

Competitive advantage of CSIRO’s digital tools and technologies

i) ***Enabling technologies –*** The NHI is powered by a host of multi-faceted technologies under one umbrella. Big data, modelling, and computation for managing complex systems and understanding of natural hazard capabilities that underpin the tools described in this case study. This includes “Geostack”, CSIRO’s Big Data focussed Geospatial Analytics Infrastructure.

ii) ***Simulation and forecasting –*** CSIRO’s simulation algorithms take input forecasts (eg., precipitation levels) and readings from sensors (eg., gauge levels) to simulate the extent and consequences of the disaster with unprecedented speeds. The simulation tools for flood prediction use 2D hydro-dynamic models and high-performance computing.

iii) ***Combinatorial optimization –*** CSIRO’s optimization algorithms use simulation results to identify the strategic and tactical decisions to mitigate the effect of disasters, suggest operational best-responses, and improve post-disaster recovery efforts. Computational disaster management involves some of the most complex optimization applications: the programs combine multiple challenging combinatorial sub-problems (e.g., routing, location, and inventory), uncertainty, time constraints, complex objective functions, and multiple objectives. In addition, many of these problems are decentralized which provides collaboration and co-creation opportunities with different organizations.

iv) ***3D Visualization –*** CSIRO's 3D visualization engine provides interface that can be conveniently used by even those not expert at 3D graphics and is capable of displaying millions of complex objects efficiently. It utilizes fundamental advances in computer graphics and graphics cards to produce real-time, immersive 3D views of the disaster, providing unequalled situational awareness.

v) ***Model data fusion –*** *research* focused on the integration of physical models with remotely sensed data is another key differentiator for the developed tools. *For bushfires* this includes vegetation detection and classification, and accurate slope estimation; *for floods,* the direct derivation of roughness estimates, asset detection and classification, and accurately "stitching" terrain with bathymetric data for floods; and *for landslides and mudslides,* the assessment of soil type, depth and moisture content, slope, and vegetation. Model data-fusion approaches are also being evaluated to improve the calibration and validation effectiveness of physics-based models.

IPs, publications and wards

i) Due to CSIRO's capabilities in Model-Data Fusion (listed above, integration of models with remotely sensed data) NHI team was invited to write a paper for the Oxford Research Encyclopaedia in the Natural Hazards Science domain.

ii) The photogrammetry-based workflow created by the team won the best student paper award at the International Symposium for Environmental Software Systems in 2015.

iii) For a list of selected publications and awards, please see Appendix A.

Collaborations, training and digital upskilling

i) Deltares, an independent Netherlands based research and consulting organisation with focus on five areas all of which are mainly water-related including flooding, adaptive delta planning, infrastructure, water and subsoil resources, and the environment is seeking to collaborate with CSIRO's NHI Team in the domain of big data analytics, remote sensing and high-performance computing utilizing GPUs.

ii) Concerns associated with the flood vulnerability of World Heritage Kakadu National Park led to the development of first tidally driven hydrodynamic model of the Kakadu region through utilisation of CSIRO's digital tools. The work internally drove many dramatic improvements of CSIRO's capabilities (including a significant increase in speed of the GPU algorithm), which have since allowed modelling complex environmental applications (Mead et al., 2016). The Kakadu model gave critical insights into the potential loss of freshwater floodplains in the region by up to the year 2100.

iii) Association with many domestic coastal councils, government departments at all three levels, international organisations (including but not limited to) in the United States, South America, Spain, Portugal, and universities globally for potential adoption, collaboration for continuous improvement of available digital tools for natural hazard management.

iv) The training imparted by the D61-NHI team helps emergency management teams make informed decisions during critical situations. The critical understanding of the fire flowpath provided by the D61-NHI team has led to saving several lives under circumstances of dynamic fire environment.

Outcomes

The primary potential users of the developed tools are the Australian Emergency Management Services, fire agencies, rural fire authorities, land management agencies with the responsibility of managing fire on public land, coastal councils, emergency managers, and infrastructural planning authorities. The beneficiaries of the developed tools and technologies are the end users and the public. The potential channels for adoption include implementation/commercialisation, communication, community engagement, co-creation and capability and capacity building through collaborations.

The key outcomes of this work relate to its adoption for the purposes of natural hazard forecasting and emergency management, collaborations for continuous improvement and domestic/international adoption, capability building, improved disaster preparedness while building a safer and data-driven society.

Technology adoption

Bushfire work

i) The fire modelling capabilities developed by the D61-NHI team has led to building strong relationships with all state emergency management agencies across Australia. The tool capabilities have been fully tested and are in the process of being operationalised in several of these organisations. Recognising the ever-evolving needs, challenges and capability gaps in the natural hazard management space, there is a keen interest to establish a consortium to contribute resources for the sustainable development and growth of these skills. This is being conducted in collaboration with AFAC, Australia's peak body for fire and emergency management.

ii) CSIRO's fire modelling tools and decades of knowledge is being employed by many organisations across Australia and internationally. Due to flexibility imparted by Spark, it has gathered interest from Chile, California, Spain, and Portugal. The work is helping with smarter-fuel burning suppression programs and shaping policy decisions in this domain.

iii) Bushfire tools and evacuation modelling has been adopted for Great Ocean Road fire assessment in the first phase. The evacuation modelling is now being conducted for all of Victoria and specific hotspot areas in the state for the purpose of strategy planning to assess associated risks and success of the models. "Test runs" within the community are being executed for different scenarios to assess the adoptability of the evacuation model as a part of bushfire safety and awareness campaign. The work is expected to expand government's focus and understanding on the utilisation of digital tools for natural hazard emergency response management.

iv) Bushfire data analytics capabilities, especially in mathematical modelling of bushfire likelihood and computational modelling of consequence, has led to collaborations to execute projects in Western Australia (WA), South Australia (SA), NSW) and Victoria between 2012 and 2017, the most prominent being CSIRO's core involvement in the Victorian Powerline Bushfire Safety Program (PBSP).

v) Spark has recently been tested to perform hundreds of thousands to millions of simulations to assess the risk of bushfires under various environmental conditions to infrastructure such as powerlines as well as critical rail infrastructure in NSW. It is being trialled by emergency management agencies around Australia in an operational context (Queensland, NSW, SA, and Tasmania).

vi) Spark's capabilities to perform engineering mathematical modelling and quantitative risk approaches in the domain of fires caused by electrical faults are being used to model the performance of new electrical protection technologies and target A$400M of powerline upgrade investments in Victoria (Dunstall et al. 2016). Latter IP is now being combined with massively-parallel ensemble runs of the Spark bushfire model to inform submissions to the energy regulator and to build decision support systems for utilities in Victoria and South Australia, see Figure 4.

vii) In Chile, Data61 has worked with Arauco, one of the largest suppliers of forest and related products in the Southern Hemisphere. Arauco initially adopted CSIRO's integrated fire and data science tools to respond to wildfire threats. After the success Phase 1, Arauco is seeking collaboration to develop a cloud-based implementation of Spark to calculate their fire danger risk on an operational basis.

viii) Spark has also been adopted by Defense services in Australia to assess risk to defense sites.

ix) Amicus is undergoing implementation in an operational context in WA (Plucinski et al., 2017)

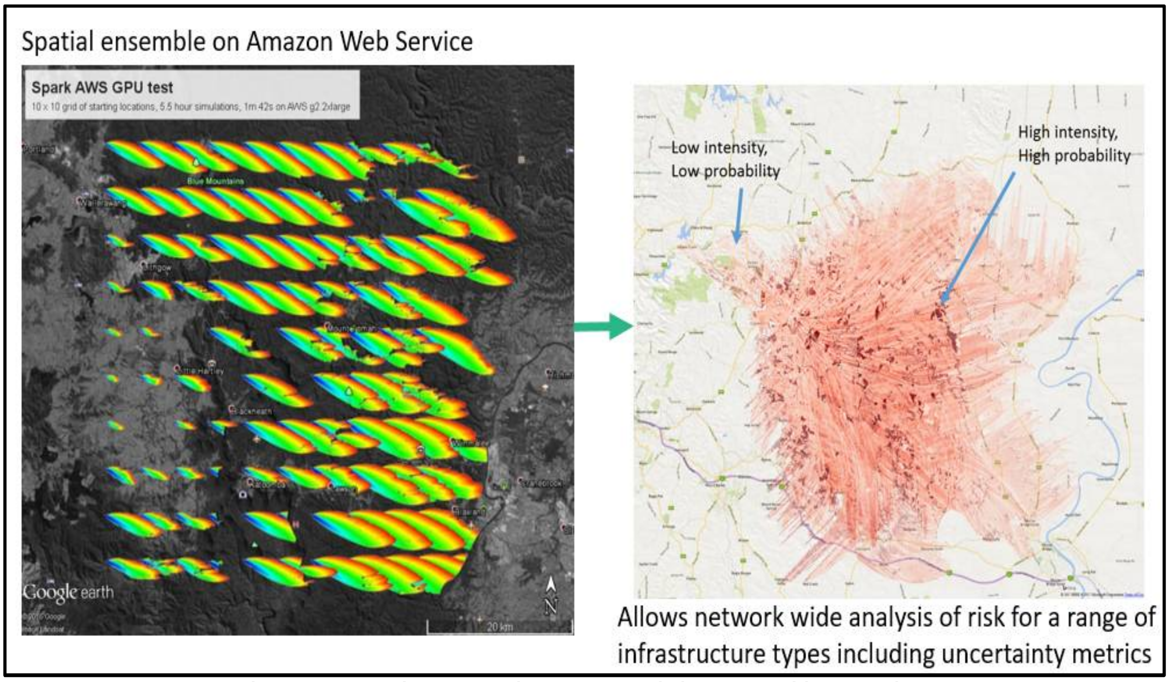


Figure 4: Spatial ensemble on cloud developed by Spark

Testimonial

At Radiant Earth, our focus is on satellite imagery, and Spark's ability to ingest multiple layers of spatial information is critical to the assessment resiliency and environmental threats across regions. I view Spark to be a truly innovative approach to bushfire prediction and analysis, and believe that it will play a key role in creating a data driven approach to disaster mitigation and resilience.

Anthony Burn,
Community Engagement Officer
Radiant.Eart, Wahington DC

I endorse Spark for its originality and innovation, public impact and further applications as bushfire tool.

Rod Rose
Senior Principal – Bushfire
Ecological Australia

Spark allows for incorporation of the various spatial layers and data formats, and for calculation of fire progression across a landscape with a high degree of computational efficiency and incorporates dynamic modes of fire propagation. The system supports visual analysis of model output to a level of sophistication and flexibility that supersedes all the simulation frameworks currently in operational use in Australia.

Jason J. Sharples
Associate Professor of Applied Mathematics, UNSW

Box 1: Spark testimonials by clients and collaborators

Flood adaptation

i) C-Fast is being used by six Australian local government areas to determine various future "before" and "after" complex flood adaptation scenarios and their utilisation.

ii) C-Fast provides the "cost-benefit" value-based pricing layer on top of the analysis; D61-NHI has the opportunity to lead this area globally.

iii) CSIRO's flood adaptation studies are being applied for the purpose of environmental conservation and protection purposes. Recognising the threats of future weather events and sea level rise (SLR) to World Heritage Kakadu National Park led to development of first tidally driven hydrodynamic model of the Kakadu region. Kakadu model gave critical insights into the potential loss of freshwater floodplains in the region by up to the year 2100.

iv) CSIRO has conducted integrated flood adaptation modelling for City of Port Phillip urban flood modelling for planning future activities (see Figure 5). The work evaluated potential coastal and catchment flooding for a range of future climate scenarios (2030 to 2100) at council-wide scale with integrated 1D drainage/2D hydrodynamic models. It included street level flood details to assist with infrastructure decisions and also studied adaptation options to reduce impact of extreme rainfall, storm surge, and sea level rise event.

v) The D61-NHI team performed 3D interactive visualisation of flooding in Townsville and conducted 2D hydrodynamic flood modelling for community engagement and education. The work effectively communicates impacts of flooding and adaptation solutions to stakeholders for evidence based decision making.

vi) CSIRO's digital tools with capabilities in Sea Level Rise (SLR) and catchment flooding have been utilised so far in the City of Port Phillips, City of Geelong, City of Bunbury and the Shire of Murray. A project is underway now in partnership with the DELWP Victoria to further extend the application of C-Fast to be used by all 11 coastal councils in Port Phillip Bay in Victoria.

vii) Data61's flood modelling and adaptation capabilities are also being used in Chile where Swift has been deployed to create simulations of urban floods and manipulate variables to inform decisions around infrastructure and provide mitigation options. California, Vietnam (Mekong Delta Region) and China (for coastal cities under sea level rise risk) are prospective partners in the near future.

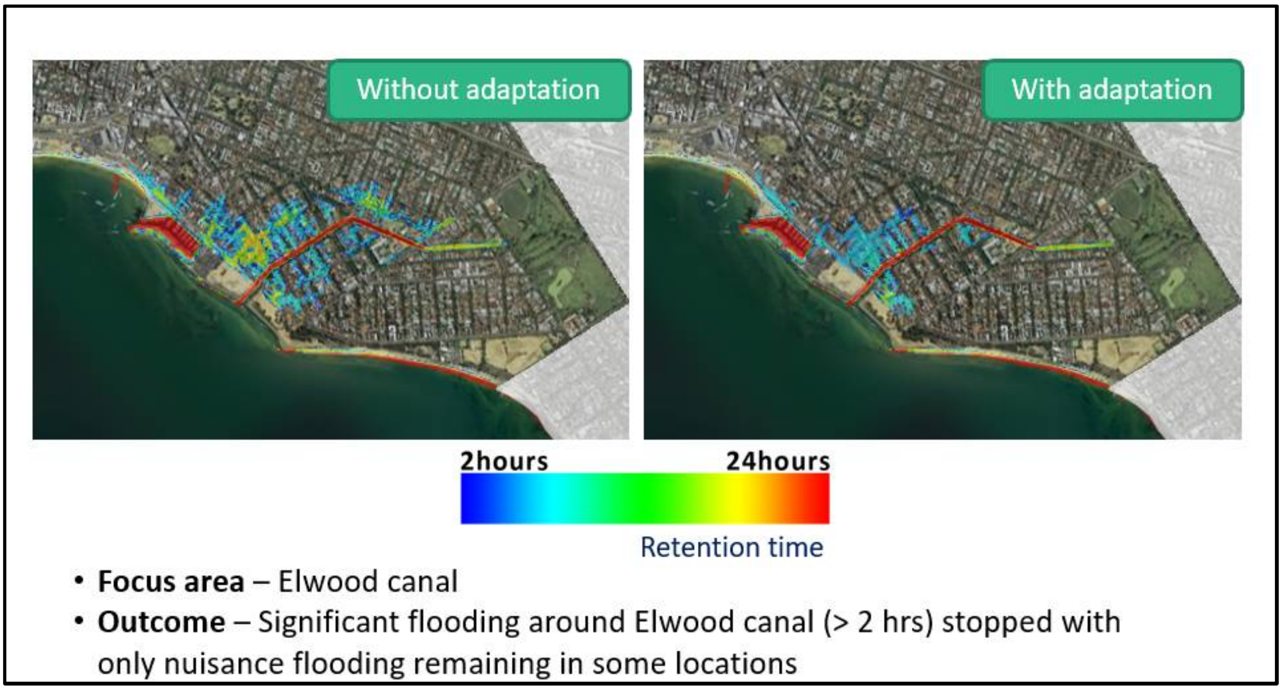


Figure 5: City of Port Phillip adaption summary – SLR 0.4 m

Testimonial

Engagement with D61-NHI (Swift and C-Fast) tool development and use 2011-2019

Initial engagement with CSIRO's D61-NHI was when the City of Port Phillip (CoPP) intended to gain a good/best practice integrated (catchment and coastal) and future (with climate change) flood model for the city that synthesised this data and provided visual simulations to demonstrate combined flood behaviour over time, especially to decision-makers and community members. CSIRO's Swift tool offered the capabilities to do this. CoPP further partnered with the CSIRO to simulate engineering solutions for the resulting flood problems, with C-Fast tool. In 2013, CSIRO and CoPP achieved this and were able to demonstrate the effectiveness (or lack thereof) of a range of engineering solutions for the Elwood area.

In 2018, CSIRO was invited by South East Water (SEW) to assist in gaining both future flood and erosion estimates in Western Port Bay and assessing the capacity of a constructed coastal wetland providing a multiplicity of benefits. The flood simulation components of this work is currently being completed utilising C-Fast. SEW are also in the process of operationalising their product – TankTalks (active, remote controlled distributed storage systems) and have recently completed a flood modelling project on the effectiveness of TankTalks in a flood-prone catchment in the City of Knox. Given the City of Knox are keen to model engineering solutions for a range of their other catchments, SEW has introduced the City of Knox to CSIRO's D61-NHI and the modelling and simulation capacities of C-Fast; with the understanding that City of Knox are now seeking to gain some further modelling with D61-NHI.

Lalitha Ramachandran
Technical Project Manager
Formerly CoPP, now SEW, Victoria

Box 2: C-Fast and Swift testimonial by South East Water

Evacuation modelling

i) The team is working with Infrastructure Managers in NSW to evaluate evacuation capability in a flooding context and with Emergency Management Victoria in a bushfire context. The tools also provide capability to perform pre-project risk analysis, now a requirement for any newly proposed infrastructural project for assessing the impact of natural hazard events on people and infrastructure.

ii) Any new infrastructural developments (residential and commercial) now need to consider potential bushfire and flooding risks in the evaluation process. The D61-NHI team's digital tools are being actively used by the consultants to carry out these evaluations during the planning phase.

iii) D61-NHI's evacuation modelling intelligent system is being used by planners for evacuation decisions. The technology, however, is in very nascent stages of adoption (see Figure 6).

iv) MATSim, an urban transportation system has been integrated into D61-NHI's modelling framework for planning and advanced operational emergency management.

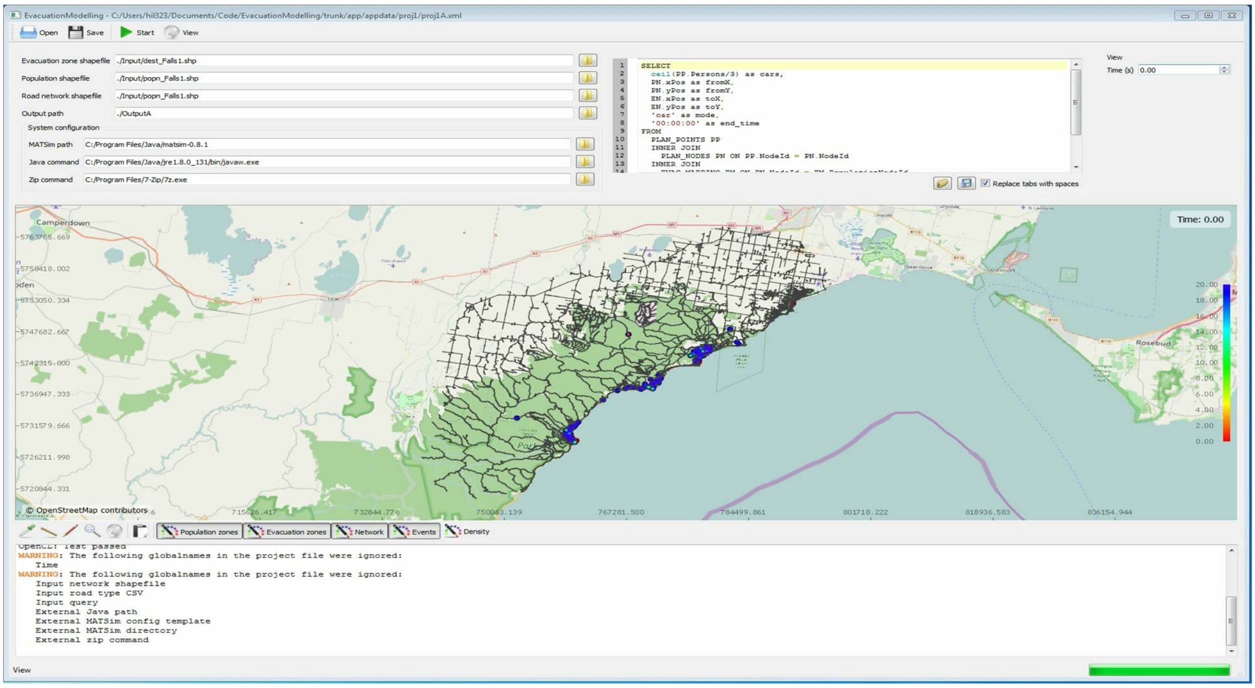


Figure 6: Evacuation modelling decision support system

Testimonial

EMV, along with other Victorian Emergency Service Organisations, turned to Data61 to develop a proof-of-concept Bushfire Evacuation Decision Support System (the Great Ocean Road Bushfire Evacuation Modelling DSS Pilot). D61 in collaboration with RMIT have developed a DSS that provides better bushfire evacuation information to a variety of stakeholders including local communities.

The proof-of-concept phase has been so successful that the Victorian Government has invested in Phase 2, which will undertake a more strategic view of bushfire evacuation modelling, whilst expanding to other geographic communities (Dandenong Ranges and the Maldon complex). We are thrilled to be on the next stage of the Bushfire Evacuation DSS development with Data61, as we develop a tool with possibilities we are yet to imagine.

Callum Fairnie
Senior Spatial ICT Business Analyst
Emergency Management, Victoria

Box 3: Evacuation Modelling Testimonial by Emergency Management Victoria

Geostack

i) Underpinning and open source flexible geospatial intelligence infrastructure that is widely being utilized for building different digital tools notably the award-winning Spark and C-Fast natural hazard disaster management tools.

ii) Being trialled by Smart Services Queensland to build an intelligent analytics platform to aid with workforce planning, forecasting, and prediction (see Figure 7).

iii) Prototyped for Smart City-based applications in collaboration with the Argonne National Laboratories, US and CGI Australia.

iv) Used for developing a Bushfire Attack Level (BAL) engine for generic use around Australia, successfully implemented in the Western Australian context in collaboration with the Office of Emergency Management and City of Cockburn, Western Australia. This tool is being used to assess the suitability of home constructions to withstand bushfires.

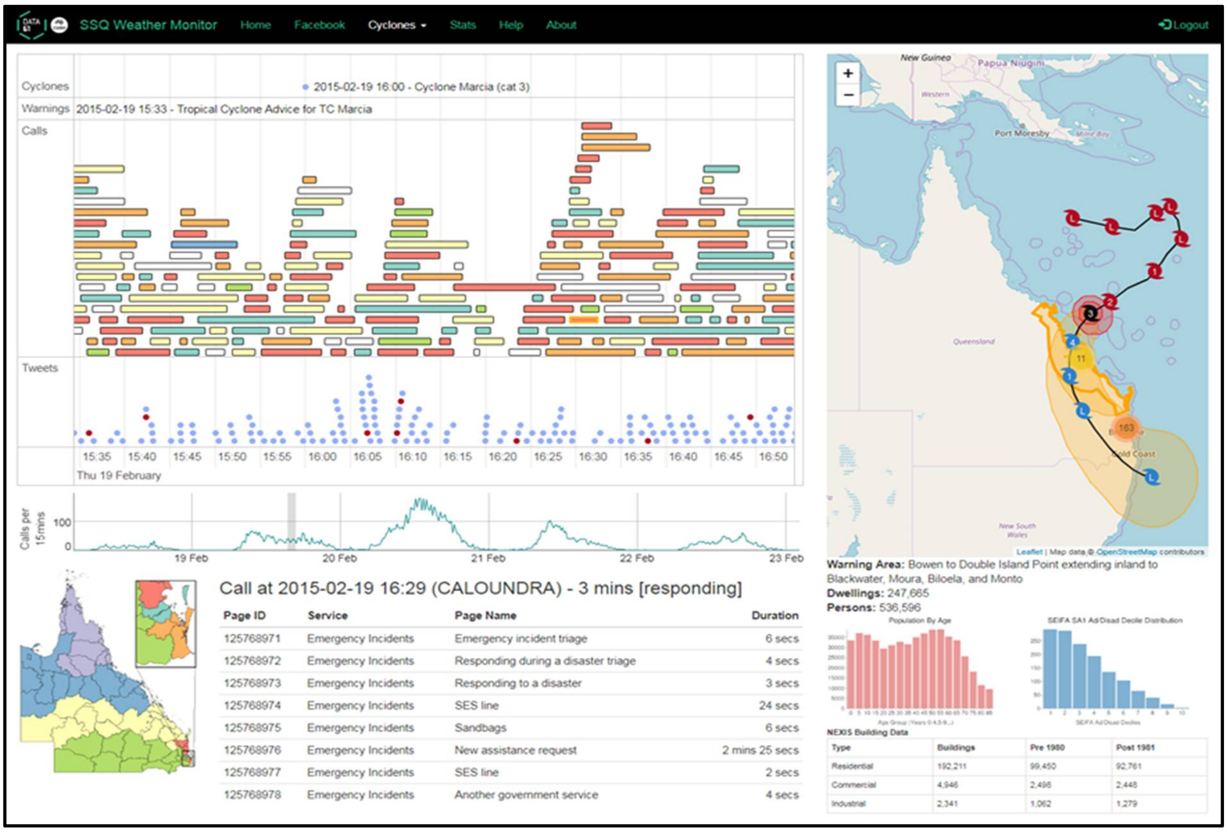


Figure 7: Data Mash-Up (SSQ Queensland), Geostack Analytics example

Emergency Situation Awareness (ESA) platform

i) ESA platform is being adopted by disaster managers in different Australian states for gaining evidence of pre-incident activity, near real-time notice of an incident occurring, first-hand reports of incident impacts and gauging community response to the emergency warning, see Figure 8.

ii) ESA, during trial runs helped provide Queensland Department of Community Safety an early warning about a grass fire at a hospital in Cloncurry in outback Queensland.

iii) The technology is gaining traction from diverse industries for adoption, collaboration, and co-creation.

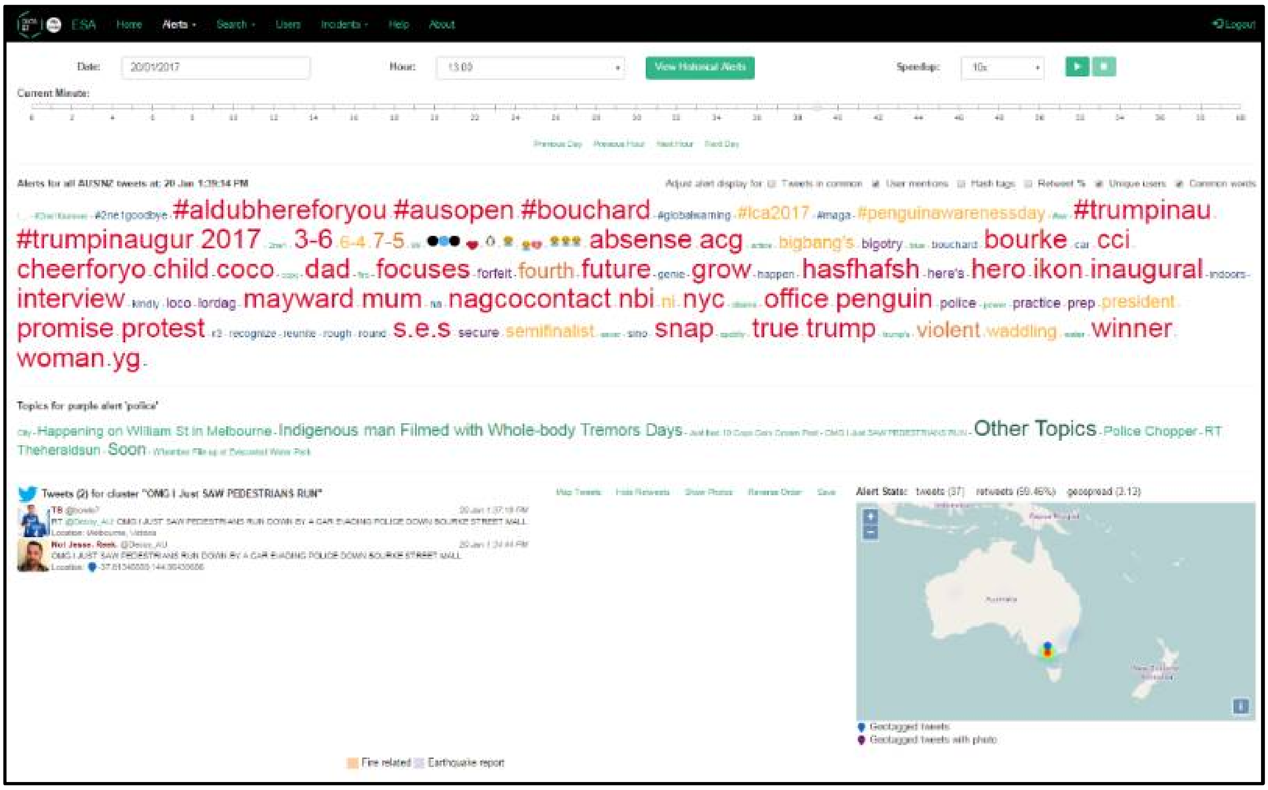


Figure 8: ESA outputs for Bourke Street Mall incident
https://esa.csiro.au/vic/

Research collaborations & global capability building

i) Spark has an open architecture that facilitates the easy adoption of work for further research, improvement, and application. The incorporation of new fire science has allowed the team to form strong links with many collaborators, UNSW in particular.

ii) Data61 is working collaboratively with the Attorney General's Department in Australia to investigate the possibility of utilising these systems as the basis to respond to the UN Sendai Framework for Disaster Risk Reduction in an Australian context.

iii) Swift and C-Fast are being developed in close collaboration with local councils in Australia who have a real need to use such tools for long term flood adaptation planning purposes.

iv) Data61 has recently signed a Memorandum of Understanding with Radiant Earth, an organisation funded by the Bill and Melinda Gates Foundation to provide remotely sensed data and analytics for free (non-commercial use) to developing countries. This MoU is exclusive for Australia and provides a significant opportunity to work on relevant joint projects accessing satellite data at various resolutions in natural hazard hotspot locations across the globe.

v) The team has also collaborated with allied industries like insurance, asset management, and banks and exploring opportunities to disrupt their traditional assessment methods as they translate to address new challenges such as the future effects of climate change on their policies and procedures. In this context the team is exploring relevant opportunities in collaboration with the Oasis Loss Modelling Framework.

vi) The D61-NHI team has been conducting one-day workshops every six months focussed on capability building. These have led to licensing, implementation and also co-development opportunities especially with larger scale consultants such as AECOM, Arup, and GHD.

Improved disaster prediction and preparedness while shaping data-driven society

The adoption of the D61-NHI team's work and its continuous improvement assists in building a pro-active rather than after the fact approach in natural hazard context. The implementation of technology provides science supporting information of possible hazard propagation, evacuation routes, and other crucial information of dire importance to safeguard human lives and material property. It has helped with strategic planning for determining optimal sensor placement, number of sensors, projection of possible evacuation routes, making investment decisions and devising policies and programs while enhancing global capabilities in this domain. The digital tools being developed by CSIRO are flexible to be applied across the world for different applications, under varying timescales and by a variety of users, which offers a significant competitive advantage.

The tools and technologies (like ESA) developed in this space also provides opportunities to create educational platforms for the community, catalyse public engagement to assist with validation of results generated by digital tools, facilitate incorporation of qualitative information based on personal experiences and build awareness thereby promoting community confidence and resilience during natural hazard events.

Impacts

Table 2**:** Summary of project impacts using CSIRO's TBL[1] benefit classification approach

TYPE	CATEGORY	INDICATOR	DESCRIPTION
D61-NHI's Digital tools for Natural Hazard risk assessment, planning, monitoring, and management			
Economic	National Economic Performance	Reduced economic expenditure and insurance claims due to natural hazard events	Capability to determine expected danger Providing point information Better response and decision making capability to lead –up to and into the hazard event
	Safeguarding infrastructure	Reduced damage of infrastructure through better preparedness of disaster management for high-consequence zones	Better efficiency and planning of operations Capability to change variables to inform decisions around infrastructure
	Policies and programs	Better informed policy decision making, resource management and funding allocation decisions for disaster handling	Application of learnings from research and implementation of technologies to facilitate better decision making Improved allocation of available resources based upon the severity of event as per modelling results

TYPE	CATEGORY	INDICATOR	DESCRIPTION
D61-NHI's Digital tools for Natural Hazard risk assessment, planning, monitoring, and management			
	Animal health and prosperity	Lowered animal deaths, livestock damage, and lowered expenses on agricultural business disruptions	Lowered impact of natural hazard events on animal wellbeing and security and farming areas
	Management of risk and uncertainty	Lower economic impact of natural hazards due to better preparedness	Saving opportunity costs for volunteer fire fighters, fixed cost of fighting natural hazards and governmental expenditure on rebuilding and compensation.
Environmental	Ecosystem health and integrity	Lower disruption to ecosystem due to better disaster preparedness	Saving or eliminating time and cost associated with Natural Hazard event for different areas. Building fire-resilient ecological conditions.
	Climate and Air Quality	Lower carbon emission and particulate matter arising out of bushfires	Lower environmental deterioration and restorative efforts needed post a disaster event
	Land, Aquatic and built environment	Lower damage and restorative time and cost	Utilisation of digital tools helps lowering the magnitude of natural hazard damage to land, aquatic and built environments
	Forestry	Reduced the extent of damage to forestry	Saving the time and cost associated with Natural Hazard event restoration
Social	Human health and wellbeing	Injury, death, and memorabilia	Domestic and global application to reduce the impact of natural disasters that cause human injury and post effects on human physical and emotional health (social disruption, trauma). This includes fire fighter as well as community security
	Quality of life	Better society confidence and confidence to deal with these events	Building societal engagement, awareness, and resilience through better understanding of intensity, location and impact of natural disasters. Lifting community confidence
	Social Cohesion and security	Social inclusion in building of these models and building a digital society where information is available to everyone	Enhanced societal awareness, preparedness, and resilience. Facilitating better decision making and social security.

5. Clarifying the Impacts

Counterfactual

The counterfactual scenario describes what happens if the D61-NHI team had not undertaken the fundamental and applied research to develop the digital tools in the natural-hazard space and/ or the preliminary assessment of these tools had not occurred thereby maintaining the status quo or the extension of the application of existing digital tools available in Australia. The key potential scenarios arising out of non-existence of CSIRO's capabilities in natural hazard risk planning and management space include:

a) **Natural Hazard related research knowledge and digital tools lacking the current level of insights and advancement:** If the D61-NHI group were not to do this work, modelling and analysis in the disaster domain, others would have to do the work to acquire a similar level of knowledge and capabilities in this space. There is no other single research group in Australia with the competitiveness of capabilities, availability of inter-disciplinary knowledge and access to multi-faceted data sources under one umbrella required to undertake the full range of R&D essential to deliver the NHI projects considered in this case study. CSIRO's developed digital tools uniquely offer advanced adaptation and mitigation effectiveness outcomes for future scenarios. Most, if not all of the other existing options in this area focus only on predictions to understand impact for current scenarios with little focus on the future scenarios, where evaluation of adaptation and mitigation options is a very key element to be able to make evidence-based plans. Hence, it is safe to assume that the absence of CSIRO's work would have added 5-10 years to reach the current level of understanding and advancement in this domain.

b) **Limited early-stage commercial uptake of digital disaster management tools**: If D61-NHI group were not to exist, getting benefits from the work of the other teams working in this area would still be possible but large scale early-stage commercial uptake by emergency managers, councils etc would become a real challenge. CSIRO's image as a trusted advisor, with length and depth of relationship with government, industry as well as international agencies has enabled widespread assessment and commercial uptake of the developed tools and technologies. The team is specifically focussed on the development of robust digital tools, their continuous improvement and capacity building with the ultimate aim of empowering Australia against the threats and large-scale consequences of natural hazards. It is safe to assume that Australia would have lagged by 5-10 years without CSIRO's strategic role in facilitating performance evaluation, commercial uptake and continuous-improvement of the digital tools.

c) **Alternate tools for disaster management:** In the absence of this work, use of other digital tools and technologies available in Australia for natural hazard management which maintain the status-quo of the associated challenges like limited adoption of models due to low consumer confidence, inability to prove veracity of model hypotheses due to lack of validation processes, or use of restricted models that cannot be applied to all regions of Australia or globally would have occurred. For a better perspective of competitive offerings of CSIRO's digital tools, key competitive advantages of D61-NHI's tools in comparison to other solutions available in the market are discussed here.

State governments could undertake this work at a local level but may hit the limitations of inconsistency and patchiness issues which would prevent aggregation to the national level, and their coverage and capacities may not result in comprehensive products.

At the international level, there are 'competitors' including the US Army Corps of Engineers, Engineer Research and Development Centre, Deltares in Netherland and Cerfacs in France with the capacity to undertake the modelling and simulation work, but they have limited expertise in the Australian region

Post consultation with CSIRO D61-NHI's research team, it has been assumed that in the absence of fundamental and applied research conducted by CSIRO, the robustness of digital tools and technologies for forecasting natural hazards would have lagged by 5-10 years. The next sections discuss the detailed assumptions and estimates underlying "with" or "without" project scenarios.

CSIRO's contribution

CSIRO has been and remains at the front runner for bushfire research in Australia and many scientific organisations have adopted this work domestically and globally. The current capability landscape in Australia in this space would have lagged in the absence of CSIRO's contribution and the central role it plays in this domain. The digital tools being discussed in this case study for bushfires, floods, and evacuation modelling, Emergency Situation Awareness technology, and Geostack infrastructure bring together knowledge, scientific concepts and their application from decades of work done by the team. It is important to note that the tools and technologies developed by the NHI team is a work in progress and their capabilities will keep evolving with time for continuous improvement in the prediction and management of natural disasters.

The tools and technologies developed by D61-NHI team is a result of a collective effort – the outcomes reflect the joint work of CSIRO, its partners and stakeholders. CSIRO is well positioned to deliver comprehensive, robust and 'fit for purpose' products that meet user needs. Furthermore, the holistic outcomes from the NHI team's work and early uptake of the solutions have been highly dependent on CSIRO's capacity to act as a 'trusted advisor' with the capability to deliver independent, quality work that is consistent (both spatially and temporally) for both scope and scale. CSIRO's established reputation as an innovation catalyst, with a talented team of multi-disciplinary professionals, industry and government outreach, and engagement with the Australian public, has helped to provide deep research knowledge, the current level of insights and incorporating unique capabilities in the developed digital tools and their adoption. The project collaborators have helped in providing funding, platforms for early uptake, continuous improvement and co-creation of the digital tools.

Since CSIRO, as well as project collaborators, were considered necessary for achieving the current level of research knowledge, capabilities and early uptake of ESA platform and Geostack infrastructure for risk assessment and emergency management of natural hazards, the focus of the economic analysis is to estimate the broader net benefit to Australia from the work and estimate the part of those benefits attributable to CSIRO. The D61-NHI team's work has also been attracting significant global attention, however, this has not been covered in this case-study, as the purpose of the case study is to explore the direct benefit provided to Australia ONLY.

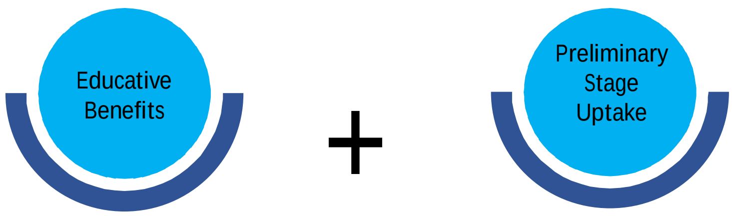
This evaluation has been undertaken by CSIRO to understand the payoff from the work and to specifically recognise the potential net benefit and success of CSIRO. It is, therefore, necessary to tease out CSIRO's costs and benefits – requiring disaggregation of the positive externalities back to either CSIRO or to other contributors.

CSIRO and its collaborators were both considered necessary to achieve the current outcomes of creating and disseminating educative benefits through the knowledge of developing a nation-wide all-hazards planning and adaptation initiative and its early commercial uptake. Since the work is currently in its early stage of uptake, it is only possible to conduct a qualitative benefits analysis in this case. The project team has received $6 million (nominal) from external funders in last 3 years. CSIRO made a co-contribution of ~ $1.2 million in 2017, but the program is self-sustaining now (0% contribution from CSIRO). However, this work builds on decades of background work conducted by CSIRO scientists; the cost numbers only reflect funding from the last 3 years of funding as there is no data available for the funding (external or internal) or funds spent on this research prior to 2017.

6. Evaluating the impacts

Digital tools and technologies being developed by D61-NHI team are an ongoing activity. Although the work builds on the knowledge from decades of work conducted by CSIRO especially in the bushfire domain, the capabilities and digital tools discussed in this case-study have been developed only in the last 3-5 years. The tools are currently in the early stages of commercial uptake by a large number of emergency management services, government, and allied industries as discussed in the Outputs section above. There are always time lags associated between early assessment (phase 1), commercial uptake/ adoption (phase 2) and realization of benefits (phase 3) through the application of new tools and technologies. Despite the significant commercial interest, as well as early-stage commercial engagement with some of the leading emergency management organizations on the state and national levels, the developed tools and technologies are considered to be in a very preliminary stage of commercial uptake. There is limited evidence to demonstrate the effectiveness and social benefit of the models and hence a robust cost-benefit analysis is not possible at this stage. We recommend revisiting the case-study to incorporate evidence-based effectiveness and commercial impact after 3-5 years and perform a complete CBA supported by longer-term time frame facts and figures.

To evaluate the influence of the D61-NHI work we assess the economic impact of the work. The benefits that should be considered in the analysis are the net benefits from the program, that is, the difference between the 'with' and 'without program' scenarios. The pathways for benefits evaluation include performing a qualitative assessment of the educative effects and the preliminary stage uptake of the digital products:



Evaluation case:

1) **Educative Benefits** in terms of **<u>new knowledge transfer</u>** to governments and the community that has originated from D61-NHI's work over several decades. A direct evaluation of the educative benefits to Australian society is difficult. However, the willingness to pay by outside organisations for CSIRO's diagnostic tools – reflected in purchases to date – can provide at least a lower bound estimate.

A longer-term scenario evaluation should be conducted in three to five years in a more comprehensive assessment of the trials of the technology currently being undertaken.

Educative benefits

D61-NHI team's work has contributed significantly to both the fundamental and applied understanding of risk assessment, infrastructural planning and operational prediction in the natural hazard space through the development of Geostack infrastructure, Spark, Amicus, flood and evacuation modelling tools and the ESA system. The tools are the outcome of decades of work performed by CSIRO scientists. The early stage commercial and government uptake has demonstrated the level of interest in acquiring the tools.

New knowledge generation

D61-NHI's work has generated **<u>new educative benefits</u>** about fire and flood risks and behaviour thereby improving the scientific understanding about multi-dimensional aspects of natural disasters mitigation and management. This has led to collaborations with a large range of research organisations and operational emergency management agencies, publications, awards, and conference presentations. In many cases, the collaborators have engaged with D61-NHI team beyond the preliminary assessment of digital tools post effectiveness and value addition demonstrated by the tools. Some examples of new knowledge generation wrt the existing tools being used in Australia in this space include:

i) Addressing key scientific challenges associated with the existing disaster management digital tools like representing the dominant physical processes in a computationally efficient manner, incorporating uncertainty in models, incorporating parameters to include effects of climate change, providing advanced adaptation and mitigation effectiveness outcomes for future scenarios, capability to perform validation processes and veracity to use models in different geographical regions.

ii) Most of the existing bushfire prediction tools adopt an empirical approach that fails to completely capture the range of behaviours expected from fires burning under more severe conditions. D61-NHI tools incorporate and improve understanding of some of the most complex interactions between the vegetation (fuel), the weather, the landscape (topography), combustion chemistry and heat transfer physics, making sense of the variables that influence fire behaviour and their interactions is a highly skilled task.

iii) Development of Amicus – a National Fire Behaviour Knowledge Base that integrates up-to-date fire behaviour, fire weather, fuel dynamics, and suppression capability knowledge and science to help fire managers better predict bushfire behaviour and better planned prescribed burns, improve understanding about the propagation and energy release of fires for more effective and safer fire-fighting and to reduce the detrimental effects of fire on our natural resources.

iv) Utilization of 3D flood modelling & visualisation instead of traditional 'bucket-fill' techniques to provide a greater understanding and practical information of fluid flow impacts at the local level. Disseminating knowledge to address risks from coastal and catchment flooding from heavy rainfall, dam breaks and storm surge events.

v) Improved understanding to support risk-based resource allocation and performance management outcomes of disaster management.

The measure of education as an output benefit is challenging. Had CSIRO not undertaken the research and development work for the fire and flood models, it can be assumed that others would have had to do so to acquire a similar level of knowledge about fires, floods, flexible infrastructure and social media analysis of emergency events. From the perspective of Australian society as a whole, it is irrelevant whether the resources used in the research and development were provided by the government (CSIRO) or the private sector. Since the research specifically addressed Australian conditions for fire and flood, it can be assumed that most of the cost involved generated knowledge gained by Australians. Once publicly disseminated, knowledge becomes a public good: the marginal cost of its use by others is zero, and its supply is non-rivalrous. So any gain to foreigners would not have detracted from the benefit of knowledge gained by Australians or imposed any additional cost.

Disaster Risk = Hazard * Vulnerability

The use of knowledge generated by D61-NHI and effectiveness of digital tools have the potential to reduce the overall disaster risk by lowering the ***Vulnerability*** factor.

Clearly, the economic and public impact risk of natural disasters is potentially high. Even a small contribution from CSIRO to provide knowledge insights and early access to better information to base risk mitigation and emergency management efforts, investments with better adaptation prospects can bring high value. Literature suggests, well designed adaptation measures can help reduce the costs of climate change (perhaps by as much as half).

Box 4: Impact of D61-NHI work on Disaster Risk

The Options created by D61-NHI's work

While the benefits of fundamental research could not be immediately quantified, it is likely that decades of CSIRO's work in this space could generate additional value in the development of digital tools and advancement in the natural hazard disaster space in Australia. Additionally, new methodologies and instrumentation created during the process may prove useful in other, new applications. In other areas research may lead to a better understanding of the implications of different options and lead to better-informed management decisions, resulting in the improved allocation of limited resources. D61-NHI is a significant provider of data and modelling that both create options across a wide range of areas, and helps to inform decisions between those options. Some examples to demonstrate the options generated by this work include:

1) Assisting allied industries (e.g. insurance) in re-framing their policies and frameworks, and thus reducing their administrative costs.
2) Utilizing the ESA platform to assess non-emergency scenarios
3) Future research work and collaboration opportunities (domestic and international) generated by the work.

Early Commercial Uptake - Benefits Quantification

Since the developed tools and technologies are in a very preliminary stage of uptake, a robust cost-benefit analysis is not possible, as discussed above. More specifically, improved levels of knowledge and understanding attained through this work, accompanied by the magnitude of effects of natural disasters, significant public benefit (whether or not directed affected by natural disaster) and growing need due to concerns caused by climate change should lead to the following benefits compared to the case that would exist without CSIRO's D61-NHI team's work (the counterfactual):

We adopt a willingness to pay approach to evaluate the benefits:

- The willingness of government (all 3-levels) and industry to pay for CSIRO's research as a proxy measure for the overall benefit. More specifically, for getting access to knowledge, insights, and capabilities disseminated by CSIRO's D61-NHI team in an effort to lower the breadth and depth of damage caused by natural disasters. Increase in willingness to pay for educative benefits imparted by D61-NHI's work in terms of knowledge transfer to governments and community.
- Increase in government and industry willingness to pay for new work to replace their traditional assessment methods as they transition to address new challenges such as better disaster risk mitigation and management, the future effects of climate change on their policies and procedures in the natural disaster management space.
- Increase in public engagement through the awareness to present new knowledge and changes in procedures.

It is difficult to quantify the educative benefit. But if we use willingness to pay approach by using external revenue received as a proxy measure, we could assume that $6.5 m R&D cost is a maximum bound of educative benefits. A proportion of this expenditure will simply be administration and programming skills, which do not represent new knowledge.

Table 3: Value of CSIRO's D61-NHI work

	Educative Benefit	**Early Commercial Uptake Benefit**
- With CSIRO D61-NHI Work (A)	Access to knowledge, insights, and capabilities imparted by CSIRO's D61-NHI team's Work	- Revenue generated through the purchase of licences (for details see the next section) - Revenue generated through early uptake/adoption
- Without CSIRO (B)	Eventual expenditure to acquire the same level of knowledge	Use of existing tools
- Benefit (C= A-B)	- Knowledge Transfer through Digital Tools, Publications, IPs and Awards; options generated. - Against CSIRO's initial investment of 1.1 million in 2017, the project has attracted overall external funding of ~6 million for this program over the past 3 years.**	- Significant but difficult to quantify yet. Some details on revenue generation are listed in the next section. Most benefit will be generated through cost savings if the digital tools are able to demonstrate effectiveness.

*** CSIRO has been working in the Bushfire domain for years. The developed digital tools stem from the capabilities acquired from this work. However, there is no data available for the funding (external or internal) or funds spent on this research prior to 2017. A comprehensive cost-benefit analysis is therefore not practicable.*

Examples from early commercial uptake and realised benefits

Infrastructure Planning

01	City of Port Phillip, VIC, City of Geelong, VIC, Shire of Murray, WA, City of Bunbury, WA. D61-NHI used CFAST to provide inputs into future infrastructure planning outcomes for these cities including population increase and climate change considerations. The total value of all these projects is around AUD 600,000 (externally funded).
02	The Victorian Department of Environment, Land, Water, and Planning (DELWP) have commissioned CSIRO D61-NHI to develop high-resolution inundation maps and related infrastructure planning tools for the whole of Port Phillip Bay using CFAST. Project duration 12 months, External funding AUD 1.2 million, CFAST component, AUD 450,000.
03	South East Water has commissioned D61-NHI to evaluate the effectiveness of soft adaptation options such as Constructed Coastal Wetlands to reduce the impact of Climate Change such as Sea level rise related inundation and erosion. Funding AUD 80,000. Project duration, 4 months.
04	Roads and Maritime Services NSW and Infrastructure NSW have commissioned D61-NHI to develop a flood evacuation modelling software which will be used to evaluate future infrastructure plans from an evacuation effectiveness perspective. Total funding provided for the project is AUD 2.5 million, D61-NHI's software development component is AUD 1.3 million over 14 months. Once this software is developed the annual license and maintenance fee is predicted to be around AUD 200,000 for just this one client.

Risk Assessment

Initial Uptake/ Commercialization Examples

01	Spark has been used by D61-NHI for risk assessment purposes for utilities and transportation. Clients include Powercor, SA Power Network, Ausnet and Sydney Trains. The total value of these projects is around AUD 340,000 with all projects running for between 3 and 6 months.
02	Completed a project worth AUD 350,000 (externally funded) investigating bushfire evacuation risk for the Great Ocean Road in Victoria. Success has led to an engagement in Stage 2 of the bushfire evacuation project which is underway now to investigate other hotspot locations around the whole state of Victoria. External funding AUD 600,000.
03	Geospatial Analytics using Geostack, Smart Services Queensland, AUD 430,000, 11-month project.

	Operational Prediction
01	The ESA tool is currently being used by upto 10 agencies around Australia for operational prediction. (License Fee: AUD 10,000 per year).
02	Spark is being evaluated for commercial adoption by Queensland, ACT, South Australia, and Tasmania. Queensland is paying AUD 50,000 per year to D61-NHI for this evaluation exercise.
03	Swift has been developed for infrastructure planning and potential operational use in Chile funded by the Department of Water in Chile (DGA). Initial funding - AUD 150,000 for one year. ***
04	The operational use of D61-NHI's evacuation modelling capability in Victoria is being discussed actively as part of phase 2 of the bushfire evacuation modelling project
	Community Engagement
01	City of Geelong engaged with D61-NHI for the use of visual products developed using CFAST for community engagement purposes. This project lasted 6 months and was funded by the city to the tune of AUD 90,000.
	D61-NHI Active Licences
04	**Active Licences:** Covey Engineering, Ecological Australia, Cardno (consultant using Spark for bushfire risk assessment) **In discussion**: Covey (Spark), Ecological Australia (Spark), Cardno (Spark), QFES (Spark operational), RFS Tasmania, ACT fire, SA Fire (Spark operational evaluation), DGA Chile (Swift/CFAST evaluation), Auraco (Spark active discussions), California Fire and Emergency Services (Spark and evacuation active discussions), ESA operational (various emergency organizations across the country including police) Benefits to residents to other countries won't be counted.****
	D61-NHI Live/ Upcoming Projects

04	a. Bushfire Evacuation phase 2 Victoria (AUD 600k) b. INSW/RMS Flood evacuation (AUD 2.5 million) c. DELWP Port Phillip Bay Coastal Hazards Assessment (AUD1.2 million) d. South East Water Constructed Coastal Wetlands (AUD 80,000) e. Flood modelling Chile, DGA (AUD 150,000) f. Sydney Trains Bushfire Risk (AUD 180,000) g. Deloitte, bushfire risk (estimated, AUD 300K) h. Cyient integration of Spark with DOME (multiple licensing opportunities at around AUD 15K per license per year) i. INSW/RMS evacuation license (AUD 200k per year) j. Geostack for QFES (AUD 250 k project with ongoing licensing) k. Geostack for City of Melbourne and City of Western Sydney (potential licensing and data revenue of around AUD 200k per year per city)

*** For the purpose of economic analysis any benefit to people outside Australia can't be counted. This example is provided to ONLY highlight international interest in D61-NHI's digital tools and capabilities in this domain.

Examples to demonstrate effectiveness of D61-NHI digital tools

Bushfires -Spark

Spark has now been nominated by Australasian Fire and Emergency Service Authorities Council (AFAC, the Australia wide Peak Body for bushfire related management) as the tool that they will support for a national scale operational product. This has been achieved due to the robustness of the tools and team's close engagement with five states around evaluating Spark as an operational tool.

Floods - CFAST

CFAST was used to develop adaptation solutions for the City of Port Phillip and City of Geelong in VIC. The effectiveness of the tool led the State Government in VIC through the DELWP to invite CSIRO D61-NHI to carry out a whole of Port Phillip Bay inundation hazard assessment. This project is worth AUD 1.3 million and the outcomes will have a direct impact on approximately 1 million people in Victoria who live in this region and many more who use the facilities around the Port Phillip Bay region.

Evacuation modelling

After the successful completion of the Phase 1 bushfire evacuation modelling project focussed on the Great Ocean Road region in Victoria, EMV and DELWP (VIC) have engaged with CSIRO D61-NHI to develop this capability further in Phase 2 so that it can be used for state wide applications and in an operational context.

Box 5: Examples to demonstrate the effectiveness of D61-NHI digital tools

Exemplification of cost savings

1. The city of Port Phillip mentioned that the flooded region as a consequence of climate change related sea level rise is worth around AUD 5 billion at current pricing. Being able to come up with effective adaptation measures that are demonstrable using CFAST was therefore seen as a significant benefit to them from an Infrastructure Planning perspective. The city of Bunbury in WA had a similar story.
2. Emergency Management Victoria mentioned that more than 2.8 million visitors come to the Great Ocean Road Region every year (2017 estimates). Ensuring that evacuation planning is given a high priority to this region is very important especially given visitors typically visit this region in summer when it is most bushfire prone. Also, visitors are least aware of local risks and how to deal with them effectively thereby making planning even more critical.
3. Sydney trains carry around 360 million passengers each year and have a capital infrastructure investment of around $500 million each year (2017-18 estimate). Ensuring that the passengers are safe as well as the infrastructure spend takes into account a range of risks including significant potential bushfire risks in sections of its network is critical for efficient and safe operation.

Box 6**:** Examples of cost savings impact of D61-NHI digital tools

7. Results

Assessment of benefits against costs

To estimate the return on all program financial contribution to D61-NHI research (including both external and CSIRO internal resources), it is assumed that all benefits to the Australian community are relevant, as this would be the measure of interest to the nation. On this basis, the return on investment for Australia is provided as below:

Educative and preliminary stage commercial uptake benefits

D61-NHI's work has generated **new educative benefits** about fire and flood risks and behaviour thereby improving the scientific understanding about multi-dimensional aspects of natural disasters mitigation and management. CSIRO has invested $1.2 million in the program over the period FY2017-2019 for the development of software for fire and flood prediction and management. External agencies have demonstrated their willingness to pay for this technology to the tune of $6 million over this period. However, these figures are not commensurate because CSIRO's expenses in FY2017-2019 would have been directed primarily at software development in terms of writing code and incorporating capabilities. The cost of developing the knowledge on which the coding was based would have been a very substantial amount over some decades, but any data on cost or funding associated with this work for the period before 2017 is not available and hence not included in this analysis. External agencies, on the other hand, are demonstrating a willingness to pay not only for the software but also the knowledge contained therein. It is therefore not possible to calculate a Net Present Value of a Benefit Cost Ratio.

Industry may well increase its future willingness to pay for the CSIRO's work if its benefits compared to current capabilities are demonstrated to be greater. Additional advantages of the CSIRO's work are likely to include determination of the future effects of climate change and ability to address Scientific Challenges associated with the existing tools.

In addition, D61-NHI's work is a significant provider of data and modelling. Such work generally creates options for the future, even where explicit benefits are not readily evident at this stage. The new options created are attributed to enhanced capabilities, improved knowledge, better knowledge, better research infrastructure, a clearer understanding of the most prospective areas for future research, and information on what areas of research might best be scaled back or abandoned until further information comes to hand or circumstances change. An example of new options is new collaborations with allied industries for re-framing of their policies and procedures.

Digital tools and technologies being developed by D61-NHI team are an ongoing activity. Although the work builds on knowledge derived from decades of work conducted by CSIRO especially in the bushfire domain, the capabilities and digital tools discussed in this case-study have been developed only in the last 3-5 years Despite the commercial interest, the developed tools and technologies are considered to be in a very preliminary stage of commercial uptake. It is recommended that the case-study be revisited in 3-5 years to perform a complete CBA supported by longer-term time frame facts and figures.

8. Limitations and future directions

In conducting a future cost-benefit analysis, it is recognised that any estimates are likely to be subject to a significant degree of uncertainty. Some of the most significant risks and issues affecting the estimates include variations to the assumptions around:

- The developed tools and technologies may still be in a very preliminary stage of commercial uptake and hence there is uncertainty associated with their long-term effectiveness and commercial adoption.
- Expected reduction of negative impacts of natural disasters through the introduction of NHI's tools; and
- Attribution (the current estimate does not take into account all other inputs required to realise the impacts). The developed digital tools stem from the capabilities acquired from decades of bushfire work done by CSIRO. However, there is no data available for the funding (external or internal) or costs associated with this research prior to 2017.

The case study presents only a qualitative evaluation of the work due to limited evidence to support a robust CBA analysis at this stage. It is highly recommended that the case-study be revisited to incorporate evidence-based effectiveness and commercial impact after 3-5 years and a complete CBA be performed, supported by longer-term time frame facts and figures.

Further, various assumptions have been used to proxy the impact that D61-NHI research has on infrastructure, essential services, and community and incremental benefits. Where possible, these assumptions have been based on scientific and/or economic literature. However, in some cases, limited information exists on the precise impact that the D61-NHI research has on broader economic, social and environmental systems.

Finally, but most importantly, this inference is based only on the application of Geostack infrastructure, bushfire, flood and evacuation tools, and the ESA platform. We have not attempted to scale up the benefits to reflect any other potential applications. Consequently, this analysis may substantially underestimate the total value that the D61-NHI research delivers. We, therefore, argue that this element of the analysis sets a conservative lower bound on CSIRO's D61-NHI's research value.

Glossary

AFAC- The Australasian Fire and Emergency Service Authorities Council

API- Application Programming Interface

AWS – Amazon Web Services

BCR – Benefit Cost Ratio

CBA- Cost Benefit Analysis

C-Fast - City Flood Adaptation Solutions Tool

CoPP - City of Port Phillip

D61-NHI- Data61 Natural Hazard & Infrastructure

DSS – Decision Support System

ESA- Emergency Situation Awareness

GPU-Graphic Processing Unit

IR - Infrared

IoT - Internet of Things

MATSim-Multi-agent Transport Simulation

MoU – Memorandum of Understanding

NCI – National Computational Infrastructure

NPV - Net Present Value

NSW - New South Wales

SA- South Australia

SEW- South East Water

SLR – Sea Level Rise

Swift - Shallow Water Integrated Flood Tool

VIC- Victoria

WA- Western Australia

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Appendix A: Publications and awards

Publications

1. Bayliss, P., Saunders K., Dutra L. XC., Melo, L, FC., Hilton, J., Prakash, M., Woolard, F., 2016, Assessing sea level rise risks to coastal floodplains in the Kakadu region, northern Australia, using a tidally driven hydrodynamic model, Marine and Freshwater Research, MF16049.
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9. Massetti, A., Hilton, J.E., Yebra, M., Rudiger, C. A., 2017. New Index for Determining Fuel Accumulation Using Optical Remote Sensing: Application to Dynamic Fire Spread Simulations, to appear in MODSIM 2017.
10. Mead, S. R., Prakash, M., Magill, C., Bolger, M., Thouret, J. C., 2015, A distributed computing workflow for modelling environmental flows in complex terrain, International Symposium on Environmental Software Systems, 321-332

Recent keynote speeches and conference organisations:

1. Mahesh Prakash, Invited Speaker, CSIRO-Chinese Academy of Sciences joint workshop on climate related research, Beijing, China, Jun 2017
2. Mahesh Prakash, Invited Speaker, Australian Computer Society's Branch Forum: "Model data fusion techniques and its future in the context of climate mitigation and adaption: Industry perspective", Mar 2017, Melbourne, Australia.
3. Mahesh Prakash, Invited Speaker, Australian Meteorological Society's (AMOS) 30th Anniversary Symposium, August 2017, "Meeting the challenge to provide localised flood and climate prediction and advice", Melbourne, Australia
4. Vincent Lemiale and Mahesh Prakash, Keynote Speakers, 8th Conference of the International Society for Integrated Disaster Risk Management, "Integrated modelling and analytics of natural hazards: A bushfire perspective" Aug 2017, Reykjavik, Iceland.
5. Mahesh Prakash, Invited Speaker, Fire, Cyclone and Flood Disaster Management and Recovery Forum, Dec 2017, Brisbane, Australia

6. Carolyn Huston, Invited Speaker, Fire, Cyclone and Flood Disaster Management and Recovery Forum, Dec 2018, Melbourne, Australia
7. Conference Co-Chairs, Mahesh Prakash, and Vincent Lemiale, 9th Conference of the International Society for Integrated Disaster Risk Management, Sydney, Australia, October 2018
8. Conference Co-Chair, Mahesh Prakash, Inaugural International Society for Crisis Response and Management (ISCRAM) Asia Pacific Conference, Wellington, New Zealand, November 2018

Awards

1. Victorian, National, and Asia Pacific Spatial Excellence Awards (Highest award in Spatial Excellence in the Asia Pacific region) for the Spark Bushfire Modelling capability, 2018
2. Victorian iAwards for Research Excellence (1st Prize) for Spark 2018
3. First Prize at the iAwards in the Sustainability Category in Victoria, Australia for the development of the sustainability tool, MyClimate for the City of Port Phillip, Victoria, 2015
4. Resilient Australia commendation award for developing a shallow water integrated flood tool for the City of Port Phillip that is able to evaluate combined coastal and catchment flooding, 2014
5. CSIRO Data61 Team Excellence Award on Industry Engagement 2018 for Bushfire Evacuation Modelling Project in Victoria.

Appendix B: Potential benefits quantification

Potential Benefits Quantification (foresighted scenario)

This high-level analysis has been developed to provide a snapshot of the expected outcomes from D61-NHI digital tools on the assumption that the work demonstrates its effectiveness in the upcoming years through enabling improved natural hazard risk mitigation and disaster management. It must be noted that this indicative CBA section is being presented for suggestive purposes ONLY. Due to the young age of the digital tools and lack of sufficient evidence, a detailed CBA can't be supported at this stage.

The analysis estimates the impacts of the D61-NHI team's research for mitigating the effects of, responding to, and recovering from, disasters such as bushfires, floods, and associated evacuations.

Cost benefit analysis

Modelling approach

Project cases

Two project cases have been developed for this evaluation (Figure 9). The cases will be used as the basis of the modelling approach to estimate a range of impacts based on applications in Bushfire, Flooding and Evacuation over time.

- **Project case 1:** Adoption of CSIRO's Geostack infrastructure, Spark, Amicus, evacuation modelling and ESA systems for predicting and managing the spread of bushfires, which have benefits across planning and emergency management.
- **Project case 2:** Adoption of CSIRO's Geostack infrastructure, flood modelling, evacuation modelling and ESA systems which focus on both catchment and coastal flood modelling, including sea level rise, for present and future flooding scenarios.

Project case assumptions

a) Since Geostack is an underpinning infrastructure and ESA provides a platform for social media analysis in a natural hazard scenario (for the purpose of this CBA); the impact of development and advancement of these tools have been assumed to be reflected in bushfire and flood modelling digital tools and capabilities.

b) There is no other single research group in Australia with the competitiveness of capabilities, availability of inter-disciplinary knowledge and access to multi-faceted data sources under one umbrella required to undertake the full range of R&D essential to deliver the NHI projects considered in this case study.

c) State governments could undertake this work at a local level, but may hit the following limitations:
   - inconsistency and patchiness issues would prevent aggregation to the national level; and
   - their coverage and capacities would not result in comprehensive products.

d) At the international level, there are 'competitors' including the US Army Corps of Engineers, Engineer Research and Development Centre, Deltares in Netherland and Cerfacs in France with the capacity to undertake the modelling and simulation work, but they possess limited expertise in the Australian region;

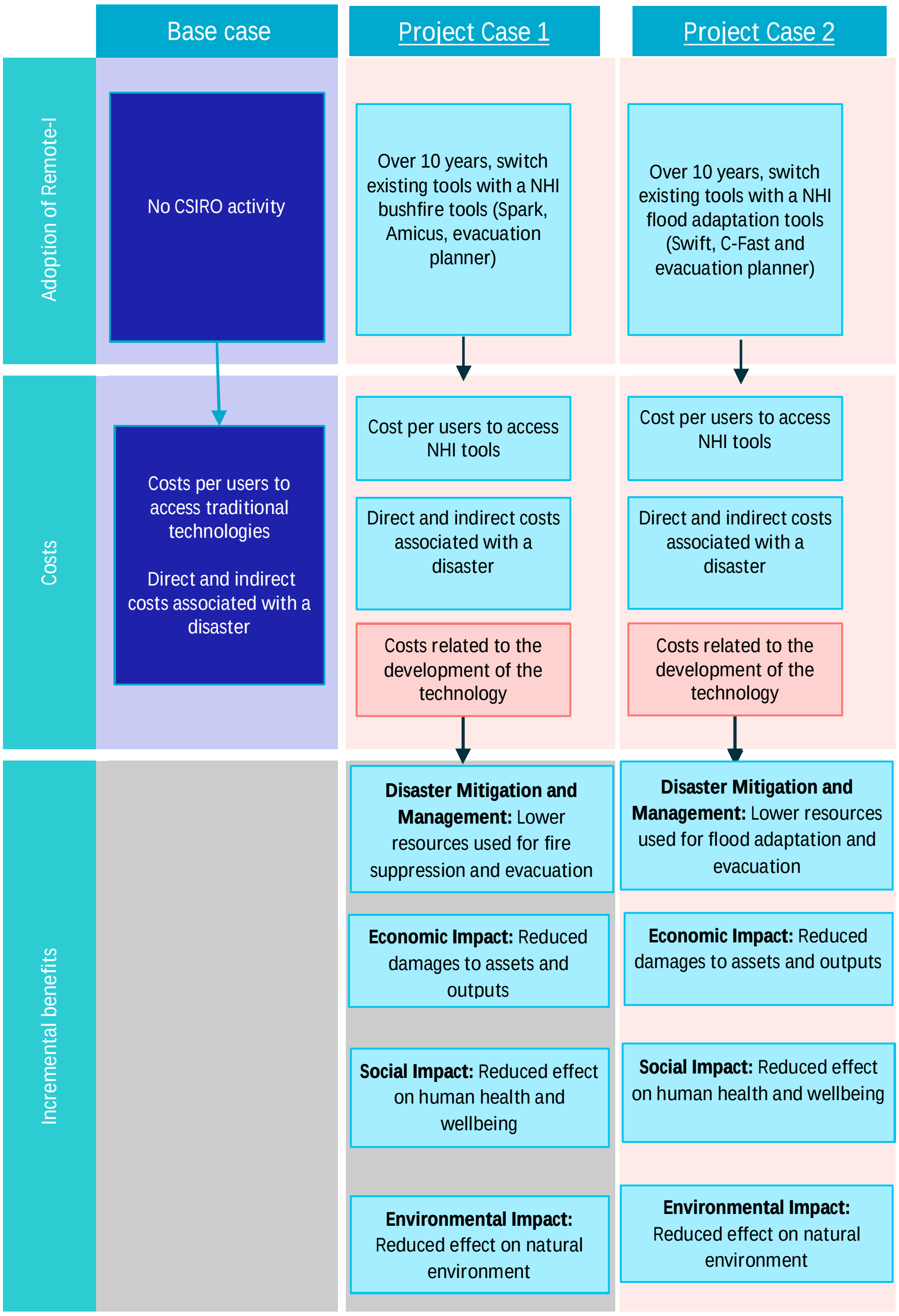

Figure 9: D61- NHI project Cost Benefit Analysis process flow

Time period of analysis

While the work being conducted by the D61-NHI team is an ongoing activity with a focus on continuous improvement of the developed digital tools, it is necessary to define a time period for this cost benefit analysis. Since this section is for indicative purposes ONLY, cost and potential benefit numbers for only 1 year are used for analysis.

In any research project, there is a lag between development, adoption of technology and realization of benefits post adoption of work. In case of a detailed CBA we usually estimate the benefits for a period of 10 years.

Costs

R&D Costs: The costs of NHI projects considered were shown previously in **Table 1.** CSIRO made a co-contribution of ~ $1.2 million (nominal) initially, but the program is self-sustaining now. The program has attracted external funding of 6 million over a period of 3 years. The year-by-year combined R&D costs of the projects are shown in NHI Project R&D costs.

Adoption costs: For simplicity, in the cost-benefit analysis it is assumed that the cost of adoption of digital forecasting tools that will be implemented by end users or others in Australia will be the same with or without the D61-NHI project i.e. the cost of adoption of NHI tools or any other tools available in the market would be the same. However, it is assumed that the adoption will be more effective in reducing the economic costs of disaster with the D61-NHI project than without the project.

Potential Benefits Estimation

We performed a suggestive CBA analysis to give some idea about the potential benefits of the natural hazard risk assessment, planning, and adaptation tools while using the counterfactual scenario as the base case. We acknowledge that the digital tools discussed in this case study are one of the many tools available for future adoption by emergency management services.

Also, D61-NHI tools represent vehicles that bring together young technologies and years of fundamental research that are in a very preliminary stage of commercial uptake due to their complexity and variety of factors that impact their successful application and widespread adoption. With the continuous improvement in robustness of the developed tools, growing needs due to high severity, high net public impact and frequency caused by climate change; their maturity, uptake, and adoption will keep evolving. This valuation is for the purpose of indicative assessment of potential benefits ONLY.

Steps for conducting potential benefits assessment for D61-NHI's bushfire, flood and evacuation modelling tools:

1) Estimate the cost associated with natural hazards (bushfires, floods) in Australia
2) Estimate how D61-NHI research benefits natural hazard costs for 2018
3) Perform a high-level benefits estimation based on the cost and benefit figures

CBA assumptions

1) Mitigation, strategic planning, and preparedness imparted by available natural hazard forecasting tools in Australia would ameliorate the economic costs of bushfire and floods in Australia relative to the counterfactual position by 10%. This is a very conservative assumption as Reference[10] assumes this to be 25%.

2) It is difficult to accurately estimate the significance of the D61-NHI research for bushfire or flood management, and its impact on current and projected bushfire or flooding costs. To evaluate the impact of this research on bushfire costs, the study adopts Taylor (1993) rule[11] a textbook policy rule and assumes 1% economic cost reduction of bushfires/floods, identified above are attributable to CSIRO's digital capabilities (Geostack infrastructure, bushfire: Spark, Amicus; floods: Swift and C-Fast, evacuation planner technologies and Emergency Situation Awareness platform).

Potential benefits of bushfire research

Modelling the economic consequences of bushfires is complex and hampered by limited current knowledge base for the impacts as well as the costs, due to underlying complexities. The DAE 2014 report concludes that it is only possible to model a subset of these potential impacts and capture some of the relevant uncertainties.

Bushfire CRC 2008 found that the total economic cost of bushfires will grow from $3.5 billion to $5.9 billion per year by 2020 (2006 prices) (see Table 3). The CRC 2008 report found that GDP losses in 2020 due to bushfires and floods are projected to cost almost 0.4 % for Australia. The intensity and cost of many of these natural disasters will be exacerbated by climate change (and potentially ameliorated by utilization of **digital forecasting tools and improved policy measures)[2].**

Table 4**:** Shows the estimates of the cost of fire in Australia: 2006 and 2020 by different elements in 2006 (million 2006 prices)

Cost elements	Cost in 2006 (mil)	Projected cost in 2020 (mil)
Agriculture and Forestry	137	223
Lives and injuries: urban	267	322
OHS of Fire Fighters	306	818
Water & carbon economy	600	890
Structural fire losses	701	1,587
Loss in business and commerce	1,444	1,973
Others	82	120
Total	3,537	5,932

Note: costs of ecosystem services were excluded due to the uncertainty of the estimates.

Source: Handmer et al 2008.

We have estimated the benefits of the CSIRO's Spark and Amicus technologies to Australia over the next 10 years (that is, from 2018-19 to 2027-28) based upon the CBA Assumptions mentioned above. The analysis period was chosen after considering the duration over which the project's outputs and findings will likely influence the design and implementation of bushfire digital tools and flow-on benefits from these activities.

The estimated 10 per cent reduction in economic costs due to the application of digital tools and 1 per cent attribution to CSIRO's role is a conservative assumption. For instance, the 2010 review of the Climate Adaptation Flagship (Assessment of CSIRO Impact & Value: Report prepared as an input to CSIRO's Lapsing Program Review; ACIL Tasman) uses figures of up to 50 per cent and 10 per respectively for these parameters.

The assumptions and estimates underlying economic impact evaluation of digital tools to reduce bushfires costs are presented in the Table 5 below.

[2] Handmer, J., Fischer, S., Ganewatta, G., Haywood, A., Robson, D., Thornton, R. and Wright, L. 2008, The Cost of Fire Now and in 2020, III International Symposium on Fire Economics, Planning and Policy: Common Problems and Approaches, Carolina, Puerto Rico, 29 April–2 May, 2008.

Table 5: NHI project economic impact calculation of reduced bushfire costs

Measure		Value	Source
With CSIRO research			
A_R	Annual bushfire costs in 2018	$5.4 billion	Handmer et al 2008
B_R	Effectiveness of adaptation (%)	10%	Author's assumptions, based upon[10]
C_R	Attribution to Spark and Amicus (%)	1%	Author's assumptions, based upon[11]
D_R	Bushfire cost savings ($billion)	= $A_R * B_R * C_R$	
Counterfactual			
A_c	Annual bushfire costs in 2018	$5.4 billion	Handmer et al 2008
B_c	Effectiveness of adaptation (%)	0%	Author's assumptions
C_c	Attribution to Spark and Amicus (%)	0%	
D_c	Bushfire costs ($billion)	= $A_c * B_c * C_c$	
Impact: word with CSIRO research - counterfactual			
	Value of additional reduction in bushfire costs-2018	= $D_R - D_c$	
		=5.4 million	

Figure 10: A high-level estimate of benefits of the NHI project in terms of the projected reduction in the economic costs of bushfire in Australia from effective adoption, based on the assumptions set out above[3].

The economic impacts quantified also include the potential impacts arising from CSIRO's Geostack infrastructure, evacuation research, and ESA platform as it is difficult to separate their impacts due to the limited availability of information.

Potential Improved flood adaptation outcomes

Swift is a flexible software system for modelling coastal and catchment flooding from heavy rainfall, dam breaks, and storm surge events. The system includes a range of plug-in packages including a coupled hydraulic model for drainage networks, and models for rainfall, evapotranspiration, and infiltration. The system is used for C-Fast, the city-based flood adaption, and solution tool, currently being developed for coastal councils around Australia. As presented in the Flood Adaptation section above, there is evidence that the adoption of the D61-NHI flood adaptation tools contributes to the reduction of risk from costal inundation and flood events.

Deakin Business School researchers have analysed economic data from each Australian state and territory from 1978 to 2014, along with information on timing and location of 36 major fires and 47 major floods. The study showed that floods had an adverse and multi-year effect on agricultural outputs[4].

Table 6: NHI project economic impact calculation of reduced flooding costs

Measure		Value	Source
With CSIRO research			
A_R	Annual flood costs	$8.77 billion	DAE 2017
B_R	Effectiveness of adaptation (%)	10%	Author's assumptions, based Upon[6]

[3] The estimated 10 per cent reduction in economic costs, and 1 per cent increase in effectiveness on the conservative – for instance the 2010 review of the Climate Adaptation Flagship (Assessment of CSIRO Impact & Value: Report prepared as input to CSIRO's Lapsing Program Review; ACIL Tasman) uses figures of up to 50 per cent and 10 per respectively for these parameters.

[4] http://www.deakin.edu.au/about-deakin/media-releases/articles/deakin-research-shows-economic-impact-of-natural-disasters-in-australia

Measure		Value	Source
C_R	Attribution to CSIRO's tools (%)	1%	Author's assumptions, based Upon[6]
D_R	Flood costs ($billion)	$= A_R * B_R * C_R$	
Counterfactual			
A_c	Annual flood costs	$8.77 billion	DAE 2017
B_c	Effectiveness of adaptation (%)	0%	Author's assumptions
C_c	Attribution to CSIRO's tools (%)	0%	
D_c	Flood costs ($billion)	$= A_c * B_c * C_c$	
Impact: word with CSIRO research - counterfactual			
Life expectancy gains attributable to CRC - 0.3%, Kievit 1990			
	Value of Improved flood adaptation outcomes ($million)	$=D_R - D_c$	
		=8.77 million	

The report, Building Resilience to Natural Disasters in our States and Territories, prepared by Deloitte Access Economics, examines the costs of flood in each state and territory over the last decade and the estimated costs to 2050. The report found the total economic cost of flood in Australia over the 10 years to 2016 averaged $8.8 billion per year. In real terms, the total economic cost of natural disasters is forecast to grow by 3.4% per year and double by 2050 per year. In the cost-benefit analysis, for simplicity, a linear relationship between time and the magnitude of flood economic impacts is assumed.

As discussed in the previous section, we assume that 10 per cent of the economic costs of flood can be reduced through adoption and implementation of digital tools and CSIRO's NHI project contributes 1 % towards reduction of damages, relative to the counterfactual position in Australia. The assumptions and sources underlying these estimates are presented in Table 5.

Estimation of potential benefits

Based upon the high-level analysis performed for suggestive purposes, the benefits generated by the work in one year i.e. 2018 alone (value of reduction in bushfire costs: 5.4 million; value of improved flood adaptation outcomes: 8.77 million) far exceed the costs of ~ 2.1 million associated with the research.

If the digital tools developed by D61-NHI demonstrate their effectiveness in upcoming years through enabling improved natural hazard risk mitigation and disaster management, there is potential to bring high value to Australia due to high economic and public impact of these events.

Other potential benefits

The impact evaluation of the D61-NHI team's research with the research team and relevant stakeholders highlighted other potential positive impacts arising out of the adoption and implementation **should the tools demonstrate their effectiveness for the intended purpose.**

This section provides an overview of the causal linkage from the adoption of the D61-NHI team's research outcomes to generate other non-quantified impacts, along with examples evidencing the extent to which they have been realised to date with a particular focus on health and wellbeing, education, community engagement, and employment. Some examples include[5]:

Direct health care system costs: Costs arising from services delivered within the health care system, including hospital, medical, paramedical and ambulance costs. Treatment may be provided by emergency services for those injured in a disaster, or someone with mental health problems or chronic disease may receive health care in hospital or by a general practitioner (GP).

Productivity loss: Poor health outcomes are likely to be associated with a reduced labour supply and lower productivity. This is valued as potential earnings lost as a result of disability, ill health or other outcomes. The human capital approach is used, which assumes that an employee cannot be easily replaced from the unemployment pool, and thus premature death or absence from work would result in a loss of productivity to the economy. Some productivity loss will be temporary and some over a person's lifetime.

Quality of life: These put a value on the loss in quality of life as a result of premature death, disability or ill health, and on the pain and suffering of friends and families.

Transfer payments: Transfer payments are not economic costs because they involve payments from one economic agent to another, but have been included to measure the allocative efficiency loss. These include social welfare payments from governments to individuals, victim compensation and accommodation subsidies.

Opportunity costs associated with natural disaster volunteers, economic costs include broader social costs which would not otherwise have been incurred had a disaster not taken place. As these costs are borne by many parties, from individuals, communities, and businesses, to all levels of government and insurers, which can make the magnitude of total economic costs hard to measure.

[5] Deloitte Access Economics (2016). *The economic cost of the social impact of natural disasters*. A report prepared for Australian Business Roundtable for Disaster Resilience & Safer Communities.