An intelligent disaster decision support system for increasing the sustainability of transport networks
Abbas Rajabifard, Russell G. Thompson and Yiqun Chen

Abstract
The increase in extreme weather events arising from climate change is posing serious threats to the sustainability of transport systems, creating the need for improved tools for decision support for more effectively managing natural disasters. There are numerous transport-related decisions that are required during the response, recovery and preparedness stages of the disaster management cycle. This paper describes the development and application of the Intelligent Disaster Decision Support System (IDDSS), which provides a platform for integrating a vast range of road network, traffic, geographic, economic and meteorological data, as well as dynamic disaster and transport models. Initial applications to the response and planning for floods and fires are presented to illustrate some of its capabilities. The IDDSS can be used to improve disaster management, which in turn will increase the sustainability of transport networks.

Keywords: Sustainable transport; disaster management; decision support systems; DSS; Melbourne.

1. Introduction
1.1. The effects of climate change and disasters on transport sustainability
Transport networks provide critical infrastructure for sustainable development. There is a need to reduce economic, social, and environmental effects associated with the impact of natural disasters on transport systems (Jaroszweski et al., 2010). Extreme weather events present a threat to the reliability of transport systems (Arkell and Darch, 2006).

Disruption to freight flows can cause substantial economic impacts since just-in-time manufacturing and distribution require a regularly coordinated flow of goods. Access to employment and markets, as well as health care facilities, is crucial for the well-being of communities. Transport networks are also vital in disaster response, especially for evacuation and the provision of food, water and medical supplies to communities immediately before and after disasters. More resilient transport systems also reduce the environmental impacts of natural disasters.

Recently there has been an increase in the prevalence and severity of natural disasters such as floods, cyclones, and fires throughout the world. In the past five years in Australia, floods in Queensland and Victoria as well as fires in Victoria and New South Wales have led to massive road infrastructure reconstruction programmes. In Queensland, over 9,000km (or 27%) of the State’s roads were affected during the floods in the 2010/2011 wet season. In early 2011, 100% of the state was declared a disaster, with approximately 20,610 km of roads closed. The reconstruction cost for this extensive flooding was estimated to be around $5.4 billion alone in Queensland (DTMR, 2014).

The increase in frequency and intensity of natural disasters as a result of climate change presents many challenges for enhancing the sustainability of transport systems. Climate change will have substantial impacts on critical infrastructure systems such as transport. There is a need to build more resilience into transport networks by considering adaptation and mitigation measures (Koets and Rietveld, 2012).

Disasters involving abrupt substantial changes in the biosphere have been identified as a major type of substantial change that can have a large impact on mobility (Van Cranenburg et al., 2012). Enhanced decision support is required for understanding the possible disruptions to transport networks from climate change-related extreme events (IPCC, 2014).
With limited budgets available for the maintenance and rehabilitation of road infrastructure, there is a need to reduce the substantial costs associated with the restoration of road pavements and bridges that have been damaged by extreme events. Improved tools for planning and managing transport systems in the face of natural disasters are required for sustainable development (Transportation Research Board, 2008).

1.2. Transport-related information needs for disaster management

Administrators require tools for supporting a range of transport-related decisions during the response, recovery and preparedness stages of the disaster management cycle. Such tools can be used to enhance the sustainability of transport systems, providing for the needs of present and future citizens.

During or following a disaster event, failure to effectively manage the risks associated with movement on the road network has resulted in a number of fatalities. As a result, emergency service organisations frequently deploy traffic management points or road blocks as part of a broader traffic management plan during a disaster. Despite the good intention, these road blocks are often sources of significant conflict both within the community and among people who have a pecuniary interest in the disaster area.

Techniques to assist with road management and to decrease related incidents are an important part of transport systems. However, currently there is no system to support emergency service organisations with the development of an optimised traffic management plan during a disaster. Emergency service providers require support in determining the most efficient assignment and routing of medical staff to injured persons. There is a need for tools to support practitioners and decision-makers in the process of conducting risk assessments of the road network during a disaster, to produce an optimised traffic management plan.

Evacuation routes often need to be determined immediately before disasters, taking into account imminent threats. Information regarding the functional status of transport links and facilities is required immediately after disasters. Efficient procedures for inspecting and clearing roads are often required.

During the recovery stage that follows a disaster, procedures incorporating the capital costs as well as road user benefits are required for scheduling repair works. Planning post-disaster reconstruction and recovery efforts for damaged transportation networks is a challenging and complex task due to the limited availability of repair and construction resources, including funding, materials, and human resources, as well as the conflicting planning and management objectives that need to be considered (Lambert and Patterson, 2002; Opricovic and Tzeng, 2002; Mesbah et al., 2009; Orabi et al., 2009; Miller-Hooks, 2012). Post-disaster recovery and reconstruction provide opportunities for reducing the risks posed by future disasters (Gupta et al., 2010). Betterment programmes that involve higher standards also need to be evaluated.

Although bridges and roads are difficult to protect from disasters, it is important to consider how to make them less vulnerable (Husdal, 2005). If damaged, some bridges and road links have major disruptions to their overall systems, especially if the topology of the networks does not provide many alternative routes. Implementing preventive measures is a proactive approach undertaken before extreme events occur, and can reduce disruption and recovery costs. Adaptive resilience methods based on preparedness are required to be developed in order to create more disaster-resistant road networks.

Methods are required to identify the most critical components of road transport networks, and then should be protected and strengthened. When there is an opportunity to reduce the impact of natural disasters by strengthening elements of the transport network that are likely to be damaged, as well as have a major roles in the functionality of the transport system, there is a need to identify cost-effective treatments for enhancing the post-disaster residual functionality of roads and bridges, before such extreme events occur. This can involve strengthening bridges and increasing the geometry standard of roads. Tools for identifying opportunities for increasing the redundancy, connectivity and modal substitution of vulnerable road elements are necessary.

Administrators require tools to identify the optimal schedule of mitigation measures implemented at vulnerable locations to reduce the degradation of transport networks in response to threats from climate change (Taylor and Philp, 2010). There is a need for more robust, reliable, and practical tools to assess the resilience of transport systems in one integrated platform.

2. The Intelligent Disaster Decision Support System (IDDSS)

2.1. Overview

Decision support systems (DDS) are widely-used in the public sphere of emergency management to solve intricate disaster-related tasks. Aggregating data from various sources, these DDS can provide a representation of disaster scenarios to assess vulnerability, damage costs and emergency response policies in disaster mitigation, preparedness, and response and recovery phrases. Usually DSS for emergency management are designed to cope with a specific type of disaster, such as floods (Todini, 1999), earthquakes (Eguchi et al. 1997) and hurricanes (Tufekci, 1995).

Very few existing DSS can provide decision support for multi-hazards. Hazus (FEMA, 2014) is one of the DSS that can provide decision support for disasters such as...
earthquakes, hurricanes and floods. Hazus includes models for predicting potential losses from natural disasters and utilises geographic information systems (GIS) to visualise high-risk locations and infrastructure. It can be used to estimate losses and develop mitigation approaches, as well as support disaster response.

The IDSS has been designed to provide decision support for a wide range of natural disasters, including bushfires and floods. In this paper, we describe the IDSS, which aims to facilitate decision-making processes in multi-natural disasters, such as floods and bushfires, by utilising a combination of disaster modelling, spatial data analysis, and visualisation and optimisation technologies. The complexity of IDSS system design comes from its mixed nature. On one hand, it is a data-driven system, which needs to access and manage homogenous geospatial data from distributed sources, as well as the validated volunteered geographic information (VGI) from crowdsourced platforms, dynamic feeds from social media channels (e.g., Twitter) and live data from sensor networks (e.g., VicRoads, Bureau of Meteorology Australia). On the other hand, it can also be treated as a model-driven system since all the modules and functionalities are designed to integrate and extend various existing disaster models.

The system design goals include:

(i) providing mechanisms for geospatial data management-conforming OGC standards;
(ii) enabling crowd-sourced VGI information;
(iii) being easy to plug-in with external disaster models;
(iv) providing universal analysis methods for disaster decision-making; and
(v) aggregating open-sourced frameworks for geospatial analysis, modelling and visualisation.

Staff from the emergency services and transport authorities participated in the development of the system by defining scope, contributing datasets and calibrating results. Current decision-making processes within stakeholder organisations were used to identify the information needs of users of the IDSS. The opportunity for input from stakeholders during the simulation allows learning to be incorporated. GIS mapping with animation provides visualisation of impacts, as well as feedback relating to management decisions.

The spatially enabled platform incorporates both spatial and non-spatial information from a variety of sources, as well as authoritative information and other relevant data and crowd-sourced geospatial data. Transport authorities and state decision-makers are authoritative stakeholders whose roles are directed by policies, regulations, and laws. Authoritative stakeholders may guide the overall response and recovery and provide initial resources to mitigate damage in extreme events, but social stakeholders, such as private industry and communities, will participate in the process as well.

The IDSS provides decision-relevant information using spatial data integration relating to the status of the transport network and the surrounding environment. This allows a deeper understanding of the interactions between risks, decisions and the performance of transport networks to be gained. The IDSS provides a platform for integrating the datasets required for simulation and optimisation modelling (Figure 1).

This trans-disciplinary perspective examines the interplay and dynamics across all pieces and focuses on developments that can produce major improvements in coordination, synchronisation, resilience, and preservation of critical transport infrastructure over space and time during the stages of disaster response and recovery from extreme events. Similar approaches have been used by governments across Asia-Pacific influencing how they build, use and administer their spatial information infrastructure, with a focus on sustainable development and disaster management (Mansourian et al., 2006; Rajabifard, 2007; Holguin-Veras, et al., 2012).

2.2. Architecture

To achieve the design goals, eight service-oriented components were identified in the platforms architecture, and together they form the skeleton of the IDSS (Figure 2). Details of each of these components can be found in Appendix A.
As the system architecture in Figure 2 depicts, all identified services in the IDDSS either directly or indirectly work with aggregated geospatial data. It is crucial to construct an integral data management solution for the IDDSS. Two open-sourced projects, Postgres (with PostGIS plug-in) and GeoServer, are employed for this purpose. The combination provides a solid foundation for the IDDSS data management, including data storage, query, analysis, conversion and publishing, and remarkably improves the flexibility and scalability of data sources configuration for the IDDSS. More details of the Postgres and GeoServer projects that are utilised can be found in Appendix B. IDDSS faithfully embraces open-source frameworks and open standards (Appendix C).

Disaster modelling and related spatial analysis is another key feature of the IDDSS. GRASS (Geographic Resources Analysis Support System), R and GeoTools libraries are incorporated in the system for this purpose. These libraries are widely accepted, and their consolidation provides the IDDSS with sophisticated flood and bushfire models, as well as advanced spatial data processing capabilities. The IDDSS focuses on utilising existing disaster models rather than developing new models, which allows the system to be used on a broad range of disasters and analysis of their impacts (such as risk areas, transportation networks and local economics) across heterogeneous data sources.

2.3. General features

The IDDSS is a platform for integrating spatial data (including infrastructure and terrain) as well as models (including disaster and traffic simulation), and can be used to investigate a wide range of disaster management issues. The IDDSS has numerous features and widgets to support homogenous data aggregation, manipulation and visualisation. This broad range of functionalities improves usability and makes it easier to extend to and apply in different scenarios.

A 3D virtual globe is used as the systems user-interface, providing the core visualisation and simulation component. The data layers, modelling and simulation analysis processes are accessed via a tab structure. Users drag-and-draw on the virtual globe to define and create their own case area for disaster events.

Once a case area is set up, users can add various infrastructure data layers to obtain background knowledge of the case area. Currently available layers include population, ambulance stations, hospitals, age care centres and road networks.

Plugging in with crowd sourcing information is another notable feature of the IDDSS. Currently we use the Ushahidi\(^1\) mobile application to collect incident reports from the public; for example, if people see fires, smoke, water on the street, or road closures, they can send a report through the app, and the IDDSS can automatically detect this information and use it as modelling inputs. Users can configure their own interested types of report (such as flood, road closure and road damage) to filter out irrelevant information. Moreover, to get a sense of how credible these reports could be, the user can turn on an optional validation

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\(^1\) Ushahidi platform provides the general public with the capability of submitting live reports via mobile phones or the internet, and all logged reports form a temporal and geospatial archive of events. See www.ushahidi.com for more details.

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service, which assigns a credit value for each piece of the report by considering both historical data and geographic topology.

Simulation modelling is used to represent disaster events and their impacts as they develop. A scenario-based approach is used to characterise the nature of disasters. This includes the scale, intensity and timing of extreme events. Estimates of the damage to transport infrastructure networks are then made. Changes to the transport demand based on the residual capacity of the network subsequently can be determined.

Following the response phase, indirect transport costs such as delays, detours and abandonment of trips can then be estimated. Changes in overall travel demand are estimated and assigned to the transport network. This involves estimating the origins and destination of travellers from previous traffic surveys and transport demand models. Trip distribution based on the gravity model as well as user equilibrium methods for trip assignment can then be used to represent the travel demand during the post-disaster recovery phase.

Demand modelling techniques are used to forecast the changes in flows on links in the transport network, based on disruptions. Indirect transport costs such as delays, detours and abandonment of trips can then be estimated. Changes in overall travel demand are estimated and assigned to the transport network. This involves estimating the origins and destination of travellers within the affected region. Procedures for estimating the origins and destination of vehicles in traffic networks are adapted from established methods (Yang et al., 1992; Liu et al., 2011).

Modelling procedures based on traffic generation, distribution and assignment methods can be used to estimate the traffic patterns during the post-disaster recovery phase. Travel demand forecasting techniques can then be utilised to estimate the demand that is affected by the deteriorated capacity of the post-disaster traffic links, as well as the reduced generation and attraction of trips, allowing for evacuation, damaged building structures and/or HAZMAT release (Chang et al., 2012). A range of open source traffic modelling tools (including MATSim and SUMO) can be utilised within the IDDSS for investigating the effects of changes in traffic demand.

A freight-vehicle-type assignment can be carried out to estimate the appropriate freight vehicle types (e.g., small trucks versus large trucks) and the associated numbers of each vehicle type. It is essential to consider the type of vehicles using the road network since large freight vehicles often cannot travel on local roads, and therefore the amount of goods they carry needs to be reassigned to different vehicle types, which can be serviced by the remaining road network. This is followed by a freight route assignment to determine the freight vehicle traffic on the altered road network.

The total traffic demand along road segments is redistributed as a result of the reduced capacity of some road elements, taking into account alternative routes for general traffic, which more or less connect from one end of the road segment to the other, and considering different vehicle types and different routes for freight traffic.

Interactions between the freight vehicle types and route choice for freight vehicles and general traffic adds complexity and veracity to the model. The models are designed to optimise the “social” objective of minimising total travel cost for all the (fixed) transport demands on the network. This cost includes components representing time, distance, energy consumption, and reconstruction cost of the damaged road network. Optimisation of the social objective will provide planners with the best possible “bottom line” for supporting the transport network demand.

3. Urban flooding case study

The Maribyrnong river region located in Melbourne’s inner western suburbs is used to illustrate the flood modelling capabilities of the IDDSS. This area has a mix of residential and commercial properties that have been affected severely by floods several times in the past. This is particularly due to its low elevation, and the fact that it is surrounded by hills, which increases the risk of floods and their potential impact. The majority of this area can be inundated by major floods (e.g., 1-in-100-year events).

The worst floods experienced in this area include the Maribyrnong River floods of 1906, 1974 and 1993. The flood of September 1906 was the largest flood on record in the area. The measured depth of water exceeded 4.65 metres above the AHD (Australian Height Datum). The flood of May 1974 resulted in 4.2 metres of water above the AHD, which affected 385 hectares of urbanised lands and resulted in damages and losses to 370 houses and businesses. Direct costs of AUD$16.5 million were incurred as a result of this flood, and the roads were blocked for over 18 hours (SES, 2012).

In 2014, over 371 residential and non-residential buildings were located in this potential flood area. Over two-thirds of the buildings are one-storey residential houses, and they can be highly impacted. In addition, a number of gas stations along Raleigh road and situated in the middle of our case study area are close to the river. In some extreme flood situations, these gas stations would be in danger, and even cause further damage to buildings and their contents by contaminating the water. Raleigh road, which is the extension of Maribyrnong road, serves as the major road connecting the township and the city. This critical road can be highly affected by floods since it was partially built over the river through a bridge. Other streets and roads in the area could be blocked as the result of a flood, and traffic could be completely disrupted by moderate and major floods.

Administrators have a number of issues when planning and managing flood prone areas, such as:
The IDDSS provides several analysis methods to help gain a clear view of the situation and facilitate the decision-making processes.

The hydrologic model “r.lake” from the GRASS library (GRASS, 2014a) can be used to simulate the progression and growth of flooding (Appendix D). Outputs include a range of flood maps (Figure 3) as well as damaged road networks (Figure 4).

For an improved understanding of the flood behaviour in the study area as well as determining its impacts on the settlements and infrastructure, a more sophisticated flood modelling tool, DHI MIKE21, has been integrated into the IDDSS. MIKE 21 is a two-dimensional hydrodynamic simulation tool, which is widely-accepted in the industry and is able to solve complex hydrological and hydrodynamic problems using shallow-water equations, and can be applied to a variety of applications (Appendix E).

The IDDSS flood damage assessment module is an add-on to the MIKE 21 flood model that can provide detailed information about the structural and content damage of buildings. This can facilitate decision-making processes for emergency response as well as recovery of the affected areas. In this module, spatial distribution of maximum depth of water in the area was extracted from the output of the MIKE 21 flood model and was spatially intersected with the buildings. Based on the averaged depth at a building location and adoption of stage-damage curves, damage levels for each building, as well as the total incurred economic costs to the case study area, were estimated.

Damage curves or functions in general show the corresponding damage level to buildings (according to their type, such as 220 m² one-storey brick veneer slab on the ground) based on the depth of water. This method is currently the state-of-the-art practice and standard approach for flood damage assessment around the world.

For the purpose of this study, the updated version of ANUFLOOD curves modified after the Queensland
floods in 2011 was adopted and utilised from previous studies.²

Comprehensive surveys of the study area, building information (e.g., number of stories, construction type and area) provided by the council, as well as property value information from the Valuer General’s office were used to determine the type and location of buildings and their values for damage assessment using damage curves. The data and the survey results were compared to previous reports and validated.

The combination of building types, damage curves, cost ranges and colour coding provided the decision-maker with a comprehensive view of potential damage to the properties in the study area (see Figure 5).

The IDDSS also has a risk area analysis (RAA) module, which can be applied to any polygon-based disaster modelling outputs. The RAA module creates a certain number of buffer rings with user defined buffer distances around output polygons. Currently, the RAA focuses on the persons and dwellings at risk, but it can be extended to support critical infrastructure like hospitals and schools. Figure 6 shows the results of applying RAA on the 1-hour flood map. Rendered in various colours, the RAA buffer rings are placed on the map and the statistics tab reports the number of people and dwellings potentially affected by the flood within each ring.

Optimisation techniques can be applied to identify solutions relating to the best schedule of strengthening

² http://www.siaqueensland.info/Resources/papers/Sargent.pdf
and recovery options, taking into consideration the net economic benefits in present value amounts. Metaheuristic procedures based on engineering economic principles have been developed. Due to uncertainty associated with the timing and intensity of future extreme events, decision rules such as maximin criteria can be selected to identify optimal schedules of protective works.

Optimising the works programmes and schedules for both strengthening and recovery is a bi-level problem. At a higher level, road managers make decisions on which link or segment of the network, the strengthening, and the restoration should take place in order to maximise the overall performance and resilience of the network. At a lower level, the road users (general and freight traffic) react to the available routes and try to maximise their benefits (e.g., reducing their travel time or cost). These methods will enable road networks in the future to have higher levels of resilience.

4. Bushfire case study

Well known for its bushfire history, Warrandyte, a northeast suburb in Melbourne (24km from the central business district), was chosen as the study area for the IDDSS bushfire simulation. It was at the centre of the “Black Friday” bushfires that occurred in January 1939, in which 71 people died, 1,300 homes were burnt and a total of 3,700 buildings were destroyed. Other major bushfires swept through Warrandyte in 1851 and 1962.

The majority of the region is classified as a bushfire prone area due to its unique location. It is situated in “a meandering gorge along the Yarra River and surrounded by forest parks and hilly bushy areas. The EXTREME bushfire risk comes from the combination of high fuel loads in the surrounding forest parks, homes nestled into bushland, the hilly terrain and a lack of accessibility with few major roads and narrow unmade local roads” (MFB, 2012). In the summer of 2014, several fires occurred on Melbourne’s fringe, including Warrandyte, where a small but out-of-control grass fire moved quickly toward residential areas and put people’s lives in danger. As a CFA head officer admitted, it would be “incredibly difficult to evacuate the town of Warrandyte, with about 4,000 residents and only one road out” (ABC, 2009). This statement begs the question, how can this situation be improved?

The IDDSS can provide information for planning evacuations. Using the bushfire model “r.spread” (GRASS, 2014b) from the GRASS library and starting the simulation with validated VGI bushfire reports (ignition points), the system can provide an animation showing how the bushfire spreads over time (Figure 7). Additionally, the simulation shows the elapsed spread time, wind speed and direction, as well as the number of persons, properties and land size that are at risk. As the bushfire spreads, markers pop up on the map. In this case, these are aged care centres that are vulnerable places and will be in danger successively as the bushfire approaches them. A typical optimisation question is what is the best strategy to use limited rescue resources to help people in these places?

The IDDSS is built as an open platform for integrating optimisation and simulation models to transform situation awareness into effective response and recovery plans as follows:
(i) optimisation of first-responders decisions, including dispatching patients based on their injuries, the status of the hospitals (which critical resources are available when), the ease of accessing these hospitals, and the creation of local medical centres close to damage areas;

(ii) optimisation of search and rescue operations taking into account the state of the transportation network and the impact of the disaster on primary and secondary infrastructure (e.g., buildings and roads); and

(iii) optimisation of plans for evacuation and sheltering, using detailed models of the transport networks over time, and capacity constraints on the resources such as buses, police and fire-fighters.

When solving these problems, the IDDSS utilises its own optimisation module called “path analysis.” Inputs including the damaged road network, threatened locations (i.e. age care centres) and rescue resources centres (such as ambulance stations and hospitals) are used to generate optimised schedules to allocate resources over the road network. This can be treated as a classic integer programming problem and the dispatch schedule algorithm aims to minimise the overall victim relocation time by taking into account variables like the number of people to be relocated in each threatened place, the number of vehicles in each rescue centre, the capacity of each vehicle and the location and capacity of shelters and refuges.

Two built-in modules “r.ros” and “r.spread” of the GRASS library are combined as the IDDSS bushfire model (Appendix F). The bushfire model output contains a pair of fire boundaries and damaged road networks for each simulation step. Figure 8 shows output layers for the final simulation step. The RAA module is applied to the fire boundary. The bushfire creates some “holes” in the local road network. The damaged parts are noticeable when they are overlapped with the original road network. Figure 9 describes the damaged road network analysis outputs, and the statistics are organised according to different road classes. In this simulated bushfire scenario, 35 local road segments, 8 sub-arterial road segments and 2 arterial road segments had been affected. The connectivity of the road network plays a vital role in the disaster management context, because it directly affects the evacuation plan and disaster logistics; therefore, based on these statistics, as well as the knowledge of local traffic characteristics (e.g., traffic

![Figure 8](image_url)

**Figure 8.** Fire boundary (grey polygons) and damaged road network (white lines) at the final simulation step. The damaged links are noticeable when overlapped with the original one (black lines).

![Figure 9](image_url)

**Figure 9.** Damaged road network analysis of each road class.
volume, travel patterns, car ownership rate, etc.), a more sophisticated analysis such as traffic diversion and road network restoration will be investigated in the future, to provide more valuable information for decision-making.

Since the IDDSS has the capability of detecting and visualising disaster-related information from crowdsourced platforms like Ushahidi, it is easy and reasonable to use validated VGI information to assist the disaster modelling. Figure 10 shows two fictitious bushfire reports in the Warrandyte area, and the following sections will discuss how to conduct a bushfire simulation and perform further spatial analysis for decision-making in the IDDSS.

There are several parameters to be initialised before running a bushfire model. In this scenario, the IDDSS detects bushfire-related reports within a case area, and automatically uses them as fire ignition points. Therefore, the first report created time is taken as the simulation start time in the first tab. By default, the modelling process is split into small steps, and the time interval between each step is set to 30 minutes. The wind conditions are set up in the second tab, which gives the flexibility of either manual configuration or auto wind data synchronisation from the Bureau of Meteorology (BOM) website. With default settings, 30 steps are assigned to the model, which will simulate the fire propagation in the coming 15 hours. The fuel and moisture parameters in the third and fourth tab point to the pre-calculated data layers in the server. In the last “Ignition Point” tab, two ignition points are inserted, representing the time and location of two bushfire reports in this region.

The model runtime mainly depends on the size of the study area and the duration of simulation. Once the model is finished, the IDDSS will generate an animation showing how the bushfire spreads over time. A monitor window shows on the screen as the animation continues indicating the elapsed spread time, wind speed and direction, as well as the number of people, properties and land size that have been affected. As the bushfire spreads, more and more markers will pop up on the map. These places are aged care centres and are vulnerable, and will be at risk successively as the bushfire approaches to them. Such information can be used to develop the best strategy to use limited rescue resources to help people in these places.

5. Conclusions

Extreme weather events arising from climate change are posing serious threats to the sustainability of transport systems, creating the need for improved tools for decision support to more effectively manage disasters. The IDDSS has been developed to increase the sustainability of transport networks. Initial applications to the response and planning for floods and fires in Melbourne were used to illustrate some of its capabilities.

Though the design architecture and techniques of the IDDSS provides itself with great potential to evolve as a useful tool, the system still has a long way to become mature enough to facilitate decision-making in real world disaster scenarios. First, from a data integrity point of view, the current system lacks the capability of gathering live data from various sensor networks (e.g., live traffic volume, river gauge, temperature/humidity). The live sensor data enrichment will make the system more valuable in the disaster response phrase. Second, according to the data quality, the current system is still missing a sound mechanism to ensure the credibility of VGI data before it can be fed into the disaster modelling and decision-making processes. Other features like large scale 3D city rendering, detailed 3D BIM (Building Information Model) visualisation and macro-level agent-based traffic simulation are also being considered for future implementation.
The IDDSS provides a platform for integrating a vast range of road network, traffic, geographic, economic and meteorological data, enabling plug-in components with innovative models and algorithms to be implemented in a systematic means. Dynamic and flexible models can be used for assessment of road transport systems, allowing evaluation of disaster scenarios. The paper illustrates how the damage to traffic networks from floods and fires can be estimated and visualised. This information can be used to estimate residual capacity of the road network, as well as plan and manage the evacuation of persons. Using the IDDSS, the concepts of risk, vulnerability and resilience can be investigated to improve disaster management, and can lead to more sustainable transport systems.

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Appendix A: architecture of the IDDSS

Modelling Service (MS) takes parameters from the web clients (WC) and retrieves data via the Data Access Service (DAS), and then runs disaster models and sends results, such as time-tagged disaster-affected boundaries and

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digestible info for the Public Safety Service, back to the GeoServer via the DAS.

**Optimisation Service (OS)** has a similar data flow to that of the Modelling Service. By taking the outputs from the MS, it executes a range of algorithms (such as risk area analysis, road network analysis, etc.) and provides data for the Visualisation Service and the Public Safety Service.

**Visualisation Service (VS)** can access results generated by the MS/OS via the DAS and translate data into client compatible formats, such as GeoJSON and CZML. The client visualisation component adopted in IDDSS is built upon an open-source project called Cesium, which provides a WebGL framework for displaying the virtual globe and geospatial data layers.

**Data Access Service (DAS)** manages data reading and writing operations between connected services and the GeoServer. It stores the MS/OS outputs in a “workspace-datastore-datalayer” stratified structure in the GeoServer, and exposes the data via the WFS (Web Feature Service) and WMS (Web Map Service).

**Public Safety Service (PSS)** works in two ways. First, it can accept requests from the mobile clients (MC) and send back general disaster information the system collected or generated from the MS/OS. Secondly, in emergent cases, it can directly push notifications to the public via third-party notification services (e.g., APNS from Apple), SMS and social media channels.

**VGI DataLayer Service (VDS)** is designed to aggregate user reported information from crowd-sourced platforms such as Ushahidi, Emergency and AUS. Validated VGI data can be used as MS inputs.

**Official DataLayer Service (ODS)** can retrieve data either on-request or periodically from authoritative data sources such as Vicroads, Bureau of Meteorology (BOM), and Vic Emergency, and store the data in the local Postgres database via the Data Integration Service.

**Data Integration Service (DIS)** can work in both offline and online modes. In the offline mode, infrastructure data layers (e.g., population, road network, schools, hospitals, facilities, DEM, etc.) from distributed data sources (e.g., ABS, Vicmap, Vicroads, CFA) are manually prepared and loaded into Postgres. In the online mode, data gathered from the VDS and the ODS is automatically processed and updated in the local database.

**Appendix B: Postgres and GeoServer**

Postgres serves as the system’s local database. It maintains the configuration tables (such as user table and model table)
for running IDDSS and more importantly, it hosts datasets provided by various authorities. As a part of the Data Integration Service, importing geospatial data of different formats (e.g., shape file, file/personal geo-database, GEOJSON, GML) into Postgres is a challenging and time-consuming, yet vital step, for the system implementation.

Important as Postgres it is, GeoServer takes a more significant position in IDDSS architecture. It is designed for interoperability and can publish data from any major spatial data source using open standards. Being used as a data hub, GeoServer in IDDSS can access data either locally stored in shape files or remotely hosted in Postgres, and then publish data consistently in OGC standards such as WFS, WMS and TMS.

Figure B1 shows the structure of GeoServer Data Storage Schema and Data Publish Services used in IDDSS. GeoServer uses a “workspace-datastore-datalayer” stratified structure for data management. The IDDSS classifies the workspaces in two categories based on the types of data that workspace maintains. The “generic” workspace consists of data stores that link to Postgres to access data from various authorities. It can be treated as a permanent or a static workspace. By contrast, the “user” workspace is more dynamic. Every time a user runs a disaster model, it creates a new data store under their own workspace, and the data store contains outputs generated by Modelling Services and Optimisation Services. The GeoServer built-in publish service provides enough flexibility for data conversion and exchange. For example, when transferring data among the IDDSS services, we can utilise WFS and translate it into one of the four formats listed aside. But if we need to display maps we can use the WMS, which can generate continuous map tiles in different levels of scale for the target data layers.

Appendix C: open source projects

The families of open-source projects and free services that make up the groundwork of the system are shown in Figure C1. For spatial data management, Postgres and GeoServer form the core component. Additionally, the Ushahidi web platform and mobile application are both integrated to collect VGI data from the crowd.

Appendix D: Grass flood model

The GRASS GIS library (v6.4.4) provides a built-in hydrologic modelling module called “r.lake,” which fills a lake to a target water level from a given start point (seed). The output raster contains cells with values representing water depth and NULL for all other cells beyond the lake. The water depth is reported relative to the specified water level. It uses a $3 \times 3$ moving window approach to find all cells that match three criteria and to define the lake:

(i) cells are below the specified elevation (i.e., water level);
(ii) cells are connected with an initial cell; and
(iii) cells are not NULL or masked.

To mimic the VGI inputs for “r.lake,” the user can directly choose the seed location on the map, from where the water level (in metres) for time interval (in seconds) can be edited in pair. The time interval is relative to the epoch value, which controls the simulation start time. Once the model is completed, the flooded area for each time interval can be loaded on the map.

Appendix E: MIKE 21 flood model

For the purpose of this study, the following data from the Maribyrnong City Council and Melbourne Water was obtained and used as input in the IDDSS prototype’s interface with the MIKE 21 model:

(i) a detailed (0.5m) contour lines of the area;
(ii) river boundary lines;
(iii) building type (e.g., number of stories, construction type, area) and their footprints from LiDAR data;
(iv) flood extent digital map for minor, moderate and major flooding (1-in-100-year event) in the area;
(v) duration and rainfall data for 1-in-100-year storm scenario in Maribyrnong river catchment;
(vi) hydrograph (Discharge level) at the boundary of the study area using RORB model;\(^3\) and
(vii) rating curve for south boundary condition of the study area.\(^4\)

A number of the above data (e.g., elevation model, building footprints) was imported and stored in the IDDSS database for further analysis. In addition, spatial distribution of the surface roughness of the study area was created according to the characteristics of the surface (e.g., roads, grass, and buildings) and stored in the IDDSS database. This provides an opportunity for a more realistic water movement in the study area. On the other hand, some of the inputs such as the north boundary condition (discharge hydrograph) and the south boundary condition (the rating curve) were created during the set-up of the model, based on the inputs from Melbourne Water. The user interface allows both manual entry and automatic input based on tabular information.

MIKE 21 is a desktop application, and creation of an automatic workflow for interaction between the IDDSS and the model is complex. This is considered to be one of the limitations of the integration of such a model with the IDDSS. However, for the purpose of this study, a manual intervention was used and a number of model inputs (e.g., elevation model mesh file) were created manually and imported to the MIKE software. Based on the contours and elevation points obtained from the council, a flexible mesh of the study area was created to be used in the MIKE 21 model.

**Appendix F: GRASS bushfire model**

The bushfire model demands various input datasets in two main categories. Static datasets such as fuel, moisture, terrain slope, aspect and elevation are all pre-calculated and stored in the server, while dynamic datasets like wind speed, direction and fire ignition points can be set up from the user interface. One limitation of the default GRASS bushfire modules is that once the simulation process starts, there is no chance to intervene with changing conditions. For instance, the simple combination of “r.ros” and “r.spread” cannot simulate the wind speed and direction changes over time in one shot, while the wind is constantly changing in the real world. To eliminate this limitation, the IDDSS breaks down the entire simulation process into small simulation steps to stay in line with the rhythm of wind condition changes. It assumes that in each small simulation step, the wind condition remains constant and the output (the fire boundary polygons) of one step will be used as the fire starting layer for the next step.


\(^4\) Extracted from Melbourne Water’s previous study of the case study area.