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A new mapping tool to visualise critical infrastructure levels of service following a major earthquake

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ABSTRACT

How can emergency management teams communicate to potentially impacted communities what a major event causing infrastructure outages might mean for them, and what they can do to prepare? In this paper we describe the process of creating a webtool for end users to visualise infrastructure outages that the Wellington region of New Zealand would face following a rupture of the Wellington fault. This webtool creates insight for three key groups: critical infrastructure owners, communities, and the emergency management sector itself. Critical infrastructure entities can use the tool to understand where they might consider infrastructure upgrades to mitigate gaps of delivery following a fault rupture, and to consider their emergency response plans for delivery in an emergency (leading to their consideration of 'planning emergency levels of service'). Communities can use the tool to understand what infrastructure outages will mean at the household level in an emergency, including the considerable distances that some community members will have to walk to access services such as food and water and prepare for prolonged outages. Finally, with a greater knowledge of the gaps in delivery and of those community members that might need assistance with food and water collection, the emergency management sector can be better prepared. The methodology for creating the webtool is described, along with the insights that the completed webtool provides for emergency planning.

1. Introduction

How can emergency management teams communicate to potentially impacted communities what a prolonged infrastructure outage might mean for them, and what they can do to prepare? To support community emergency preparedness, and help infrastructure providers define targets for the delivery of services in an emergency event, the concept of 'Planning Emergency Level of Service' (PELOS) was created, as detailed by Mowll, et al. [15,17]. Many infrastructure providers use the term 'level of service' to describe features of infrastructure, through 'asset condition, performance and other relevant outputs' [4]. While the term and use of levels of service is a well-understood tool in the management of infrastructure, Mowll et al. [15] found that there are few examples internationally of utilities publicly stating measurable and timebound levels of service that are specific to emergency response. One of the few examples in Aotearoa New Zealand of a publicly available emergency level of delivery of service is Wellington Water's '20 litres of water per person, per day, within 1 km of dwellings, by day 8' [31]. Such a statement demonstrates Wellington Water's planning intention (hence the term '*Planning* Emergency Level of Service' [PELOS]), and their goal for delivery in an emergency. This Level of Service is based on well-researched and authoritative sources [20,34]. However, other sectors such as energy, telecommunications and transport are not rich in similarly authoritative sources, and therefore it is harder to establish thoroughly researched PELOS for those sectors [15]. This paper is presented as a case study of how a tool can be developed as a means for end-users

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and planners to visualise infrastructure outages from a rupture of the Wellington fault and to understand the relative likelihoods of PELOS being achieved in such an event. The infrastructure providers will see where, and where not, PELOS are likely to be achievable with existing infrastructure in the region, providing information on where infrastructure upgrades could be considered, or where emergency response plans might need to be developed to deal with outages. For the public, the implications of the outages detailed by the Wellington Lifelines Group (WeLG) from a rupture of the Wellington fault (see below) will provide information on household planning for a major event. For the emergency management sector (including the delivery agencies of critical needs, such as healthcare), a knowledge of existing gaps in the ability of infrastructure providers to deliver services will help to guide where effort should be made in developing response plans. It is recognised that there are other ways of assessing and visualising risk to infrastructure and communities, however the webtool in this paper is presented as a way for the above three sets of stakeholders to visualise the impacts in one tool. This mapping tool could be created for other geographic locations.

The adoption and communication of PELOS can support emergency planning undertaken by critical infrastructure entities (referred to as lifeline utilities in New Zealand) and the emergency management sector, by creating targets for delivery in an emergency. The Wellington Lifelines Group (WeLG) works 'to co-ordinate the physical risk management activities of Wellington utility and transport service providers' [26]. The Wellington Region Emergency Management Office's (WREMO's) mission is 'Empowering communities to build the resilience and continuity necessary for the region to be prepared to respond to, and recover from, emergencies' [28]. WeLG and WREMO have led the creation of PELOS to not only inform the intentions of critical infrastructure providers in an emergency, but also help infrastructure providers and emergency management inform each other of their response intentions. This inter-organisational work helps the providers to understand interdependency issues, as each critical infrastructure entity will be able to view the modelled levels of service of the other sectors, and therefore understand how those outages will impact their own levels of service. For example, the water provider will understand the power utility's targets for resumption of services, therefore informing the timeframe for restoration of networked power to pump stations.

The power of providing mapped visualisations using web-based GIS mappings are well recognised [6,7]. This paper describes the process of creation of the webtool and the benefits that it is intended to produce. In essence, this webtool takes the outputs of a WeLG project which calculated the infrastructure outages that would be sustained in a rupture of the Wellington fault [25] and presents these in a webmap, comparing the outages against the PELOS developed for the region. While detailed analysis was carried out through that work, it presented infrastructure outages mainly at the suburb-level, which is reflected in the results presented in this webtool. This work provided information on the relative levels of resilience of the infrastructure networks (along with a proposal on how the infrastructure could be made more resilient). While this represented only one hazard scenario (there are many fault locations in the Wellington region (GNS [5])) and other hazards that could impact the Wellington region [27], as detailed by the [25], the Wellington fault presents a maximum credible earthquake scenario, and therefore an event that can be planned against (for discussion on this aspect, see Section 4.4).

This paper therefore both describes the process of creation of the webtool and the benefits that it is intended to produce. It describes the methodology of the creation of the tool (Section **2)** before giving an overview of key features of the tool (Section **3).** A discussion on the features and use of the tool is in Section **4**. Conclusions are drawn in Section 5.

The webtool produced is available at: https://apps.uintel.co.nz/wremo

2. Methodology

2.1. Research context

The mapping tool presented enables community members, critical infrastructure entities and members of the emergency management sector to visualise how infrastructure outages from a rupture of the Wellington fault would impact them. This visualisation can be seen 'for [the] public', showing walking distances to water, food and community hubs, and 'for [the] planners', showing numbers of people impacted and areas that have either good, or poor, service coverage.

The work presented in this paper is a component of a broader study which firstly proposed a PELOS framework for a large earthquake on the Wellington fault [15,17] and then operationalised this framework [15,17]. The overall PELOS project was carried out using Action Research methodology, where a researcher who works within an organisation researches an aspect of the work [12]. This methodology was utilised as the lead author of this paper is the Project Manager of WeLG and the Lifeline Utilities Co-ordinator with WREMO. Such a process is not unique in New Zealand, as the lifelines groups around the country participate in collaborative projects (for example, [33]). For the research/project methodology, the overall process for the broader study is described in [14], however the key steps for creating the mapping tool are, as shown in Fig. 1.

2.2. Steps taken in developing the webtool

This section broadly follows the steps taken in Fig. 1, but gives greater detail on the steps shown in the figure. The source of the data used in the webtool is described in Section 2.3.

2.2.1. Mapping tool created to compare 'best guess' PELOS vs modelled outages

To test the usefulness and viability of comparing PELOS to modelled outages, a prototype mapping tool was developed. This prototype was relatively simple in its format and functionality but demonstrated that a comparison between the PELOS and the outage times identified from the above reports could be mapped. The prototype was discussed with emergency managers to ensure that proceeding with further work on the tool was worthwhile and some improvements suggested by emergency management staff at WREMO were incorporated at this stage, regarding features of the webtool including how infrastructure in parts of the region then not covered by the webtool were shown (for example, emergency water provision to the Wairarapa in the east of the region. Having established that there was an appetite to develop the tool further, the following steps were then taken.

2.2.2. Community group asked for feedback on PELOS framework, updated/refined PELOS and prototype mapping tool

To evaluate the usefulness of PELOS and the prototype mapping tool, two additional workshops were held with community members. The first workshop focussed on the usefulness of the concept of PELOS [14]. A second community workshop then asked participants for feedback on the usefulness and functionality of the prototype mapping tool. The question sheet used for that workshop is included as supplementary information to this paper. In summary, the community workshop members ran through a set of tasks used to establish the user-friendliness of the tool, and how easy it was to extract relevant information from it. At the time of the second workshop, the mapping tool opened on the 'for planners' section, with a separate button available for inserting the tool-user's address. Therefore, this workshop covered both the 'for public' and 'for planners' sections.

The output of the workshop was a set of suggestions for improvements, considering both the usability of the tool and its visual appearance. The collated feedback from the community workshop is also included in the supplementary information. As can be seen from that

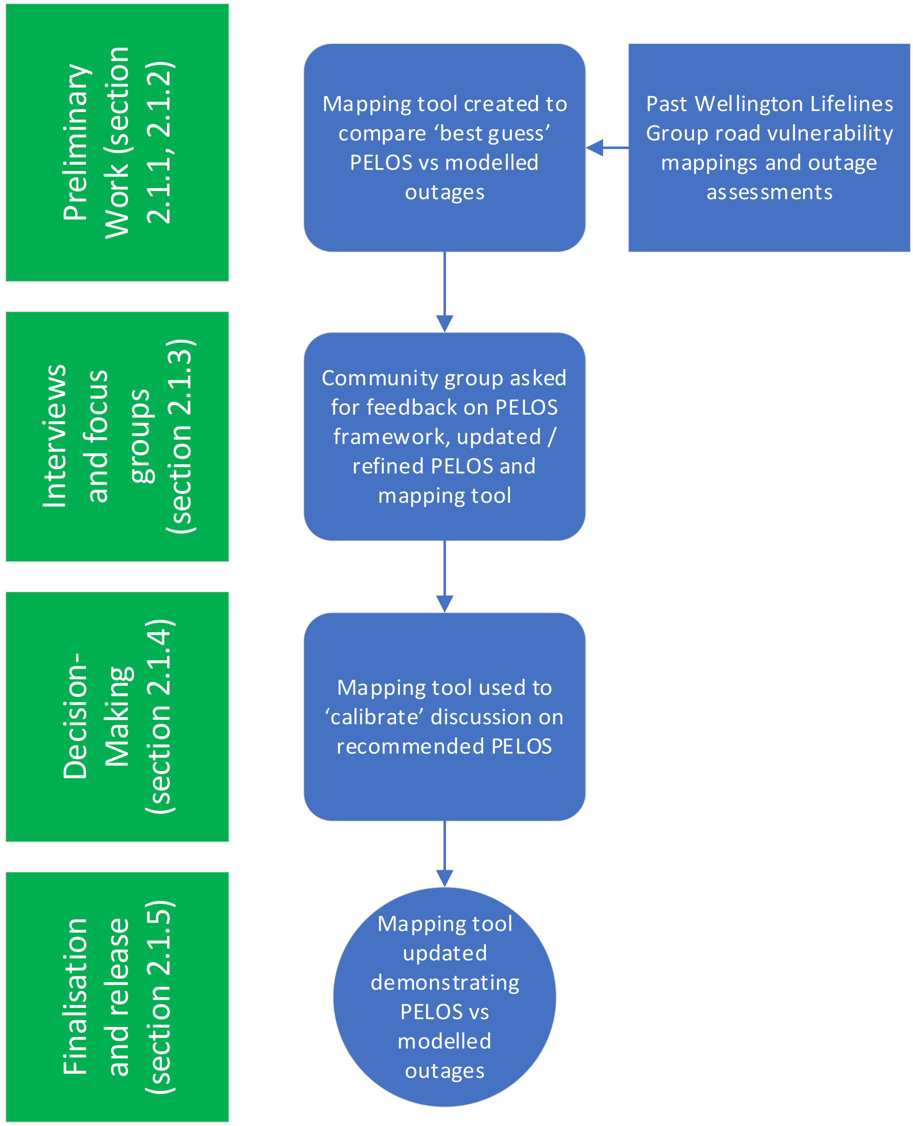

Fig. 1. PELOS mapping tool creation process. Part-reproduced from Mowll et al. [14].

output, some of the questions posed to the workshop participants required free text responses (e.g. 'during days 8-14 after a disruption, is the New World [supermarket] in Karori expected to be open or closed'). These tested whether the webtool was easy to use by participants to ascertain information. In the case of that question, four participants responded correctly and two incorrectly. This indicated that that function of the webtool was not fully intuitive to use, leading to the development of the 'tutorial' function in the webtool. Additionally, participants were asked to provide ratings to some questions, for example, 'As a resident, does the site provide adequate information around how to prepare for a disaster?', with responses requested from 'definitely not' to 'definitely' (in this case, there was a spread of responses from 3/5 to 5/5). This again led to various site improvements including, links from the webtool to the WREMO preparedness website [30].

From this process, key updates from community feedback included the following:

- After the landing page, the website was split into two access points 'for public' and 'for planners', so that the public are directed to a simplified output relevant to their address and planners can carry out greater analysis on resilience and emergency management issues.
- Various colours and visibilities of text on the website were updated to ensure that key aspects of the website were highlighted.
- The tutorial button was introduced into the 'for planners' page, to enable users to get help on using the website.
- An autocomplete was included, so that when users are inserting an address, it makes confirmation of the address easier.
- Updating the wording used on the 'for public' section of the webtool, including changing some of the language to be more suitable for laypersons, such as renaming 'wastewater (wees and poos)' to 'toilets'.

2.2.3. *Mapping tool used to 'calibrate' discussion on recommended PELOS*

The prototype mapping tool was then updated using the 'operationalised' PELOS framework, which is presented by Mowll et al. [16]. The changes between the PELOS stated in the preliminary framework and the operationalised framework were not different in terms of how they would be presented in the mappings, so no significant changes on the PELOS used in the preliminary and operationalised framework were required. Once this updated mapping was complete, it was used to engage key decision makers on the finalisation of the PELOS stated in the operationalised framework. This was carried out during a workshop held with the key stakeholders, mainly critical infrastructure entities and emergency management bodies of the Wellington region (for further details of this process, see Mowll et al. [14] for details on the methods, analysis and results of this workshop).

2.2.4. Mapping tool updated demonstrating PELOS vs modelled outages

In addition to these updates from the community workshop, WREMO staff members from the Community Resilience team, who work with Wellington region communities to raise preparedness for emergencies, provided feedback to ensure that the mapping tool used language and messaging consistent with the language used by WREMO on its public-facing products. Further updates to the webtool were also made at this time, based on the latest information available, such as the locations of supermarkets (see section 2.3.1).

2.3. Underlying data used in the tool

When considering what infrastructure services communities need in an emergency, it is necessary to consider both the provision of critical infrastructure at the property level as well as the accessibility of operational amenities from dwellings [3,9]. To assess this, Python, Open Source Routing Machine, and various open-source datasets were utilised. This section discusses the required data inputs, processing methods, and development required to formulate this information and house it within a webtool.

2.3.1. WeLG road vulnerability and infrastructure outage assessments

In order to understand the scale of potential durations of infrastructure outages for the region, it was necessary to have some base-line information as a starting point for discussions on both PELOS and for creating a mapping tool. Information gathered from previous Wellington Lifelines Group reports were used as the base infrastructure outage information for the mapping tool. The road vulnerability mapping shown by the Wellington Lifelines Group [24] (in Appendix 2 of that report) and the grid matrix used to outline road outage times by the Wellington Lifelines Group [25] (in Fig. 5.2 of that report) were used as the sets of base information for understanding road outage durations. For the webtool, this is used as a basis for demonstrating when supermarkets can be re-stocked. Both of those reports are based on the hazard of a rupture of the Wellington fault, producing a large earthquake impacting the region, which is why this mapping tool is based on that hazard. The outages of other utilities (e.g. power (electricity), water, telecommunications) used in the webmap were taken directly from the Wellington Lifelines Group [25] report.

2.3.2. Population and facility data inputs

Community members and emergency managers, or 'end users', are the crux of emergency management planning. Using 2018 census data from [21,23] for the Wellington Region, spatially explicit information on various socio-demographic groups (e.g., people with mobility-impairments, or classed as vulnerable or socially deprived) was used as an input to the webtool. In New Zealand, this spatially explicit information is provided at the statistical area 1 (SA1) level and statistical area 2 (SA2) level. SA1 is the smallest census spatial area produced by Stats NZ and includes, on average, 100–300 people. It includes information such as population, ethnicity, social deprivation indices, and household income. This is important to enable planners to identify areas that may require more support to prepare or recover following a prolonged infrastructure outage.

SA1 level information gives useful results when assessing a regional or suburb-scale picture but lacks granularity when compared with individual household information. Building outlines [8] were used as an input to the webtool to amend this. This information enables property specific results to be reported and communicated. This is discussed further in section 3.

The Transportation Network is a required input to understand if users and goods can be transported between locations. Ultimately, this indicates whether critical infrastructure can be accessed for repair and maintenance, if supplies can be made available at specific locations for the function of certain amenities, and the ease with which users can reach locations of interest. Roading information for this analysis was taken from two sources, (1) OpenStreetMap for routing [18], and (2) the road outages from the Wellington Lifelines Group [25] report.

The Amenity (Destination) categories refer to locations that provide a vital function, post-event. Determining the types of amenities to include should be based on the needs and values of the community and, in practice, should be selected based on engagement with local governments and communities [19]. The amenities used within this study are summarised in Table 1.

The Infrastructure categories include power (electricity), telecommunications (phone and internet service), FM/AM radio & TV, and toilets (on the 'for public' section or 'wastewater (wees and poos) on the 'for planners' section). These infrastructure types are considered at a sub-regional level and are mapped based on infrastructure coverage. The webtool does not use or require the location of the nodes and edges within each network, but rather the area that they service, as defined in the Wellington Lifelines Group [25] report.

2.3.3. Infrastructure functionality data inputs

To provide accurate and informative information we utilised expert elicitation to understand how each network will react to the potential event and therefore, what level of service it may provide over each timeframe. For the amenity categories, this requires knowing whether the infrastructure supplying any given amenity is functional. For example, for a supermarket to operate, it requires power and water supplies and, an operating internet connection to process debit card transactions (acknowledging that some supermarkets can 'cache' transactions during an outage, until the internet connection is restored). Each of these functions was taken from the Wellington Lifelines Group [25] report. Expert elicitation was used to interpret where there were gaps in the information available in the report, for example, where a supermarket was located close to, but not within, the area being assessed.

The method for assessing this functionality, described in section **2.1.1**, determines the state of all amenities and all infrastructure service areas for each timeframe. These classifications are described in Table 2. The functionality of critical infrastructure matches the descriptions in the WeLG report [25].

These results are analysed and mapped over timeframes modified from Mowll et al. [16]. We define the day the hazard event occurs as day 0, before mapping the varying levels of service for the timeframes of 0–7

Table 1
Details of the amenity types used within this study and their source.

	Amenity	Description	Source
	Health Service	Medical centres and hospitals.	Logan et al. [10]
	Community Emergency Hub	A Community Emergency Hub is a place where neighbours can go to help each other in a major emergency.	Wellington Region Emergency Management Office [29]
	Water Distribution Point (or 'Collection Points')	Locations for the community to collect water from, in an emergency.	Wellington Water [32]
	Supermarket	Supermarkets based on supermarket company information as they existed in 2020.	Land Information New Zealand [8]; [10]
	Fuel Station	Fuel station, also known as a filling station, petrol station, gas station and petrol garage.	OpenStreetMap Contributors [18]

Table 2
Functionality classifications of amenities and critical infrastructure.

	Amenity Classification		Critical Infrastructure Classification
	Open		Functional (80%+)
	Open – stock dependent		Partially Functional
	Closed		Non-Functional or Unknown

days, 8–14 days, 15–30 days, 31–90 days, and 90+ days. This modification includes the addition of the 'days 8–14' timeframe, a timeframe that is not included in [16]. This amendment was made due to the availability of data for the mapping and was seen as a useful addition by the webtool developers and WREMO to add further detail on the restoration of services.

2.3.4. Access to facilities data inputs

To demonstrate on the webtool access between inputted addresses and operational amenities the webtool uses street network routing from every building in the region using methods described in [1,11]. For each timeframe after the hazard event, the webtool uses inputted addresses as origins, and pre-determined operational amenities as destinations, and uses a modified transport network that allows pedestrian access on otherwise non-operational roads. Using Python, SQL, and Open Source Routing Machine, the origin and destination pairs were prepared and analysed. This analysis returns a matrix of distances and durations for each origin and destination pair. The shortest distance is kept and reported in the webtool output.

Access is visualised at a regional level by aggregating information at a SA1 level by the average distance each SA1 would have to travel to the selected amenity. This is grouped into six bins as demonstrated in Table 3.

The bins for grouping and visualising access can be changed depending on the population and amenity. The choice of 2 km and 1 km as a walking distance to the respective amenities is detailed by [16]. The colours shown in the webtool for access to supermarkets, health care, community emergency hubs, and fuel stations commence with the 0–2 km distance and rise in 2 km steps. This shows the distance that residents would have to travel from their home to the nearest operational facility following an event. This process was mirrored in the access to water category, noting that the PELOS for water is 1 km to dwelling [16], with the steps shown for water in 1 km steps. (As described in Mowll et al. [16], the 1 km distance for water collection matches the World Health Organisation's basic access to water standard, and the 2 km distance to supermarket is the distance based on the available literature and expert opinion.) The advantage, for planners, of being able to view those different distances is that emergency planners will be able to see how many community members may require assistance in an emergency to access water and food.

2.3.5. Household level impacts data inputs

To provide household-level information for PELOS at each timeframe post event within the webtool, each building was reverse geocoded. This enables users of the tool to enter their address to the webtool and receive instant results on potential impacts. Reverse geocoding is a process that assigns an address to a particular location, such as a building, based on its coordinates. By reverse geocoding each building outline to its respective address, it is possible to display modelled information at the property level, which provides more granular data than what is available at the census level. In this way, it is possible to report and communicate property-specific results for infrastructure services, which is a clear advantage in the use of this webtool for enabling community level preparedness.

For visualisation purposes, the web-tool shows results aggregated from the household level to the SA1 level. This enables viewers to better understand the variation in level of service around the region.

2.3.6. Coding the web-tool

The development of the web-tool to visualise the modelled results involved the use of standard front-end development programming languages and tools, including JavaScript, Leaflet, HTML, and CSS. These languages and packages were chosen for their ability to create dynamic and interactive web functions, as well as their ease of use and compatibility with a wide range of web browsers. One of the main challenges in developing the web-tool was how to effectively communicate the vast amount of information stored in the database to users in a way that was clear, concise, and easy to understand. To achieve this, the iterative approach that utilised stakeholder and user feedback as detailed in section 2.2.2 was followed.

3. The tool: An interactive dashboard

This tool aims to provide a comprehensive view of PELOS, both regionally and at an individual property level. The webtool was structured with three key areas: the landing page, a section 'for public' and a section 'for planners'. While all three sections are intended to be available to all users, each serves a distinct purpose.

3.1. Landing page

The landing page provides the context for the webtool, including information on the base data used in the mappings. Ultimately, this page

Table 3
Walking distance categories for access to amenities.

	Walking Distance	
	Supermarkets, Health Care, Community Emergency Hubs, and Fuel Stations	Water Distribution Points
	0-2 km	0-1 km
	2-4 km	1-2 km
	4-6 km	2-3 km
	6-8 km	3-4 km
	8+ km	4+ km
	Isolated	Isolated

is designed to introduce the webtool while also providing additional resources to either encourage emergency preparedness or better understand the information presented in the webtool. The 'for public' and 'for planners' sections are linked from this landing page.

3.2. 'For planners' section

The information provided in the 'for planners' section shows numbers of residents receiving different levels of service to both amenities and networked infrastructure sectors. This includes an overview of the region and sub-regions over time, as well as a graphical representation of various demographic types. For first-time users of the webpage, a tutorial set of instructions appear on first-use of the site (and can be re-seen via the 'Tutorial' button to the right of the page). While WREMO staff may carry out walk-throughs of the site with community groups, the tutorial part of the webpage was tested (see Section **2.1**) and then considered by WREMO and the authors to be sufficient to enable users to engage successfully with the tool). These functionalities in the 'for planners' section can be seen in Fig. 2.

3.2.1. Networked infrastructure sectors

As an example of the output of the webtool, we consider the provision of critical lifeline services to residents over the first 90 days post-event. Fig. 3 shows how the level of service for electricity varies across the region over different timeframes. This is, essentially, a visual representation of the outage mappings produced by the Wellington Lifelines Group [25]. It allows for an easy comparison against the PELOS outlined in [16].

3.2.2. Accessing key amenities

The webtool also enables residents to determine their access to key amenities in terms of walking time.

Fig. 4 depicts how access is slowly returned to residents, where some supermarkets reopen, as shown by the changing colours over the geographical area (see Table 3 for the colours used). However, there are several areas that will remain very far from their nearest open supermarket. This shows walking distances in those areas of >8 km. During the timeframes of 8–90 days, supermarkets shown with a yellow icon, seen within the Hutt Valley, are only operational based on the emergency response plans to re-supply stocks to those areas, which would depend on an emergency supply chain, as the main roads serving the Hutt Valley are known to be vulnerable to outages [25]. Again, this highlights the need for both community members and emergency planners to plan for lengthy outages of road access.

3.3. For public

The 'for public' area is an simplified output of the outages relevant to individual addresses. In this section, a user can input a street address, and this will provide information about what levels of service they can expect and should prepare for following a prolonged event. The intention is to help householders understand the potential impacts of, and prepare for, potential emergency events. An example output is shown in Fig. 5.

The walking distances to access food, water and a Community Emergency Hub following an event can be modified by updating the number of trips they expect they will need per week to visit each of those services and shows the total walking distance in kilometres that they would need to travel. Further, a toggle allows the webtool user to switch from distances walked per week to number of minutes taken to walk to the various services per week. The networked infrastructure outages for the address are also shown immediately below the walking distances table (as taken directly from the 'for planners' section of the webtool).

Finally, a 'print results' button allows the webtool user to print the results for their selected street address, allowing householders to compare their predicted levels of service alongside key emergency

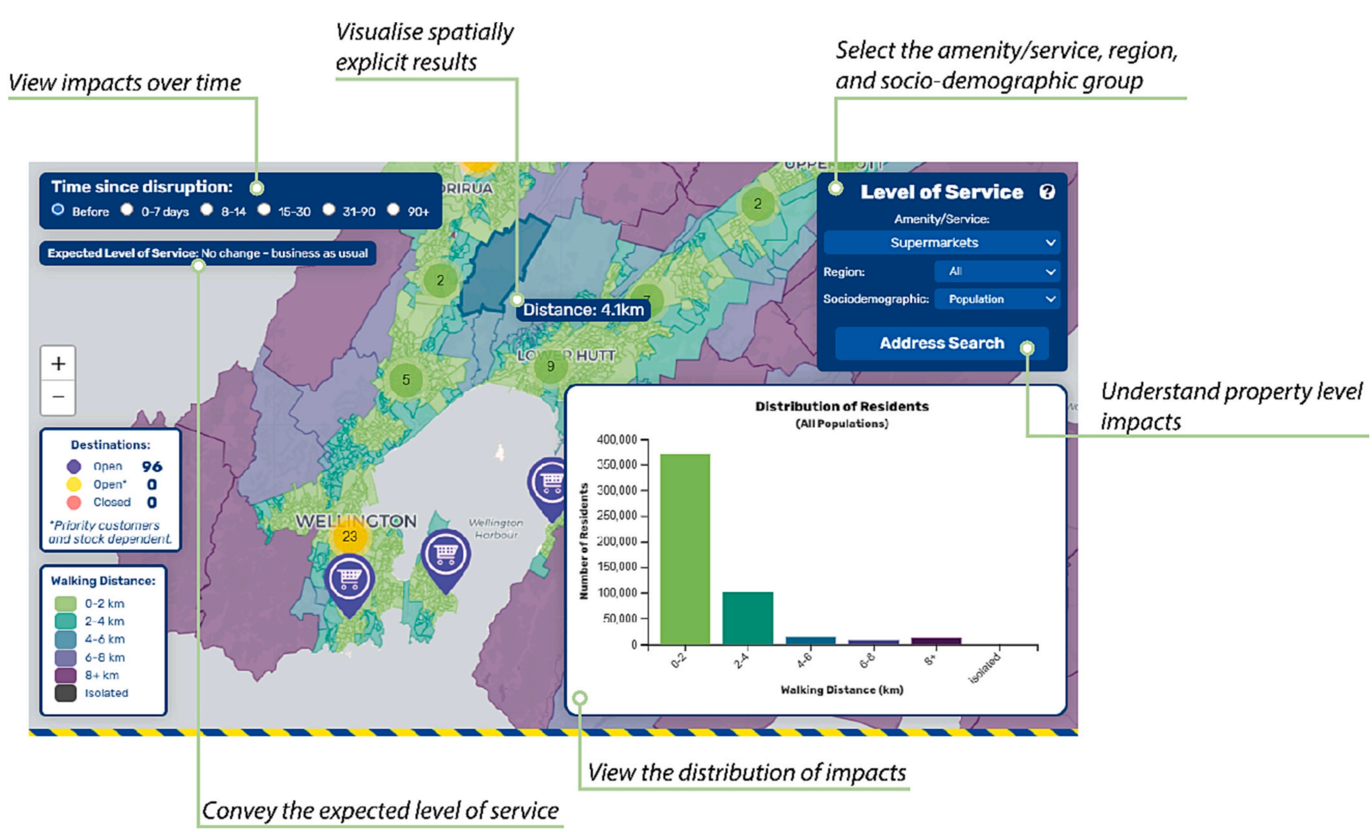

Fig. 2. Functionalities of the 'for planners' site section

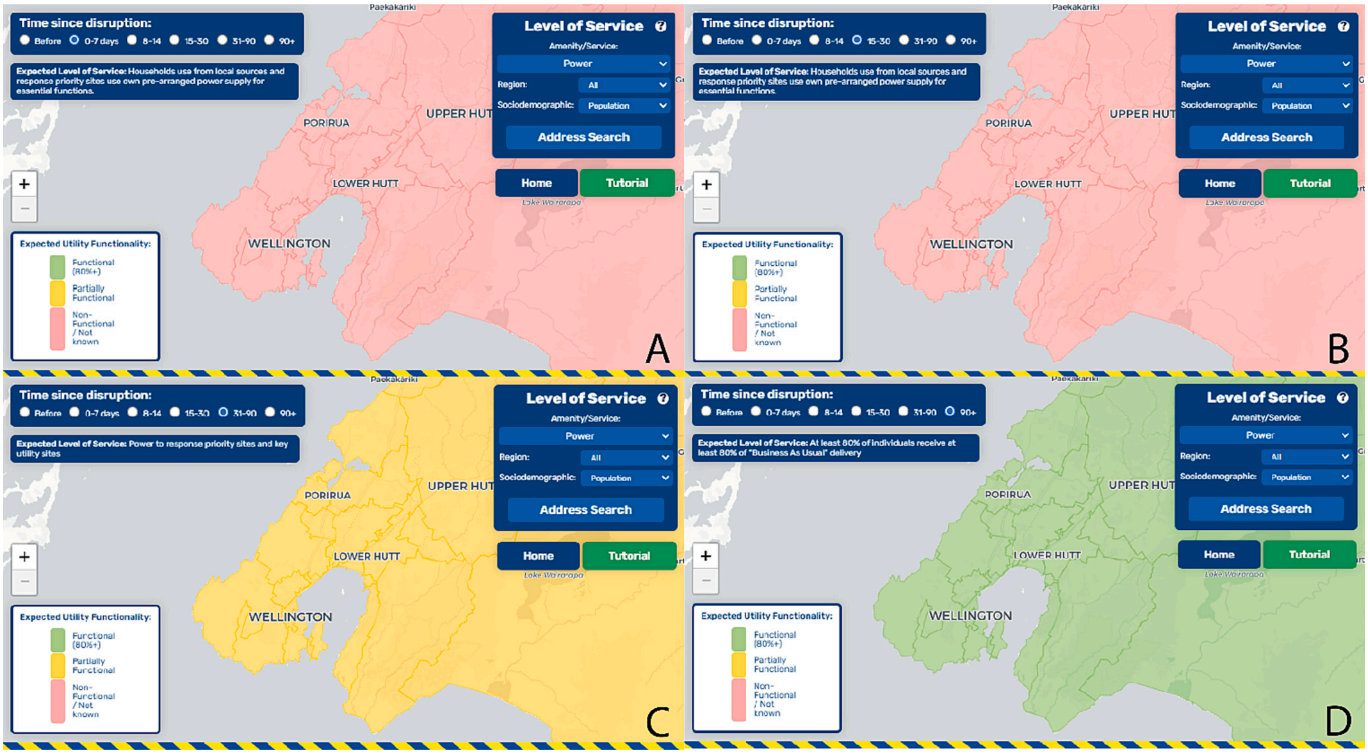

Fig. 3. Electricity level of service over time. Region-wide view demonstrating the ability for facilities and homes to access power. A) 0–7 Days. B) 8–30 Days. C) 31–90 Days. D) 90+ Days. Red describes that the service is non-functional; Orange/Yellow is partial functionality; Green is >80% functionality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

preparedness messaging provided by WREMO, which is included in the print version of the outputs.

4. Discussion

4.1. Functionality of the webtool

So, how can emergency management teams communicate to the potentially impacted communities what a rupture of the Wellington fault might mean for them, and what they can do to prepare? The objectives of the webtool, as highlighted in Section 1, were to provide a visual representation of PELOS, and for critical infrastructure providers, community members and the emergency management sector to be able to visualise planning and response/recovery timeframes.

For the demonstration of water and food access PELOS, the webtool provides two key features. Firstly, in the 'for planners' map function, the colours provided on the map for 0–2 km distance for distance to an open supermarket and 0–1 km distance to a water distribution point provide a quick visualisation. This helps the water and emergency management sector understand the areas that are outside the PELOS (1 km and 2 km respectively), and therefore the areas that communities may require additional support to access services, post-event. Further, the bar chart provided in the bottom right corner of the 'for planners' section gives a quick visual indication of the numbers of community members that are within each access zone. This is further enhanced by the breakdown in the top right corner of the 'for planners' section of the webtool for suburb-level areas and for those community members that either have difficulty walking or are socially deprived. These features satisfy the original intention of demonstrating PELOS against a model of outages [25], and indeed deliver the additional benefits of demonstrating the impacts on potentially further impacted communities.

The 'for public' section of the webtool has the potential to give good insights for households to understand the scale and features of immediate post-earthquake events. A key feature of the webtool is that the information is not just delivered without context but is shown alongside WREMO messaging for preparedness actions the community can take. The intention here is to inform community members of modelled outages, but to then help people proactively prepare for 'worst case scenario' emergencies.

Comparing, therefore, against the original webtool objectives, from the perspective of providing a technological tool, the authors believe that those objectives have been satisfied. The usefulness of the tool to the public will be better understood on its release.

Comparing to other tools that are available for other contexts is difficult, as this is a novel tool that focusses on PELOS (we are not aware of other regions having developed PELOS in other regions), but there are other dashboards. The closest example is the paper on access to services by Logan and Guikema [9] which outlines how a hurricane impacted access to Wilmington in the USA in 2018 (dashboard available at https://research.uintel.co.nz/resilience-florence/), including how access changed over time. Otherwise, a range of community emergency and climate preparedness tools are available from the and the University of Central Florida [22] however these do not have computational analytics behind them, as were developed for the WeLG/WREMO webtool.

4.2. Process/approach overview

Was the methodology taken appropriate to achieve the above objectives? The methodology taken for the creation of a PELOS framework and this webtool, as demonstrated in Section 2, is iterative in nature, in that four separate versions of the webpage were required: a prototype to demonstrate that the webtool could be created, another version for the critical infrastructure providers to visualise modelled outages, an updated version used for feedback at a community workshop and the final version (as presented in this paper). While this required multiple steps to create the final version, it has created a more polished product that satisfies the original objectives of the webtool. Without such an iterative process it is unlikely that such a relatively polished product

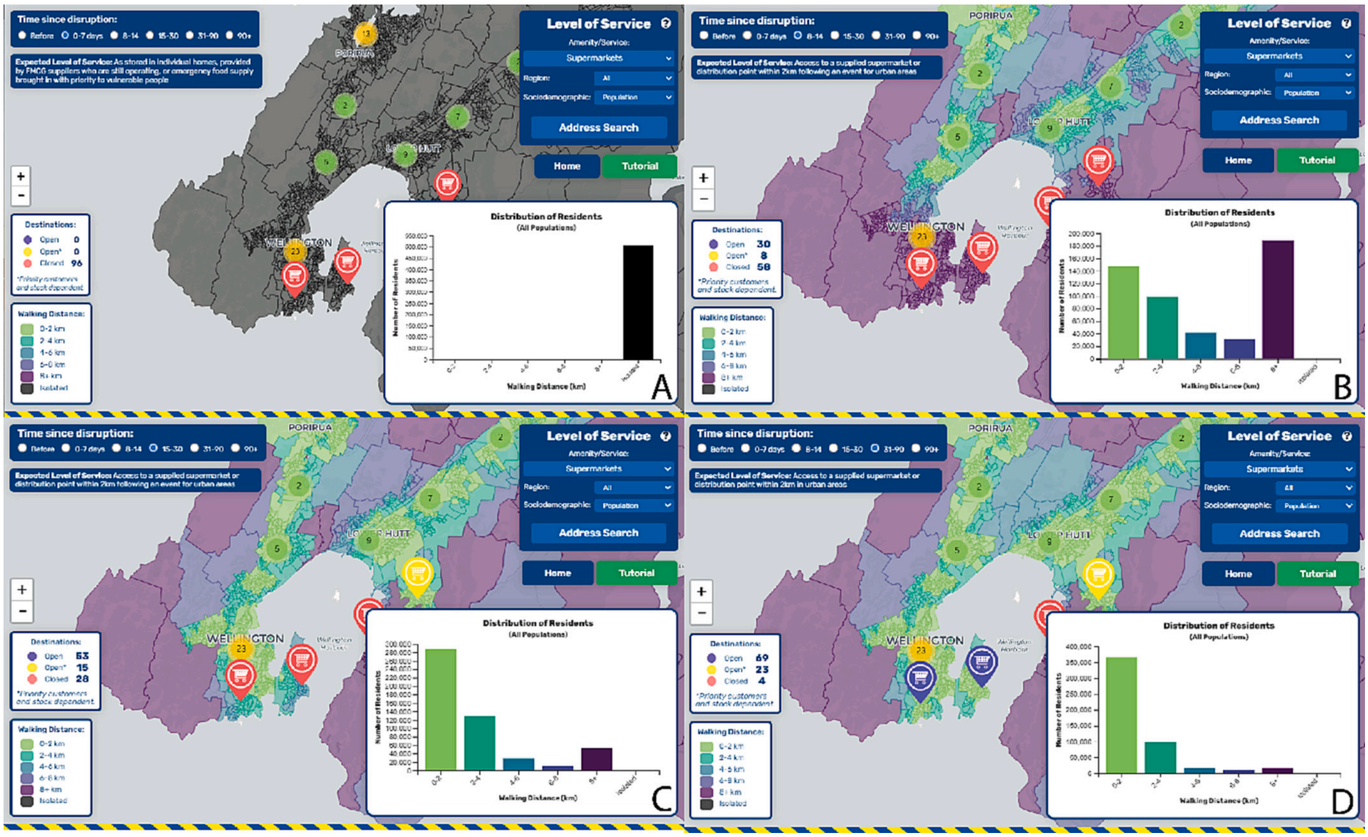

Fig. 4. Accessibility to food sources over time. Shows how access to supermarkets changes over four time periods post-event: 0–7 days, 7–14 days, 15–30 days, and 31–90 days. Fig. 4(a) shows the total loss of access to supermarkets (due to loss of road access between distribution centre and the supermarket, meaning that re-stocking is not possible by road), demonstrating why residents throughout the region should store enough food supplies for their household for the first seven days post event (as highlighted in WREMO's household preparedness resources [30]).

could have been created.

4.3. Key insights from the webtool

As demonstrated, the mapping functionally demonstrates where PELOS have been compared to modelled infrastructure outages. One of the key learnings gathered is the long walking distances required for many households. One example, using the suggested 'generic' address given in the 'for public' section of the webtool – 2 Turnbull Street, Thorndon, is that over days '8 to 14' a person making 14 trips to collect water (assuming two people reside at the address and just one person is collecting the water), three trips to an open supermarket and three trips to a community emergency hub per week would have to walk 61.7 km that week (an average of 8.8 km per day), of which 10 km would be transporting 20 kg of water and 19 km would be carrying shopping. This is in addition to any trips to medical centres or other facilities. This is a substantial amount of walking, even for the fit and healthy. As highlighted in Section 3, those that are less mobile (the very young, old or those having difficulty walking) will not be able to access water and food themselves. Some of these people may be provided for by their carers (e.g. the parents of small children), but this creates an additional burden of collection on those carers. Some community members may not have carers to provide for such needs. This highlights the need for working pre-event to identify where gaps may exist for the delivery of services to the community, and where work can be carried out to bridge those gaps. By days '15–30′, the distances drop to 26.4 km overall, but the issues of collection persist. For a community member seeing these figures, it is hoped that this will provide a prompt to store water and food at home to minimise walking distances post-event. There may be many reasons why community members have not stored water or food at home [2,13], but this webtool does provide a basis for the planners to understand where there might be gaps for some community members, and therefore needs, to address.

4.4. Limitations

There are presently some limitations of the inputs to the model. Firstly, the modelled infrastructure outages, as taken as an input to the webtool from the Wellington Lifelines Group [25] report, are relatively simplistic, showing only 'on' or 'off'. That report details that power supply should be viable '3 to 6 months' following a rupture of the Wellington fault for a large part of the Wellington region. This does not allow for some facilities (for example the hospital) having their own generators, as detailed in the relevant PELOS, with the webtool only showing power is out for an area or the potential for degraded supply being available for parts of the response in some locations. This is not an aspect that can be immediately addressed through this webtool, however the concept of PELOS (which is referenced in the landing page of the webtool) does provide some of that context and texture and can be accessed by webmap users that require further information.

Methodologically, a key limitation of this research has been the relatively limited engagement with end-users, with a single community workshop conducted on the use of the webtool. While the workshop was valuable in demonstrating the ease (or otherwise) of the use of the tool, it provided a relatively limited set of perspectives. Greater engagement with other community members or groups would help in understanding how those, for example, for whom English is not their first language, or with accessibility issues would engage with the webtool would enhance it further.

The walking durations do not consider elevations or unknown access

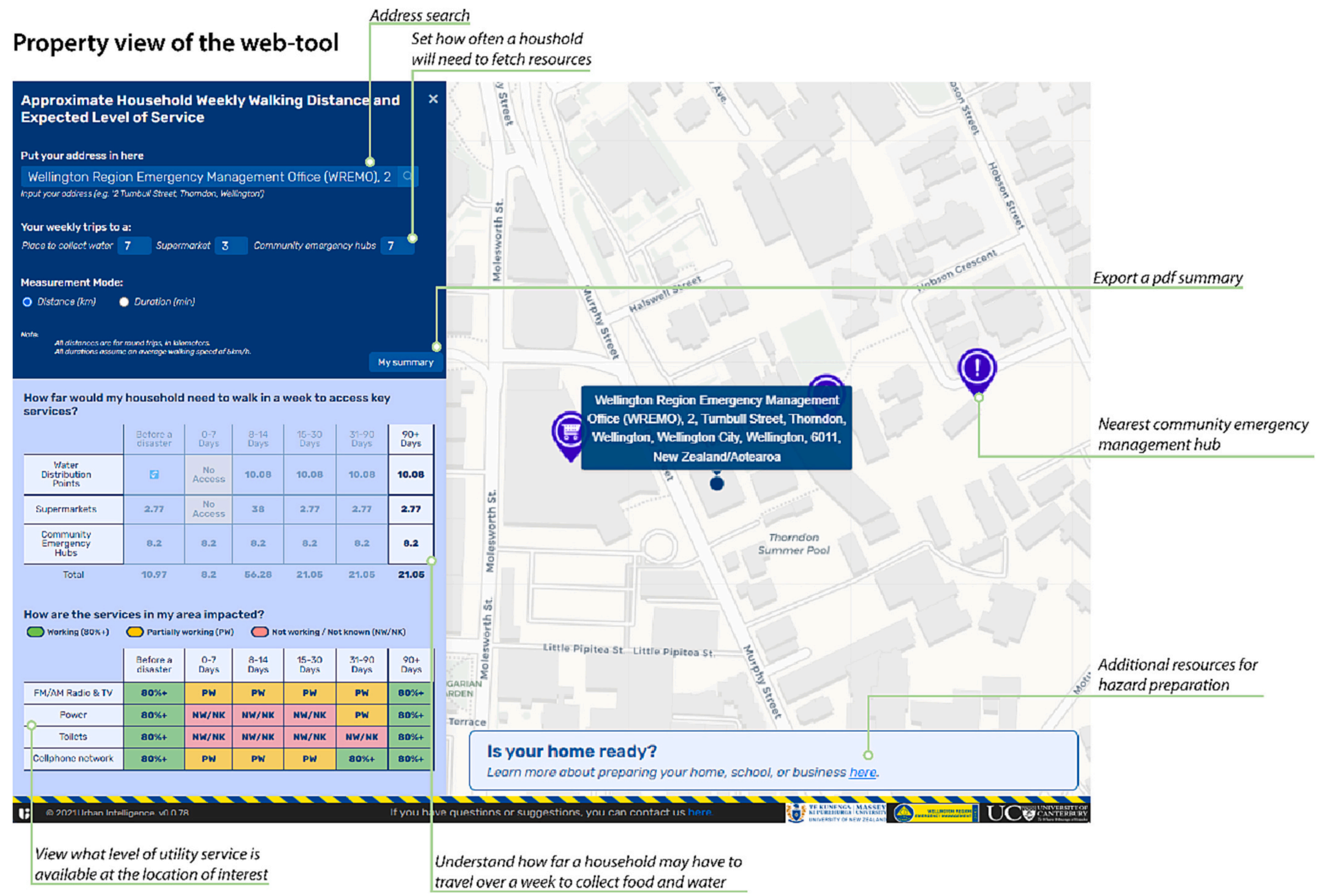

Fig. 5. Option for residents to explore what their levels of service are over time based on their address.

limitations post-event. Many of the suburbs in the Wellington region are relatively hilly, meaning that the transport of water or supermarket shopping up hills will likely take longer, as the current travel times assume a 5 km/h walking speed. The adjustment of walking times to allow for hills would improve the tool.

An additional limitation of this study is that the population data used is based on the 2018 census, which is now five years old. This data may not accurately reflect current population dynamics, potentially limiting the generalizability and applicability of the results. The source data for the population can, however, be updated with each census, allowing for the most recent dataset to be used.

Additionally, it is impossible to predict with certainty which services will, or won't be, available post-event in an emergency, particularly a major earthquake. For example, supermarkets and medical centres may not be operating post-event for a variety of reasons, such as loss of infrastructure services or lack of staff. Further, water collection points may be moved to suit specific circumstances post-event, landslips may unexpectedly block some roads and nearby building damage might limit access through some routes. Thus, the 'disclaimer' information provided on the landing page is important, to demonstrate that the information shown is only at the level of certainty that such a model can provide. This 'disclaimer' reads:

> "No infrastructure service can ever be guaranteed, especially following a major event such as a rupture of the Wellington fault. Please note that in an actual event the services available will depend on exactly what damage has happened and what staff are available to respond."

A further limitation is that only one hazard scenario has currently been used to demonstrate the achievability of PELOS against modelled outages (a rupture of the Wellington fault). A similar presentation of outages and walking distances etc. may be possible if future modelling is carried out on outages from tsunami impacts or other hazard events/ scenarios. At present, the rupture of the Wellington fault has been taken as a relatively unlikely, but representative, 'worst case scenario' earthquake event [25], and is therefore the only hazard event represented on the webtool.

Another limitation is that one of the caveats given in the PELOS framework is that 'end user experience may vary'. This is an acknowledgement that services cannot be guaranteed to all locations to a particular level of service, post-event. For example, there may be long waits to collect water at distribution points, or to collect food from the supermarket, where, additionally, only limited food options may be available. Equally, as these are a set of planning emergency levels of service, with the emphasis on 'planning', this webtool should primarily be considered as a preparedness tool. Communicating this difference is a key factor that was considered by WREMO and the WeLG and Wairarapa Engineering Lifelines Association members before agreeing to publicly release this mapping tool. Balancing the usefulness of the information shown against the potential for misuse of the information post-event (in the case that delivery did not match the modelling) was a key factor in this decision.

Finally, the webtool is based on a single hazard scenario – a rupture of the Wellington fault. Future versions could potentially include other scenarios such as tsunami or flooding impacts.

From the above, future potential enhancements include the depiction of other hazard scenarios, for example from climate change impacts, and the incorporation of other changes based on the public use of the site and therefore feedback gathered from the Community Resilience team at WREMO. There is currently no formal process for gathering feedback and providing an assessment on this webtool, as WREMO will gauge the level of interest from the public before considering whether further development justifies further development resource.

4.5. *What have we learnt from this process?*

The webtool has created a visualisation of the impacts on infrastructure and households of a rupture of the Wellington fault in a way that should be understandable to community members. The Action Research methodology used in this research allowed the lead author to carry out research within his organisation, a factor that allowed freedom to explore the development, and potential use, of the webtool. The steps taken in the methodology for this project (as outlined in Section **2.2**) allowed for an iterative process to develop the webtool.

The key issues highlighted through the overall methodology are that, it has been functionally possible to compare, on a webtool, modelled outages [25] against a set of PELOS [16]. Secondly, producing a webtool such as the one presented better informs following emergency planning steps for both the emergency management professionals and the community. This presents opportunities for communicating Wellington fault rupture impacts to three different groups: infrastructure managers, the emergency management sector, and the community. There is the potential for wide adoption of this type of approach internationally.

One of the key values of a tool such as this is the stress testing of the underlying ideas due to the accessibility of the information. Assumptions and, in some cases, limited theoretical bases for them, become more apparent. Wider adoption and uptake would drive additional investigation into some of these limitations for disaster resilience planning worldwide.

Additionally, viewing the webtool allows stakeholders and community members understand the implications of outages. For example, how will emergency services drive (or not) on roads to responses? 'How long will power outages be where I live?' The webtool allows such thoughts, leading to conversations around the relative resilience of infrastructure. It is hoped that this will lead to conversations on how resilience is valued, and how all parties can prepare for emergencies whilst the current infrastructure is in place.

4.6. *Applicability to other regions*

The key aspects of the production of the webmap that aided a good outcome were to have clear platform objectives and have early engagement with the users. As detailed in Section 1, the objective of the tool was to demonstrate where PELOS could, and could not, be achieved in a way that could be understood by the public. For engagement with the users, WREMO staff were involved in the development process from an early stage and engagement with end users was carried out to ensure that the public would be able to interface with the tool.

While the mapping of modelled outages through a similar webtool could be created in any region that has access to modelled outages, this mapping tool could only be used in a region that has also defined its own PELOS, or choses to adopt similar ones to those identified for the Wellington region [16].

5. Conclusion

A mapping tool has been developed to visualise PELOS. It serves as a valuable resource for planners and emergency managers alike, allowing them to better understand the unique requirements of different communities. Additionally, members of the public can access this tool to obtain specific information about how their community may be impacted in the event of an emergency, allowing them to take proactive measures to protect their homes and businesses. In summary, this tool plays a critical role in promoting community preparedness by providing essential information to both planners and members of the public. Through its comprehensive approach to PELOS, it is intended to empower individuals and communities to take proactive steps to ensure their safety and security in the face of future emergencies. The tool enables users to examine the modelled outages after a potential Wellington fault rupture over five different time periods for five different amenities and four different networked infrastructure sectors. These include access to food, hospitals, water, emergency management hubs, and fuel/LPG; and the functionality of electricity, telecommunications, radio broadcast, and wastewater services.

While there are limitations on the usefulness of the tool, including that it currently has focussed on one hazard scenario, and that it cannot consider the variabilities of end-user experience, we propose that this is a useful tool forcommunicating the general outcomes on infrastructure outages that may be seen in following a major earthquake impacting the Wellington region. Ultimately, with the insights that the webtool provides, alongside the concept of 'planning emergency levels of service' households, communities, infrastructure providers, the emergency management sector, and the Wellington region, can plan for emergencies better, and therefore become more resilient. As the data and outputs used in the tool are drawn from open-source repositories and methods, different regions, have the option to create a similar mapping tool using their own modelled infrastructure outages and PELOS, or using the PELOS created in the Wellington region.

The methodology used, including the collaboration between academic researchers, the critical infrastructure entities and the emergency management sector has been proven to deliver a webtool that will help emergency preparedness communication. The implication is that this tool, or similar can be developed and used in other contexts and for other hazards. As detailed in Section 4.4, there are various improvements that can, in time, be made to the webtool.

CRediT authorship contribution statement

Richard Mowll: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mitchell J. Anderson:** Data curation, Formal analysis, Resources, Software, Visualization, Writing – review & editing. **Tom M. Logan:** Formal analysis, Software, Writing – review & editing. **Julia S. Becker:** Funding acquisition, Supervision, Writing – review & editing. **Liam M. Wotherspoon:** Supervision, Writing – review & editing. **Carol Stewart:** Supervision, Writing – review & editing. **David Johnston:** Supervision, Writing – review & editing. **Dan Neely:** Writing – review & editing.

Declaration of competing interest

There are no competing interest issues to declare.

Data availability

Data is included in the supplementary information.he end of the paper, as supplementary information.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pdisas.2024.100312.

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