
Household adaptations to infrastructure service outages in an Alpine Fault earthquake scenario (AF8)

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ABSTRACT

Many households across Aotearoa New Zealand have experienced prolonged electricity and water service outages during recent disruptive events, and similar disruptions are likely in future disasters. To date, relatively few studies have examined how residents adapt and respond to extended service outages, limiting understanding of household-level impacts and the associated planning and response requirements. This study presents an agent-based simulation of household responses to the impacts of a major Alpine Fault earthquake, using the AF8 (Alpine Fault magnitude 8) scenario. New empirical functions for assessing household adaptive capacity and residents' decisions whether to remain or relocate are developed through analysis of a detailed survey of households affected by Cyclone Gabrielle. Simulation results indicate that the prolonged service disruptions modelled for many communities in the AF8 scenario are likely to lead to substantial levels of displacement, alongside significant challenges for households attempting to remain and adapt. This study showcases ongoing efforts to inform and extend models that forecast the societal impacts in natural hazard events, providing detailed evidence for planning, response and recovery.

1 INTRODUCTION

Recent earthquakes and severe weather events in Aotearoa-New Zealand (A-NZ) have demonstrated the vulnerability of the country's infrastructure and the impacts on societal functionality. The 2010-2011 Canterbury earthquake sequence and 2016 Kaikōura earthquake caused extensive infrastructure damage and

prolonged disruption to service provision due to ground shaking and mass movements. Severe weather events are frequent, with network disruption common due to flooding, wind, landslides and debris. Cyclone Gabrielle (2023) impacted multiple regions across A-NZ and highlighted the lack of redundancy in infrastructure networks. Electricity was cut to approximately 225,000 people, water supplies were restricted, communications impeded, bridges and roads rendered unusable, and an estimated 11,000 people displaced (Harrington et al., 2023; IDMC, 2024; Wilson et al., 2024).

The concurrent impacts of major events can overwhelm the response and recovery capacity of emergency management agencies, infrastructure providers, and communities. Households can be faced with the decision whether to remain in their homes and adapt to disruption or relocate elsewhere. There is a critical need for improved decision support tools that can assess the holistic impacts to societal functionality and the adaptive capacity of households.

How households respond to electricity and water supply outages depends on their degree of reliance on the systems, their ability to adapt, and their tolerance to disruption over time (Coleman et al., 2020; Esmalian et al., 2021a; Esmalian et al., 2021b; Lamadrid et al., 2025; Mitsova et al., 2021). Despite the frequency of damaging events in New Zealand and worldwide, there remains a paucity of literature and data essential for examining the factors influencing household behavioural responses to disruptions of critical infrastructure services. The strength and weighting of influential factors in complex events are challenging to assess (Abramson et al., 2015; Cutter et al., 2003; Levine et al., 2007; Mitsova et al., 2021; Sutley and Hamideh, 2020), however this information is essential for understanding and modelling the potential impacts of future events (Bhattacharya and Kato, 2021; Burton et al., 2019; Costa et al., 2022; Paul et al., 2024).

This paper first presents an overview of the recently developed Stay-or-Relocate Model (STORM) (Scheele 2026), applied to the prominent AF8 scenario (Orchiston et al., 2016; Orchiston et al., 2018). STORM is a flexible and extensible agent-based model designed to represent heterogeneous household-level impacts across broad spatial and temporal scales. Drawing on detailed data from a post-event household survey of residents affected by Cyclone Gabrielle, preliminary analyses are presented and empirical functions are developed to represent household tolerances to water and electricity outages prior to relocation, the difficulty of maintaining household routines, and adaptive behaviours. These functions are implemented within STORM to enhance assessment of disaster impacts, with their application demonstrated through the AF8 scenario.

2 THE AF8 SCENARIO

The Alpine Fault is one of A-NZ's major sources of earthquake risk, with an estimated 75% probability of rupturing within the next 50 years and an 82% probability of the next event exceeding moment magnitude (M_w) 8.0 (Howarth et al., 2021). An Alpine Fault earthquake is likely to cause widespread impacts across the South Island of A-NZ, stretching the response capacity of national and regional emergency management groups, and posing significant challenges for recovery. In response to the need for detailed hazard and impact information to plan and prepare, the AF8 scenario was first developed in 2016 (Orchiston et al., 2016), comprising an suite of modelled and qualitative hazard and impact components (Orchiston et al., 2018). The scenario was recently used for Exercise Rū Whenua in 2024, a major national emergency management exercise, and Exercise Pandora by regional CDEM groups in the same year.

A northeastern-directed rupture of the Alpine Fiordland to Kelly (AlpineF2K) segment is most commonly used for the AF8 scenario, representing a maximum credible event. Ground motions for a M_w 7.9 earthquake were simulated by Bradley et al. (2017), indicating significant shaking across much of the South Island, with particularly high intensities in the West Coast Region (Figure 1). A simplified isoseismal representation of an aftershock on the Hope-Kelly Fault was used in Exercise Pandora, and within this present study.

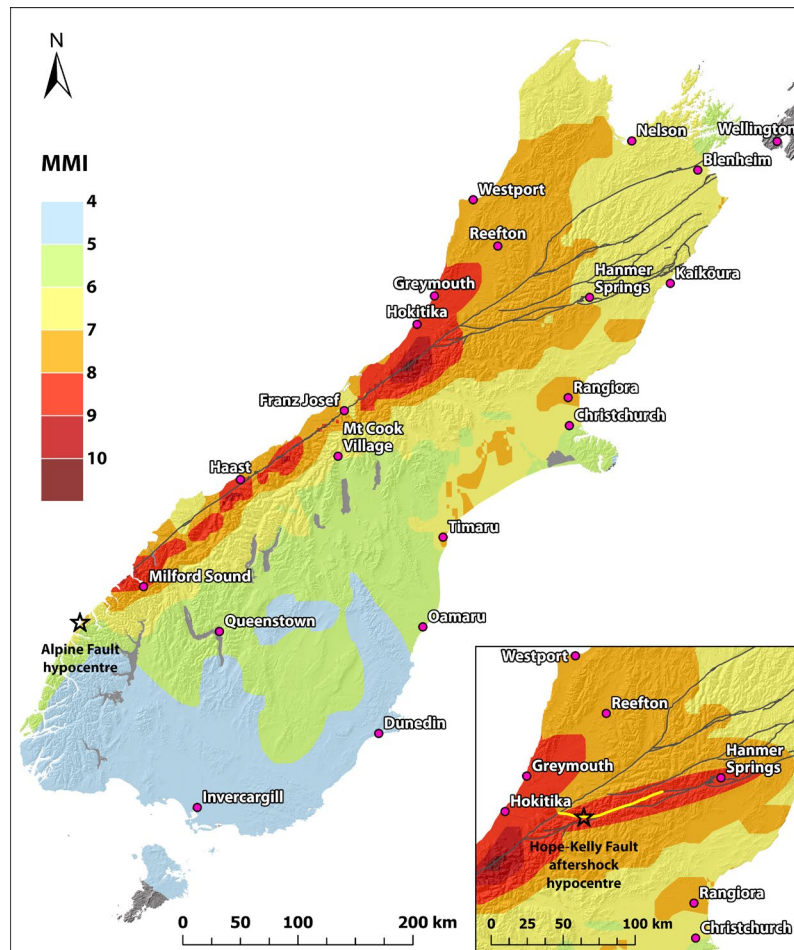


Figure 1: Modified Mercalli Index (MMI) from simulated ground motions (Bradley et al., 2017) of the AlpineF2K scenario. Inset: Merged maximum MMI from a Mw 7.3 aftershock on the Hope-Kelly Fault (T. Robinson pers. comm., 2024).

Various impact models have been developed, focused on the West Coast Region and peripheral areas. The following have been integrated into STORM, including water supply recovery estimates for urban areas (Robinson et al., 2015), state highway network damage and access loss over time due to landslides and rockfall (Davies et al., 2021), and electricity network outages and restoration estimates (Davies et al., 2021). Additional inputs include representations of disruptions to road access, water supply and electricity for the Queenstown area, derived by expert-judgement (T. Robinson pers. comm., 2024).

3 STAY-OR-RELOCATE MODEL (STORM)

STORM is a hazard-agnostic societal impact model developed for assessing the impacts to households and the decisions of residents whether to remain or relocate. An overview of the modelling process is shown in Figure 2. STORM is an agent-based model coded using GAMA (Taillandier et al., 2019). External model inputs form the basis for components within STORM that evaluate the disruption each household may face. Households are represented by a synthetic population model (Scheele et al., 2021) linked with individual residential dwellings contained within a national building inventory (Scheele et al., 2023). Each household has fundamental attributes indicating capacity/vulnerability, including household composition, tenure (renting or owning), household income, number of individuals and number of dependent children. Preparedness attributes are assigned to provide further indicators of behaviour or needs in disasters.

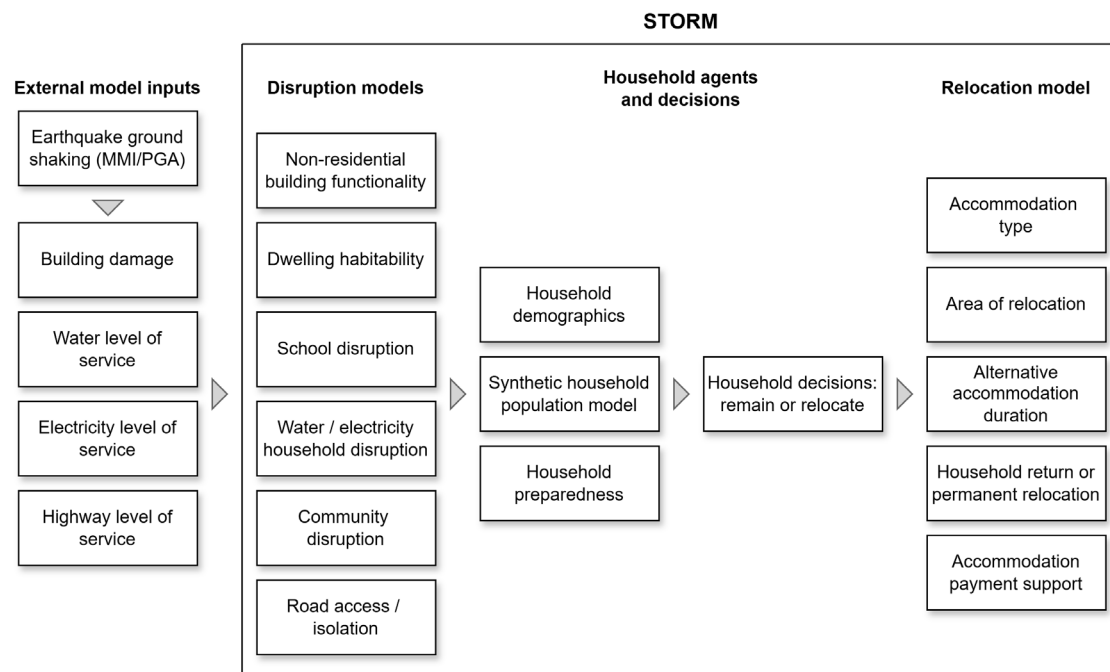


Figure 2: Simplified overview of the modelling process for STORM.

Household decisions whether to remain or relocate are evaluated in STORM by considering household characteristics and changing circumstances over time (Figure 3). These decision components include dwelling habitability, water and electricity disruptions, loss of school functionality, community liveability, and aftershock anxiety/tolerance. Households that relocate may move between multiple alternative accommodation types or locations before returning home if circumstances allow (assumed for homeowners) or relocating permanently (assumed for renters if return is not possible within two months). An empirical relocation model (Scheele et al., In preparation) is used to determine selection of alternative accommodation type, area of relocation, duration at each location and the need for financial assistance with accommodation.

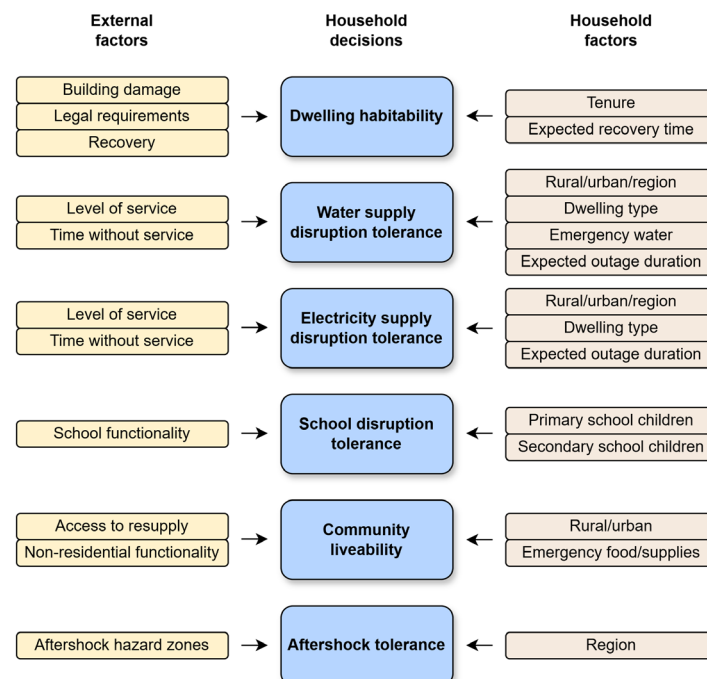


Figure 3: Household decision components in STORM, incorporating external and household factors.

The modelling components and assumptions within STORM are grounded within insights from the international literature, modified with consideration of the local context, and informed by local data where possible. STORM has also been applied to a multi-hazard multi-phase volcanic scenario in Taranaki Region (Scheele et al., in review). For a detailed description of STORM and the application to the AF8 scenario, please refer to Scheele (2026).

4 HOUSEHOLD IMPACTS AND POPULATION DISPLACEMENT IN AF8

The number of individuals affected or displaced in the AF8 scenario as assessed through the six components of disruption Figure 2 and associated household decisions Figure 3 are shown in Figure 4. The total number of displaced people over time is also shown, with multiple forms of disruption potentially exceeding a household's tolerance, leading to relocation. Additionally, the number of individuals isolated due to state highway access disruption is evaluated, although isolation is not considered a reason for relocation in this iteration of the modelling (which may be updated with further evidence).

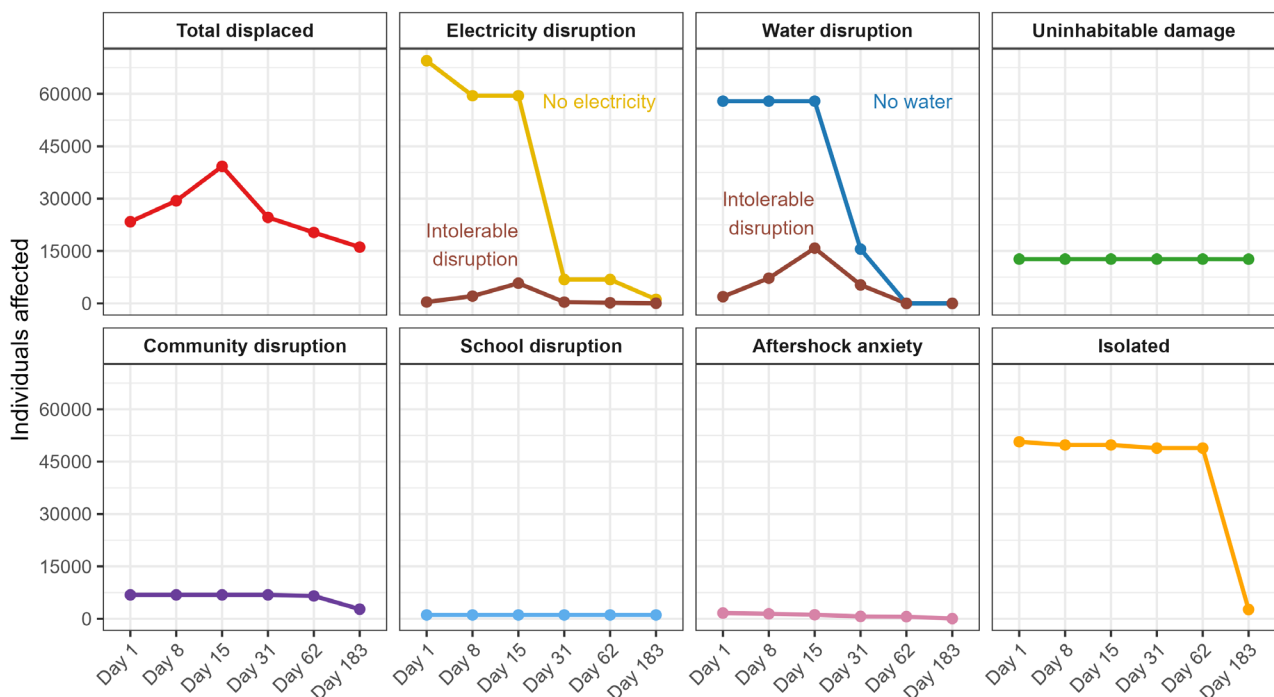


Figure 4: The total number of individuals displaced and those affected by disruption over time, alongside those living in isolated areas due to state highway network disruption.

Water and electricity supply disruption are of particular relevance to this paper. The probability of a household relocating due to each outage is loosely based on survey data indicating increasing levels of unhappiness over time (Stock et al., 2023), alongside the increasing indication of intention to relocate as an adaptive action (Abbou et al., 2022). Water supply disruption was considered as significantly less tolerable than electricity outages by survey respondents. The survey data includes respondents who experienced service outages in recent US natural hazard events, alongside those who did not but provided their assumptions for behaviour in future events (Abbou et al., 2022; Stock et al., 2023).

Rather than use the time-dependent plots from these studies directly, which do not differentiate by household characteristics and likely overestimate relocation, modifications were made when incorporating within STORM. A scoring system was developed, accounting for different household tolerances to outages based on service type, urban versus rural residents, expected outage duration, and possession of emergency water supplies. Assumptions were made based on insights from existing studies, such as the relatively high

adaptive capacity of rural farming households relative to lifestyle property owners and urban residents (Andresen et al., 2023; Barton 2020; Smith et al., 2011; Whitman et al., 2013). As shown in Figure 4, households experiencing disruption to water or electricity supplies are only assumed to relocate once their tolerance threshold is exceeded. The prolonged service outages within the AF8 scenario indicate that significant numbers of households would favour relocation as tolerance deteriorates, particularly around two weeks following the main earthquake before services are restored to a majority of areas within one month (Davies et al., 2021; Robinson et al., 2015).

5 CYCLONE GABRIELLE HOUSEHOLD SURVEY ANALYSIS

A paper-based survey of households impacted by Cyclone Gabrielle was delivered to 5,000 residences in Hawke's Bay, 18 months post-event. The survey questions covered damage, electricity and water outages, adaptations, relocations, preparedness, and demographics. Approximately 1040 responses were received, providing an approximate response rate of 21%. Areas that had prolonged electricity outages were prioritised, covering a range of urban and rural communities (Figure 5). Approximately half of respondents were from urban areas (55.6%), 14.5% lived in rural settlements, 24.5% occupied lifestyle properties, and 5.3% were from rural farming areas. Almost all respondents (n = 995) experienced electricity outages and around a third (n = 332) experienced water supply disruptions. Prolonged outages of at least two weeks were experienced by some respondents (n = 160 for electricity, n = 99 for water). The survey data provides a rich dataset for examining the impact of disruptions on households. Analysis and function development for modelling are at the preliminary stages, and the following sections describe some relevant early findings, function development and model implementation within STORM. For analysing relationships between categorical variables, Fisher's Exact Test (FET) was used to test for significance of association and Cramér's V was used examining effect strength. Logistic regression analysis was used to examine binary outcomes, and ordinal regression for ordered categories.

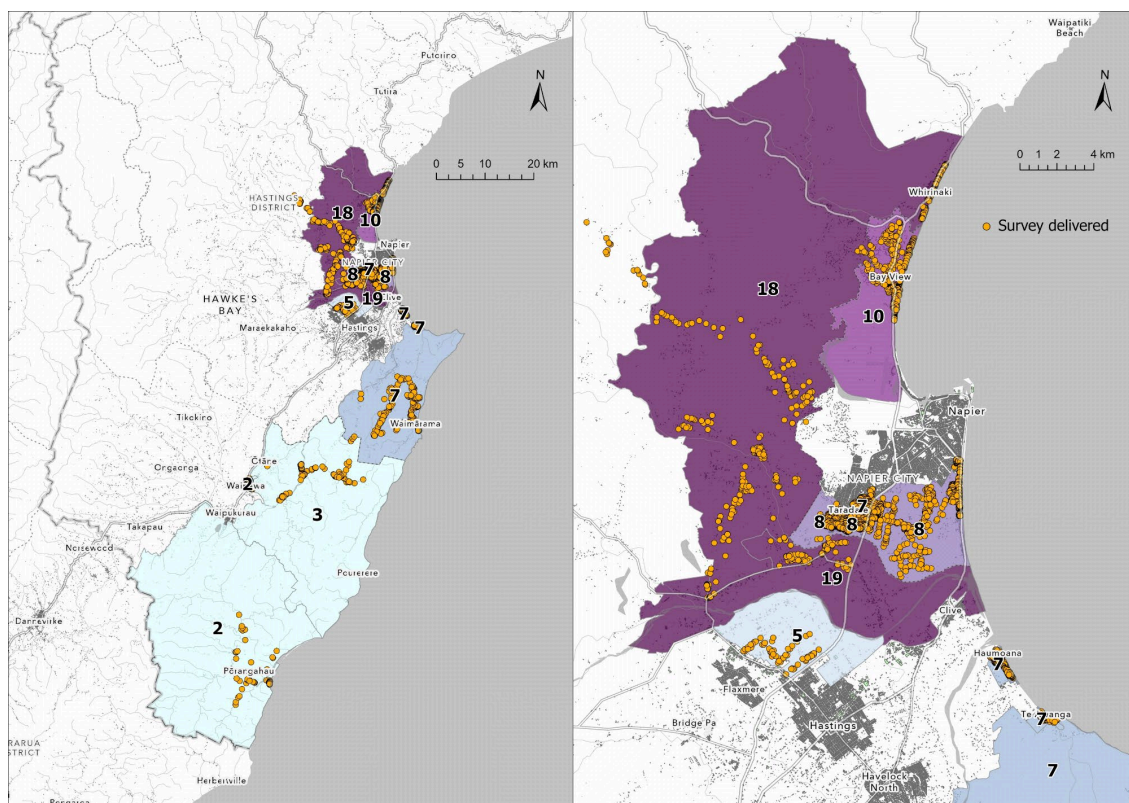


Figure 5: Cyclone Gabrielle household survey deliveries. Numbers represent the median days without electricity reported by respondents within each area.

5.1 Water and electricity disruption tolerance prior to relocation

The household survey data includes several questions of relevance for examining the probability and timing of household relocation due to intolerable service disruption. Given the diverse and confounding impacts to households in Cyclone Gabrielle, the simplest route was a direct question related to future intentions. For both water and electricity disruption, respondents were asked “*In a future disaster event, how long would your household tolerate loss of [water/electricity] before relocating elsewhere?*”, specifying a timeframe or indicating that their household would not leave due to a loss of service. The four categories of rural-urban communities (listed in the section above) were evaluated against respondents’ indicated timeframes before relocation for each service, binned into 7 days or less, more than 7 days, or would not leave. FET indicated a significant association between rural-urban classification and relocation category ($p < 0.001$) for both services. A small-to-moderate effect was found for electricity ($V = 0.17$), and a moderate-large effect for water ($V = 0.28$). These results indicate that rural–urban classification may be a meaningful variable to incorporate in modelling. The cumulative probability of relocating by day is plotted in Figure 6, accounting for those who indicated they would not relocate.

While clear and specific, these results do not reveal the actual behaviour of residents affected by outages during the event, and the intentions to relocate after a given day are likely to be overstated compared to reality, a phenomenon also observed by (Abbou et al., 2022). The household survey data includes responses on whether residents left their home to seek alternative accommodation, the reasons for leaving and the duration away from home. Multiple reasons were often specified for leaving, and these were ranked by respondents to indicate the top three reasons. The timing of relocation was not specifically asked in the survey. However, the indicated tolerance to service disruption in future events, while not a causal threshold, can reveal respondent preferences.

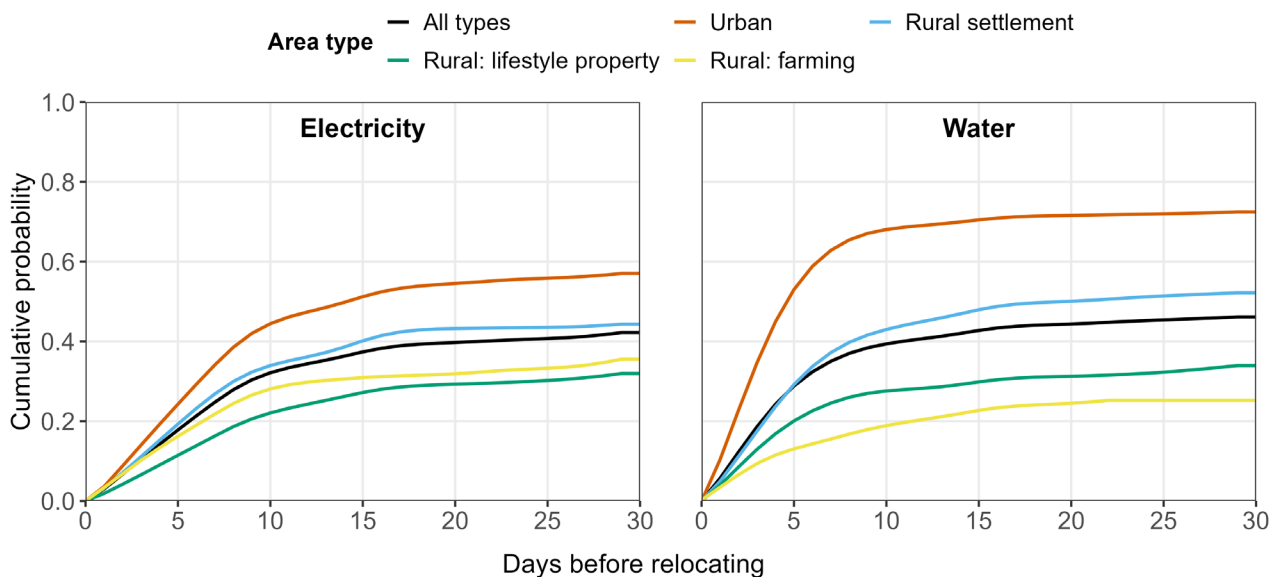


Figure 6: Indicated household tolerances to future service outages prior to relocation.

For analysis, a hybrid approach was taken using reported relocations in Cyclone Gabrielle alongside the indicated timeframe before relocation in future events. First, the responses were filtered and flagged to include only those who indicated either electricity or water disruption, or both, within their top three reasons for relocating. Those who indicated dwelling damage were excluded, as loss of services was likely inconsequential in these cases. For each service, the probability of having relocated was calculated by including all respondents who experienced each service disruption. The indicated day before relocation in

future events was then compared against reported service outage durations in Cyclone Gabrielle, to examine the proportion of households relocating during outages longer (disruption tolerance exceeded) or shorter (tolerance not exceeded) than their indicated day. The probabilities in Table 1 indicate that respondents who experienced service outage durations that exceeded their stated tolerance timeframe were much more likely to have relocated than those who experienced outage durations that were shorter.

Table 1: Probability of respondents having relocated during service outages, prior to or after the indicated time point in future events (service disruption tolerance).

Service disruption tolerance	Water disrupted	Electricity disrupted	Both services disrupted
Not exceeded	0.032*	0.033	0.032
Exceeded	0.296*	0.257	0.361
Exceeded for water only	-	-	0.231
Exceeded for electricity only	-	-	0.167

* Calculated based on Eq. 1 for use in modelling.

Logistic regression was used to further examine this association, and to test whether it holds despite some households stating multiple reasons for relocating. The findings show that those who stated they would leave in future were around three times more likely to leave than those who stated they would not, for both electricity ($OR = 3.3$, 95% CI: 1.9–6.3) and water ($OR = 3.0$, 95% CI: 1.5–6.5). The model intercept further indicates that respondents who stated they would not leave were very unlikely to have relocated due to service disruption. The findings support the relationship between indicated intentions and observed behaviour among respondents, suggesting that is utility in combining these indicators for function development. Additional logistic regression analysis showed that service outage duration alone was a poor predictor of relocation behaviour, with no statistically robust association found for either electricity or water outage durations ($p > 0.1$).

Very few respondents ($n = 15$) experienced disruption to water supplies without loss of electricity, posing an issue for meaningful analysis and subsequent function development for application to scenarios where this situation is possible. Given households tend to report lower tolerance to water outages than electricity disruption, a weighted-blend probability was calculated for when only water supply is disrupted:

$$P_w = P_e + 0.5(P_b - P_e) \quad (1)$$

where the relocation probability if service disruption tolerance is exceeded is represented by P_w for water, P_e for electricity and P_b for both services.

Within STORM, each household agent randomly selects a tolerance time point (or may never leave) for each service outage from the cumulative density functions shown in Figure 6, according to its rural-urban classification. Each simulation cycle (day), water and electricity service levels are assessed, and the corresponding probability of relocation is selected from Table 1. This probability is used to stochastically determine whether a household relocates within a 7-day window.

The effect of implementing the survey-informed functions, compared with the original approach (Section 4), is shown in Figure 7. The similar patterns observed for water and electricity intolerances under the survey-informed functions reflect the fact that most affected households experience concurrent loss of both services within the first few weeks of the AF8 scenario, whereas the original functions treat water and electricity

disruptions independently. Over the time period considered, the survey-informed functions result in a substantial reduction in the simulated number of displaced households relative to the original approach.

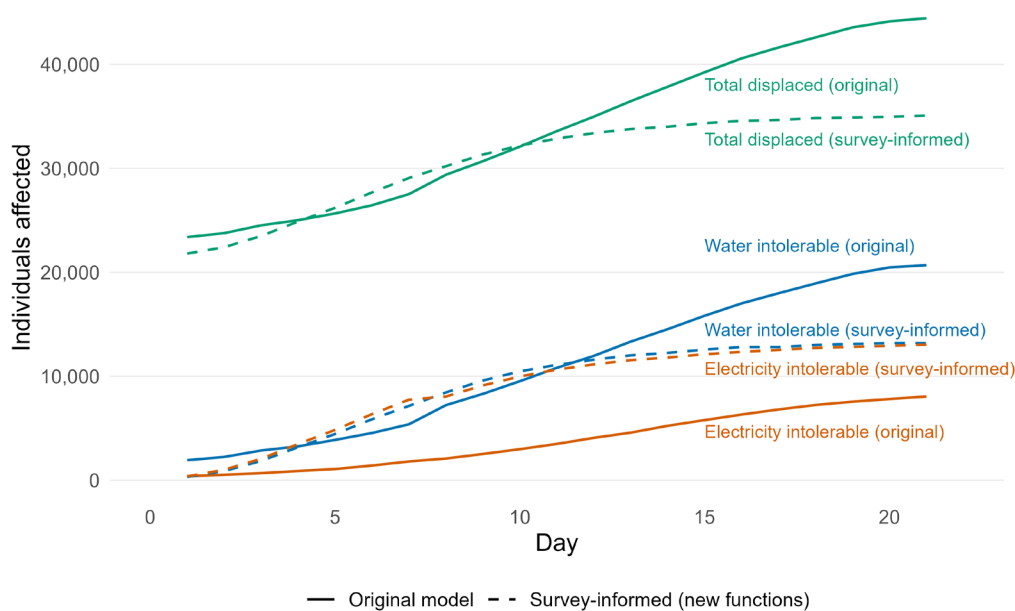


Figure 7: STORM simulation of the AF8 scenario comparing outputs from the original model and survey-informed functions governing household tolerance to electricity and water service disruption.

5.2 Adaptations to service outages

Survey respondents that experienced service disruption reported which adaptations they undertook. For tests of association, reported area type was grouped to maintain sufficient sample sizes across binned service outage durations, as either urban (including rural settlements) or rural (farming or lifestyle properties). For electricity, only small rural-urban differences were found, except for generator use which showed a moderate association ($p < 0.001$, $V = 0.26$). Significant associations were found for several water disruption adaptations. However, these are not presented here, as further analysis is required to account for the complexity of mains and private water supply arrangements reported by respondents, which are likely to influence adaptive behaviours.

The probability of respondents undertaking each adaptation during electricity outages and rural-urban is shown in Figure 8. Generator use shows a strong association with increasing electricity outage duration, as well as a significantly higher probability for rural households. The decrease in undertaking several adaptations for outages longer than three weeks may be explained by the increase in households who relocated. Some respondents noted that remaining in their homes was conditional on the availability of fuel to run a generator, usually for the purpose of maintaining the functionality of private water supply systems.

Generator use was incorporated into STORM based on the probabilities in Figure 8. The results of the simulation indicate a gradual increase in generator use over time, rising a peak of about 44% of households that continued to experience prolonged electricity outages one month after the main earthquake. Further analysis will be undertaken to examine the effect of adaptations on outcomes for residents affected by service disruptions, potentially revealing insights into adaptive capacity that may inform modelling.

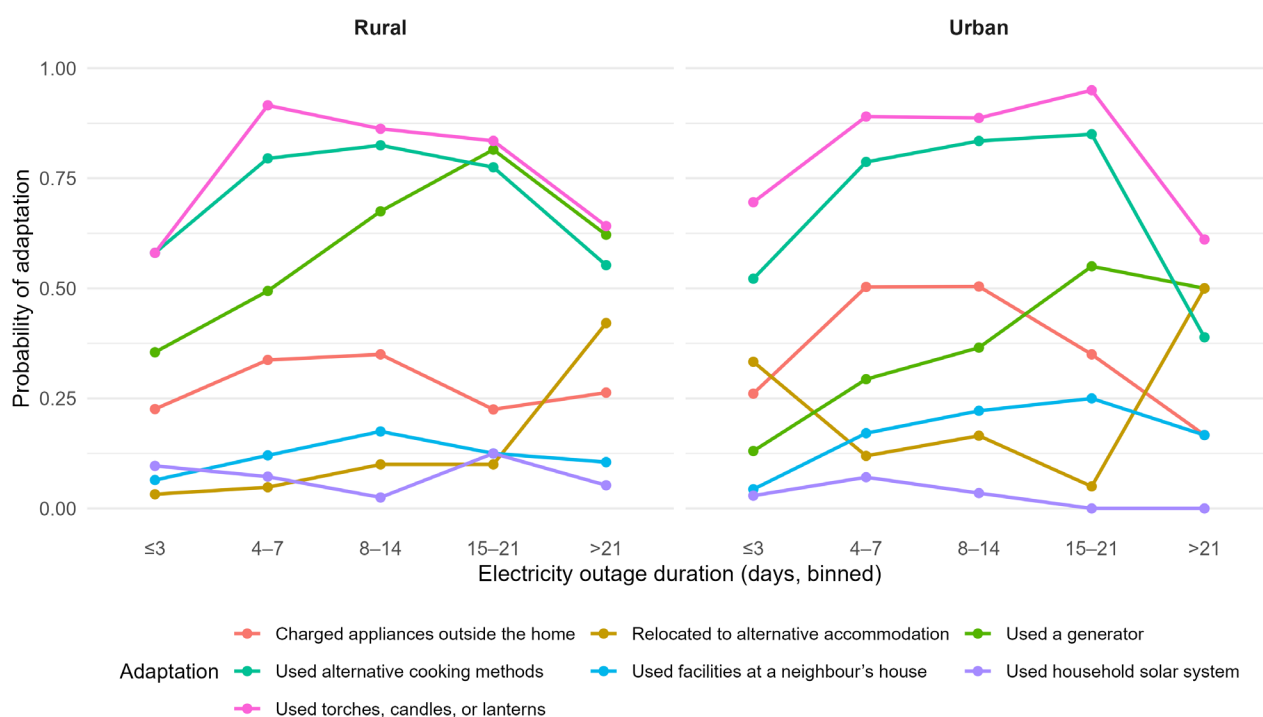


Figure 8: The probability of undertaking each adaptation by electricity outage duration and rural-urban.

5.3 Difficulty maintaining household routines

For electricity and water disruption, survey participants were asked “During the [service] outage, please select the level of difficulty your household experienced due to the outage in continuing regular household routines”. Specific, representative time points and four levels of difficulty were provided. During analysis, the difficulty levels were first converted to a score, before calculating the mean score for respondents that experienced outages at each time point. The results are plotted in Figure 9, showing an increase in mean difficulty for most outage duration cohorts across the first week, and a decrease in difficulty for households that experienced longer outage durations.

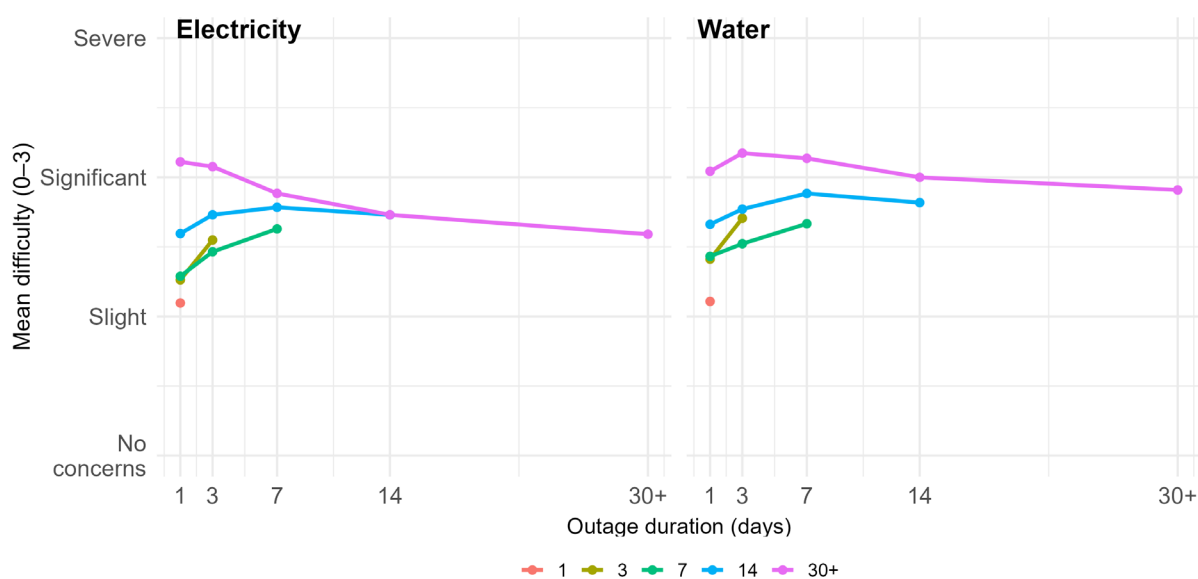


Figure 9: Mean difficulty score by service and outage duration reached or exceeded.

For both electricity and water outages, ordinal regression analysis of outage-length confirmed cohort and time since outage onset were strongly associated with reported difficulty ($p < 0.001$). In contrast, rural–urban classification was not statistically significant after controlling for these factors (electricity: $p = 0.20$; water: $p = 0.055$). Pending further analysis to examine other potentially explanatory variables for difficulty (e.g. demographics, impacts), the distributions underlying Figure 9 were incorporated into STORM to identify the level of difficulty experienced by affected households over time (Figure 10).

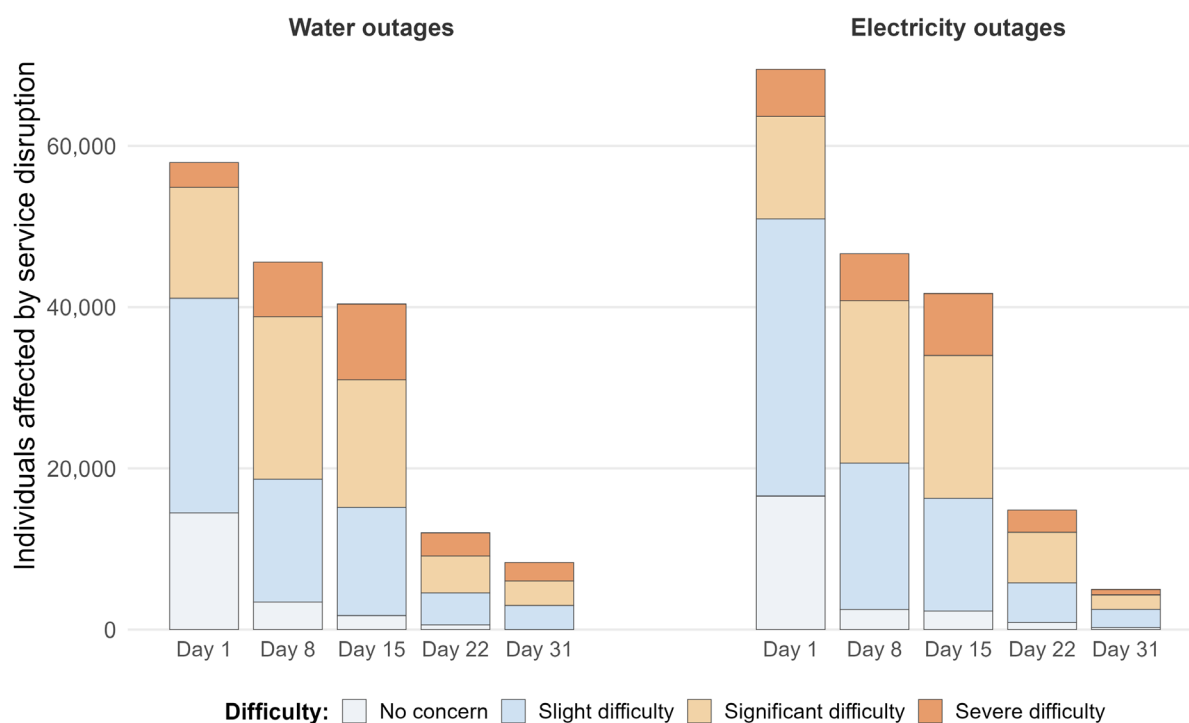


Figure 10: Difficulty continuing regular household routines for households affected by service disruptions in the AF8 scenario.

6 CONCLUSIONS AND FUTURE WORK

This paper presents new advances in understanding and simulating household impacts in disasters. Preliminary analysis of the Cyclone Gabrielle household survey has enabled the development of novel predictive functions, and their implementation demonstrates the flexibility and extensibility of STORM. Together, these improvements support more realistic representation of household adaptive capacity and behavioural responses to prolonged disruption, addressing the critical need for enhanced decision support tools.

A key assumption underpinning this work is that findings from the Cyclone Gabrielle survey are generalisable to other events and contexts within A-NZ. This is supported by the diversity of respondents, which captures a wide range of communities and impact experiences. Ongoing analysis of the full dataset will further examine whether household characteristics are determinative of adaptive behaviours.

Future work will focus on applying and validating STORM in Hawke’s Bay, integrating multiple data sources to assess the model’s ability to represent societal impacts based on observed outcomes following Cyclone Gabrielle, such as emergency accommodation demand. Additional post-event household surveys are also planned, including for areas affected by prolonged electricity outages during the severe wind event of October 2025. Collectively, this ongoing research will strengthen the capabilities and confidence in models designed to represent societal impacts.

7 ACKNOWLEDGEMENTS

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