Article

Applying principles of uncertainty within coastal hazard assessments to better support coastal adaptation

Scott A. Stephens [1], Robert G. Bell [1] and Judy Lawrence [2,*]

[1] National Institute of Water and Atmospheric Research, New Zealand; scott.stephens@niwa.co.nz
[2] Climate Change Research Institute, Victoria University of Wellington, New Zealand judy.lawrence@vuw.ac.nz
* Correspondence: scott.stephens@niwa.co.nz; Tel.: +67-7-856-7026

Abstract: Coastal inundation is an increasing problem. Sea-level rise will greatly increase the frequency and depth of inundation, forcing vulnerable communities to adapt. Communities will need to decide when and how to adapt. The process of decision-making along adaptive pathways is now being used internationally to plan for adaptation over time by anticipating decision points in the future however it unfolds. This process requires risk and uncertainty considerations to be transparent in the scenarios used in such planning. We outline a framework for uncertainty identification and management within coastal hazard assessments which recognizes different types of decision and identifies the types of uncertainty that must be accounted for, such as statistical, scenario and deep uncertainty types. We show how coastal-inundation hazard can be mapped and presented in a way that clearly separates sources of uncertainty, so that they are transparent within a dynamic adaptive pathways planning process. Traditional coastal inundation maps show inundated area only. We present maps of inundation depth and frequency which clearly show the degree of exposure, where that exposure occurs, and how much sea-level rise can be tolerated. The new uncertainty framework and mapping techniques can better identify decision points and their expected time range, which provides more useful input to the adaptation process than traditional coastal inundation assessments.

Keywords: Sea-level rise; coastal hazard assessment; uncertainty; coastal adaptation

1. Introduction

Coastal inundation is an increasing problem. Sea level has been relatively stable during the last 2,000–3,000 years [1] and civilization has developed near the upper limits of the sea's reach on the premise of a relatively "stable" sea level [2, 3]. Global sea level began to rise in the late 1800s [4]. With a sea-level rise (SLR) of ~0.2 m since 1900, low-lying areas of New Zealand are seeing an increased incidence of coastal storm inundation [5, 6]. In the USA, SLR is causing deeper floods during extreme sea-level events, and regular "nuisance" flooding is occurring more often during high tides, causing millions of dollars of insurance claims [7]. The rate of SLR is projected to accelerate over the coming century and beyond [2-4], and this will greatly increase the frequency of flooding [e.g. 6, 7, 8], forcing communities to adapt in some way. Communities will need to decide when and how to adapt. For example, "decision" (or "trigger") points [9] might occur when the 1 in 100-year event becomes 1 in 5 years, or when the 1 in 5-year event occurs several times per year.

The purpose of a coastal hazard assessment is to provide the information necessary for decision making, in a way that is clearly understood. A coastal hazard assessment must identify the spatial extent and magnitude of hazards, both now and with future higher seas, and quantify the likelihood of occurrence of the hazards, ideally in probabilistic terms, or by way of scenarios supported by expert elicitation. This information is required by planners, asset managers and decision makers and for input to the engagement process with potentially-affected communities (property owners and residents), iwi/hapū and stakeholders [9].

Government policies recognize the need to reduce coastal hazard risk over long timescales to account for rising sea levels. The New Zealand Coastal Policy Statement (NZCPS) 2010 (Policy 24) requires the identification of areas in the coastal environment that are "potentially affected" by coastal hazards, and assessment of the associated risks over at least the next 100 years. The NZCPS requires a *risk*-based approach to managing coastal hazards (Policies 24–25 and 27) – which requires determination of the different *likelihoods* of different magnitude events and their *consequences*: Risk = likelihood × consequence.

In this paper we address the treatment of *uncertainty* during coastal hazard assessment, and how uncertainty affects our understanding of *likelihood*, which in turn affects our perception of *risk*. We discuss different types of uncertainty [10], such as *statistical uncertainty* for storm tides and *deep uncertainty* for SLR, and argue that we must separate and treat these uncertainties differently within coastal hazard assessments, to increase their transparency and usefulness for decision making. We outline a framework, developed for the revised coastal guidance for local government in New Zealand [9], for uncertainty identification and management within coastal hazard assessments. It recognizes different types of decision and identifies the types of uncertainty that must be accounted for each decision type. We show how coastal-inundation hazard can be mapped and presented in a way that clearly separates sources of uncertainty, so that they are transparent within a dynamic adaptation pathways planning process (DAPP) [9]. The approach is demonstrated through a case study, where an advanced level of mapping is more useful for decision making than traditional maps of inundated areas. By isolating both inundation depth and frequency, these maps clearly show the degree of exposure, where that exposure occurs, and how much SLR can be tolerated, which can then enable more informed community engagement and decision making.

2. How certain are we? Uncertainty is important

When undertaking coastal hazard assessment, there are four types of uncertainty that lead to different types of decisions/policies [9-11]. We can assume that future coastal hazards:

1. Are knowable or known (<u>little uncertainty</u>).
2. Will behave probabilistically or stochastically in much the same way as the past (<u>statistical uncertainty</u>).
3. Are well-described by a few simple over-arching scenarios (<u>scenario uncertainty</u>).
4. Are unknown or disagreed upon by experts and/or stakeholders with no consensus of what the future might bring (<u>deep uncertainty</u>).

Some or all of these types of uncertainty will typically be involved in decision making in practice [9, 10]. In a risk-based context, determination of coastal hazard likelihood can be difficult, because it can involve a combination of the types of uncertainty above for different components causing inundation.

The greatest demands on coastal hazard assessments is for existing, exposed developments, where ongoing adaptation will be required to cope with rising sea level. The relative importance of the sources of uncertainties change over the time: local coastal processes are the most important during the first part of this century, whereas uncertainties of future SLR scenarios largely dominate beyond 2080 [12]. Statistical uncertainty is relevant over short-term planning timeframes (≤ 2050), but after a transition period, scenario and deep uncertainties become dominant over longer planning timeframes (≥ 2080), driven mainly by the increasing uncertainty in the rates of SLR up to and beyond 2100 [9, 12].

For example, the frequency and magnitude of storm tides (a combination of storm surge and high tide) can be modelled by fitting an extreme-value model to the historical observations of very high (e.g., annual maxima) sea-levels (Figure 1). The extreme-value model has a maximum-likelihood ("best") estimate (solid line in Figure 1), and a <u>statistical uncertainty</u> around the best estimate (dashed 95% confidence intervals in Figure 1). Climate change may also alter the frequency and magnitude of storm tides in future.

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Unlike large storm tides, it is not possible to model the statistical likelihood of future SLR, which instead must be modelled using scenarios [13].

2.1. Sea-level rise scenarios

The revised coastal hazards and climate change guidance for New Zealand [9] provides four SLR scenarios out to 2150, which are based around three greenhouse gas representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5). Three of the scenarios are derived from the median projections of global SLR for the RCPs presented by IPCC in their Fifth Assessment Report [4] and extended to 2150 [9]. The fourth 'H^+' scenario is at the upper-end of the "likely range" (i.e. 83rd-percentile) of the large ensemble of SLR projections based on RCP8.5 [9, 14]. In particular, this higher scenario reflects the possibility of future surprises (deep uncertainty) towards the upper range in SLR projections of an RCP8.5 scenario. It is representative of a situation where more rapid rates of SLR could occur in the latter part of this century and beyond from emerging polar ice sheet instabilities or as-yet uncertain understanding of dynamic ice sheet processes [9, 13].

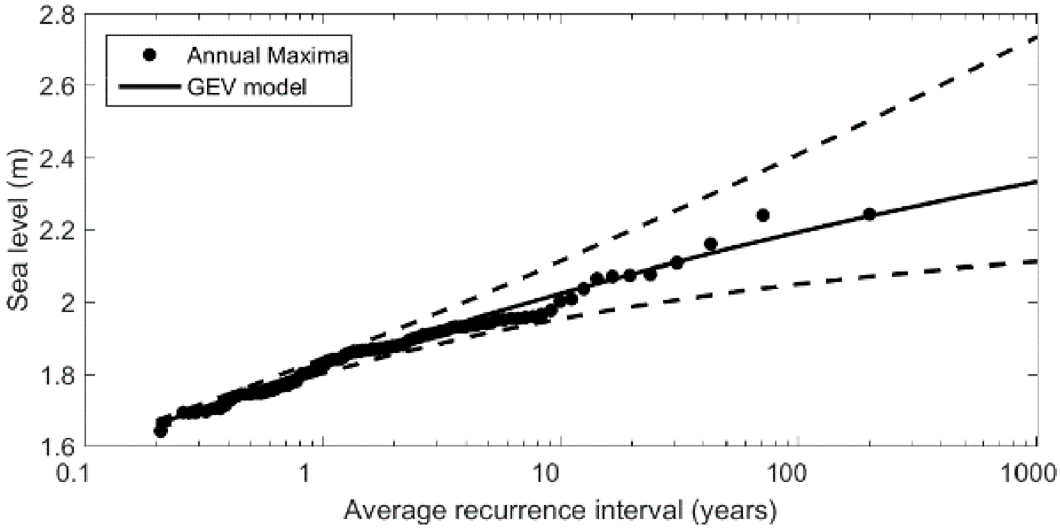

Figure 1. Generalized extreme-value model fitted to annual maxima sea level at Auckland, NZ. Dashed lines mark the 95% confidence intervals (statistical uncertainty).

A quantitative likelihood (or probability of occurrence) for one RCP emissions pathway versus another cannot be assigned, and therefore quantifying an overall likelihood distribution for SLR by 2100 or 2120 or beyond, is not possible [13]. Thus, uncertainty surrounding future rates of SLR must be dealt with by testing various SLR scenarios (scenario uncertainty), and stress-testing using an H^+ scenario to account for deep uncertainty in our understanding of possible upper-range SLR.

In her 2015 report, the NZ Parliamentary Commissioner for the Environment recommended that "in revising [New Zealand] central government direction and guidance on SLR, specify that "best estimates" with uncertainty ranges for all parameters be used in technical assessments of coastal hazards" [15]. We note that while it is desirable to specify statistical uncertainty ranges for some parameters, this may not always be possible. The longer the planning timeframe, the increasing dominance of SLR on the outcome [12], and neither a best estimate nor can statistical uncertainty be robustly derived for SLR. In such situations, the *likelihood* component of risk must be handled some other way, such as using adaptive approaches like DAPP [9, 13, 16].

With consequences for existing development rising non-linearly with increasing SLR, use of a "most likely" SLR (i.e. hazard exposure) is not commensurate with managing risk as required by the NZCPS [9]. DAPP interactively embeds the likelihood or emergence aspect, where the time to reach pre-agreed decision or trigger points can be adjusted through regular monitoring and reviews as climate change effects unfold [9]. This is an appropriate way of addressing future coastal vulnerability and risk management in an adaptive manner, which will enable uncertainties to be

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worked around, rather than adapting now to a pre-determined future by selecting a best or likely SLR estimate or a "worst-case" scenario [9].

In contrast, some studies have confused statistical and scenario uncertainty, providing results that give a misleading assurance of the true likelihood of outcomes, which could potentially lead to misinformed decision making. For example, Horton et al [17] combined the probability distribution functions (pdf) of RCP 4.5 and RCP 8.5 SLR projections, assuming a 50% likelihood for each to produce a single pdf for SLR, which they then convolved with storm-tide distribution. The study provides statistical confidence of extreme sea levels being reached, but the combined distribution provides a false assurance, because the true likelihood of SLR scenarios used is largely unknown (within a wide range of possible futures beyond 2100 and uncertainty around how quickly global carbon emissions can be curbed).

3. The dynamic adaptive pathways planning approach (DAPP)

Assessment and management approaches that explicitly deal with uncertainty and the changing character of risk need to be used in coastal areas. Such approaches can assess the *risk* and *consequences*, but *likelihood* of future SLR and climate change impacts cannot be quantified. Rather, the focus should be on "testing" responses to climate change against a range of future scenarios, before making decisions on pathways to reduce or avoid risk and reduce social vulnerability. This approach allows decision points or triggers to be identified, where the adaptation pathway may be altered in response to signals of any future coastal climate impacts [16, 18]. The change in course (pathway) may be delayed if slower than anticipated SLR occurs, and earlier change may be implemented if SLR is more rapid than expected, or if progress on reducing global emissions is limited. This process of decision-making along adaptive pathways is known as dynamic adaptive pathways planning, and is now being used internationally to plan for adaptation over time to anticipate decision points in the future however it actually unfolds [9, 13].

Risk and uncertainty considerations need to be transparent in the scenarios and the story lines used in such planning. This rest of this paper focuses on producing hazard analyses that support DAPP, by providing hazard scenarios with clearly defined sources of uncertainty.

4. Using uncertainty to guide coastal hazard assessment

A clear understanding of the relevant uncertainties can guide the approach to coastal hazard assessment. Figure 2 shows relationships between the type of coastal adaptation decision being made, the appropriate level of uncertainty that should be considered for that decision, the scenarios required to account for that level of uncertainty, and the associated modelling hazard assessment complexity and cost. The type of decision being made and the type of uncertainty that needs addressing will guide the choice of hazard assessment (e.g. modelling scenarios and the resulting complexity and cost).

 doi:10.20944/preprints201706.0104.v1

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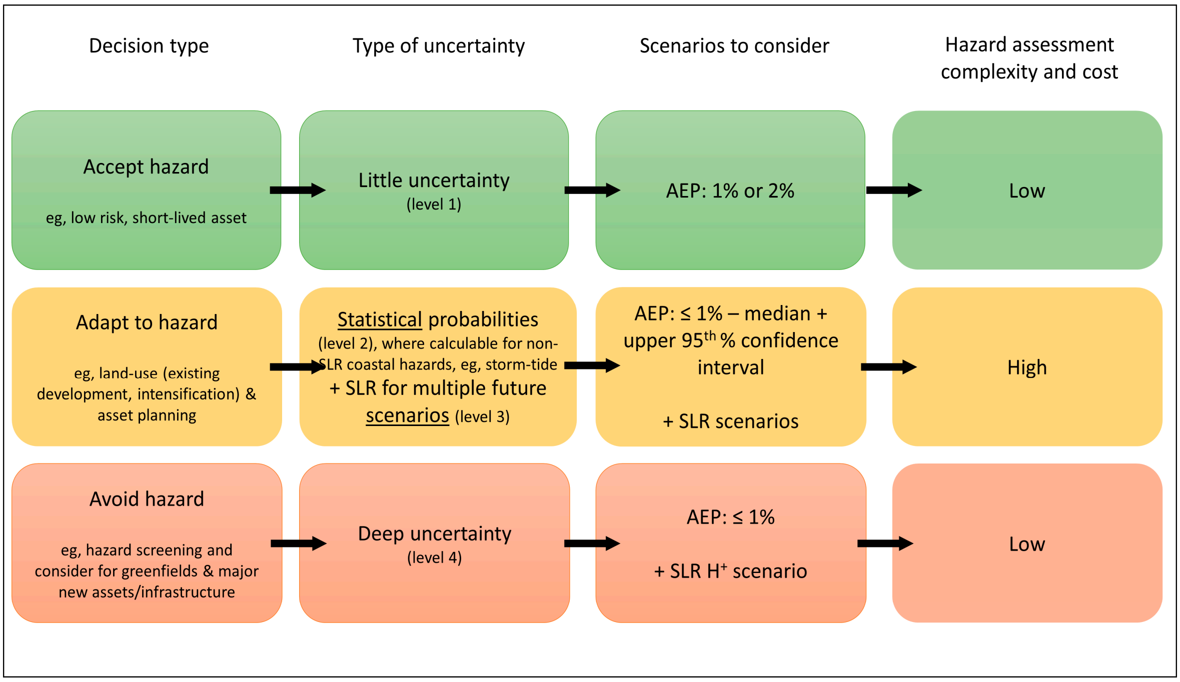

Figure 2. Relationship between the decision type (situation), related uncertainty, hazard scenarios to model, and hazard modelling complexity.

The type of decision being made is grouped into three categories:

1. Accept hazard – where for non-habitable use, the risk of damage from coastal hazards and SLR is low, or the asset can be easily adapted to cope with future SLR. Examples might be a toilet block, a surf-lifesaving lookout, or a culvert supporting a minor access way. The future for such assets is reasonably clear i.e., they are relatively easily replaced or relocated, so modelling effort can be kept simple and low-cost, perhaps employing a simple "building block" model to allow for various coastal hazard sources, or relying on expert judgement to decide on an appropriate floor or culvert elevation or setback distance.
2. Adapt to hazard – such as for existing areas of higher-value development the hazard assessment must provide sufficient information to inform the decision(s) to be made and when risk may emerge, often involving both present-day statistical uncertainty (where calculable for non-SLR coastal hazards such as storm-tide), plus several SLR scenarios – thus, it is likely to be more complex and costly.
3. Avoid hazard – for instance, in establishing new greenfield development, modelling effort can be kept relatively straight forward and low-cost, focusing on an upper-range hazard scenario of at least the maximum-likelihood 1% Annual Exceedance Probability (AEP) hazard plus a higher SLR scenario e.g., the H^+ SLR scenario [9, 13]. The effects of this higher SLR are generally considerably larger than the uncertainty in the derivation of the 1% AEP hazard. Such assessments also need to consider tsunami-hazard exposure from any regional study undertaken, to inform a multi-hazard risk reduction approach.

Figure 3 provides a hypothetical example of three communities with different exposure to coastal hazards. The following paragraphs explore how the framework in Figure 2 might apply to these three communities [9].

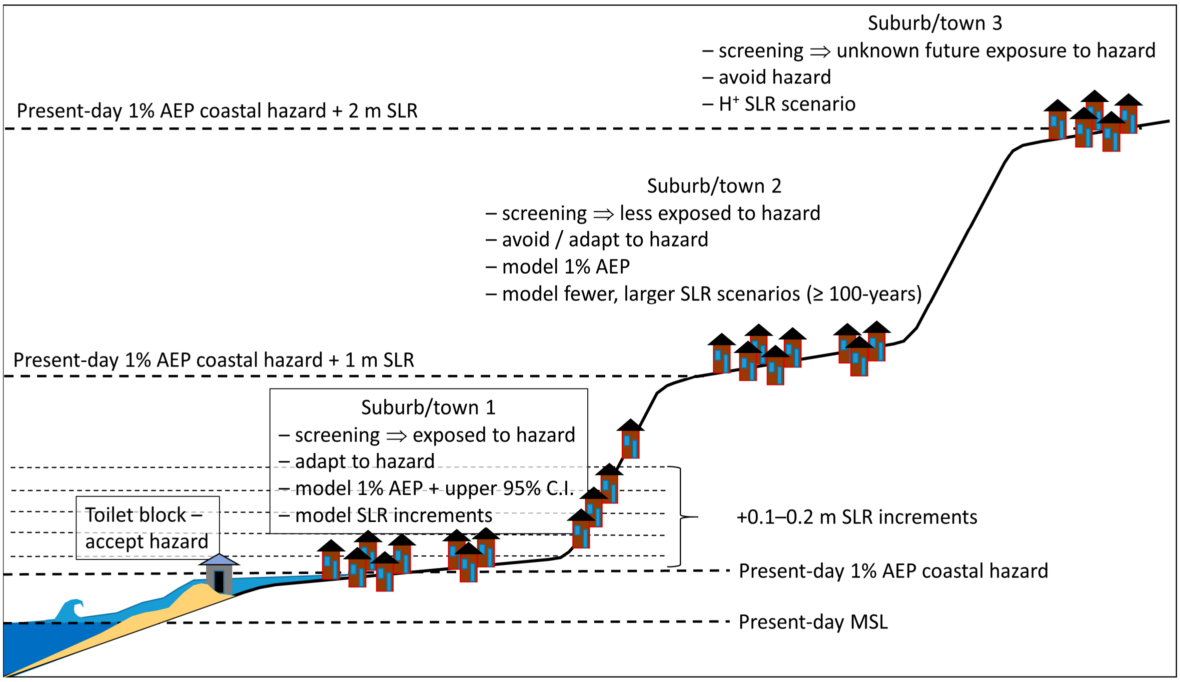

Figure 3. Choice of coastal hazard assessment model scenario based on hazard exposure. The degree of exposure indicates the level of uncertainty the coastal hazard assessment should address, the modelling scenarios required to assist decision making, and the likely complexity of the hazard assessment.

For communities that are already vulnerable to coastal hazards, it is likely that critical decision points could be reached at relatively low SLR thresholds, such as for Suburb 1 shown in Figure 3. Suburb 1 is built on low-elevation land, close to the coast, and will need to adapt to coastal hazards with an early emergence of SLR impacts. The depth and extent, and frequency, of the inundation and erosion hazards will grow incrementally with SLR, and decision points (e.g., frequency of nuisance or damaging inundation or severe erosion events) may be reached well before 1 m of SLR occurs (which is often used as a single SLR scenario in hazard assessments). Areas on the hill slope will become progressively exposed as sea level rises incrementally. In this case is would be useful to assess the impacts of a few regular small (e.g. 0.1–0.2 m) SLR height increments (on top of both the median and upper 95% of the 1% AEP inundation hazard) to identify potential trigger points for input to the DAPP process and community engagement.

Suburb 2 is built on a raised coastal platform (Figure 3) approximately 1 m above present-day 1% AEP storm-tide level. Hazard screening shows no exposure to 1% AEP coastal inundation or erosion at present-day MSL, but increasing hazard exposure after about 0.5 m or more of SLR from later this century. There is little need to model the effects of small SLR increments. Coastal hazard assessment could instead focus on fewer SLR scenarios accounting for at least 100-year timeframes, such as 0.5 m, 1.0 m, H^+ SLR. Greenfields developments in this suburb will require careful scrutiny to avoid increasing risk in the future beyond a 100-year timeframe.

Suburb 3 is built on a raised coastal platform approximately 2 m above present-day 1% AEP storm-tide level (Figure 3). Regional hazard screening shows no exposure to 1% AEP coastal inundation or erosion at present-day MSL, and SLR is not expected to impact on this suburb for more than 100 years. To avoid the hazard, a coastal hazard assessment could use a single median 1% AEP hazard + H^+ SLR scenario as input to any long-term adaptation planning.

5. A coastal inundation assessment case study to support dynamic adaptation pathways planning

This section provides a case study on different ways of presenting the coastal inundation hazard. We then discuss the usefulness of the maps to DAPP.

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Figure 4 presents an aerial photograph of Mission Bay, Auckland, New Zealand, along with results of a coastal inundation assessment in the form of shaded areas representing the horizontal extent of the 1% AEP storm-tide at: (i) present-day mean sea level (MSL); (ii) present-day MSL + 1 m SLR, and (iii) present-day MSL + 2 m SLR. These type of hazard maps are typical of many recent coastal hazard assessments in New Zealand. They provide a useful summary for planning authorities, showing both the present-day hazard, and also identifying the potential future hazard of at least a 100-year timeframe, as required under present legislation (NZCPS). Maps such as these form the basis for development controls in the Auckland Region [19].

Although useful, such hazard-exposure maps in Figure 4 have several limitations:

- They show land either as 'in' or 'out' of the hazard area, but provide no information of the gradient in hazard magnitude away from the sea (e.g., a property at the landward edge of the 1% AEP +1 m SLR area will only be affected towards the end of the planning timeframe);
- They provide no information on the timing of the emerging hazard;
- They provide no information on the increasing frequency of inundation with future SLR;
- The hazard analysis for the +1 m and + 2 m SLR scenarios may not be that useful for adaptation planning, if inundation begins to occur frequently at lower SLR.

The analysis in Figure 4 has also acted as a hazard screening tool, showing that much of Mission Bay could be affected by inundation after + 1 m SLR, and, similar to the Suburb 1 example in Figure 3, parts of Mission Bay are likely to reach decision points before +1 m of SLR occurs.

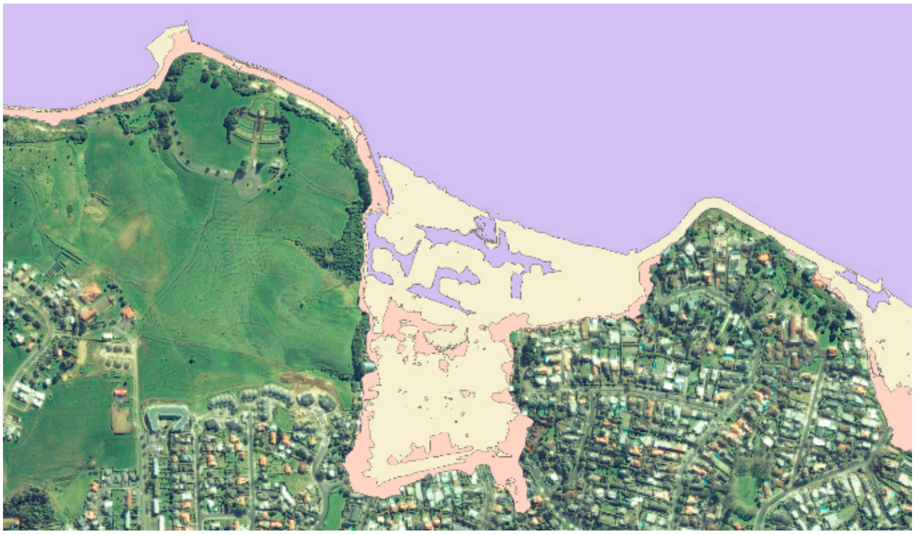

Figure 4. Coastal-storm inundation mapping example at Mission Bay, Auckland. Aerial photograph of Mission Bay with present-day 1% AEP storm-tide plus wave setup elevation superimposed (purple shading), plus 1 m SLR (light shading), and plus 2 m SLR (orange shading). Source: [19]

The uncertainty framework in Figure 2 suggests that for such locations, the impacts of regular small (0.1–0.2 m) SLR height increments should be assessed (on top of both the median and upper 95% of the 1% AEP hazard) to identify potential trigger points for input to the DAPP process and community engagement.

Figure 5 uses a static mapping technique to add 0.1 m SLR increments directly on top of the present-day median (maximum-likelihood) 1% AEP storm-tide elevation. Figure 5 provides extra information to Figure 4, and clearly indicates how inundation extent might change incrementally with SLR, depending on location. Properties on low-elevation land close to the sea will face inundation after a modest SLR, so will be affected sooner. Properties located further inland on higher elevation land are less exposed and will have longer to adapt to rising sea level. Such maps also assist councils to assess the emergence of risks to roads and other utilities and services (e.g., blues areas in Figure 4). The mapping of small SLR increments will be more useful for adaptation

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planning, as it relates a gradually increasing inundation extent to gradually increasing SLR. However, Figure 5 provides no information on the depth and frequency of inundation.

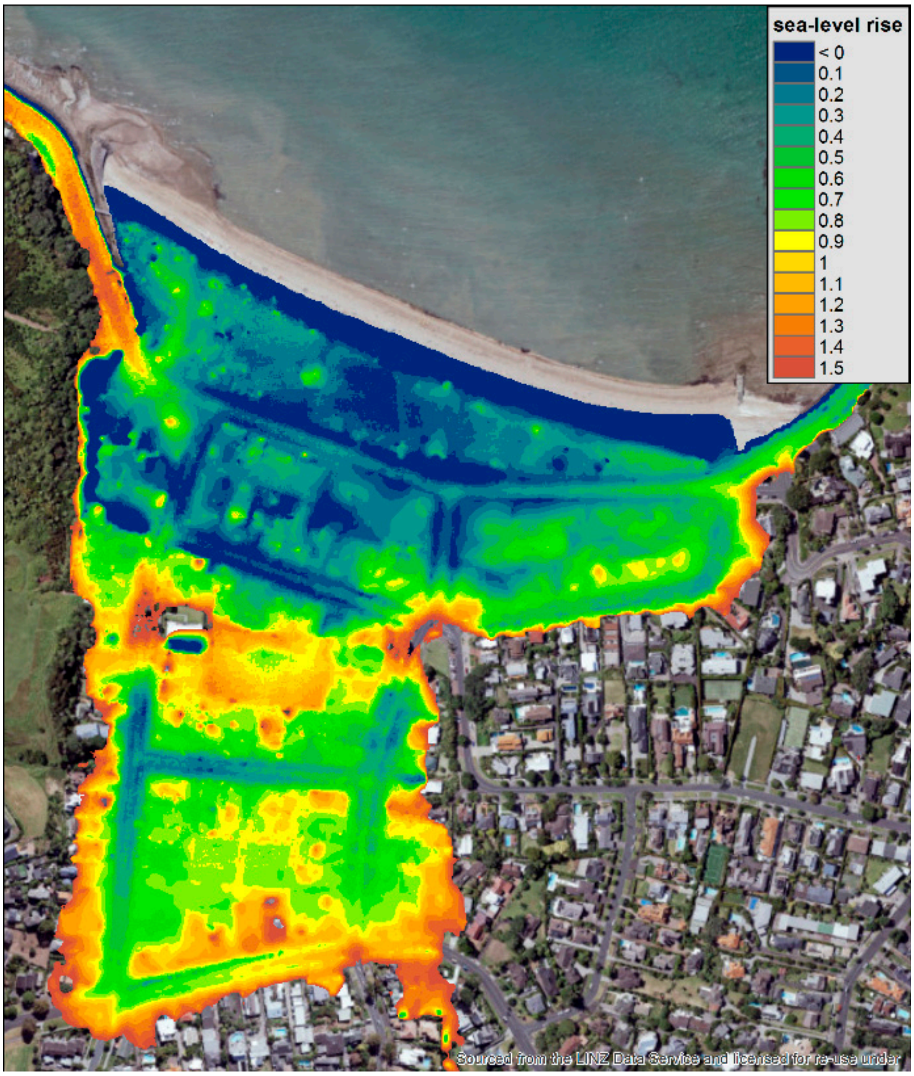

Figure 5. The effect of 0.1 m SLR increments on coastal-storm inundation exposure at Mission Bay (Auckland). SLR increments have been added onto the 1% AEP storm-tide elevation, which was calculated for the present-day mean sea level.

Figure 6 and Figure 7 provide even more information, mapping the expected depth and frequency of inundation for various SLR scenarios.

Figure 6 shows the depth (and area) of inundation for a 1% AEP storm-tide at present-day MSL, plus two SLR scenarios (+ 0.4 m and + 0.8 m). The maps show the increasing area and depth (severity) of future inundation as the sea rises. The changing frequency of inundation was determined by vertically translating the empirical sea-level distribution to account for SLR [7, 20]. The sea-level distribution was first merged with an extreme-value model to create mixed-distribution model that represented the full sea-level distribution [6, 20].

Figure 7 shows the frequency (and area) of inundation for a 1% AEP storm-tide at present-day MSL, plus two SLR scenarios (+ 0.4 m and + 0.8 m). The maps show that coastal-storm inundation becomes increasingly likely with SLR. In combination, Figure 6 and Figure 7 show both the expected depth and frequency of future inundation.

The combination of these plots (Figure 6 and Figure 7) provides information that is more useful for decision making than any of the other plots in isolation. For example, a property located beside the first street back from the sea is not presently exposed, but after 0.8 m SLR can expected to be inundated by about 0.5 m or more of water, about 10 times per year. Clearly the owner of this

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property will face a decision point before 0.8 m of SLR occurs, and certainly well before 1.0 or 2.0 m SLR occurs.

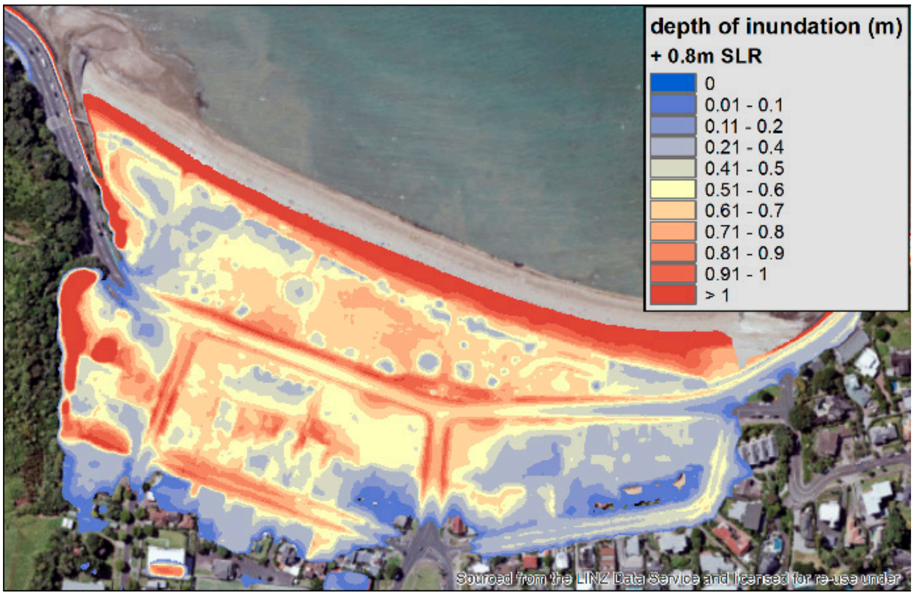

Figure 6. Depth of inundation at Mission Bay, Auckland, for a 1% AEP storm-tide at present-day MSL + 0.8 m SLR. Inundation was modelled using a static GIS technique. All areas below the modelled sea level are shown as inundated, regardless of connection to the sea – some inland areas may not become inundated as shown.

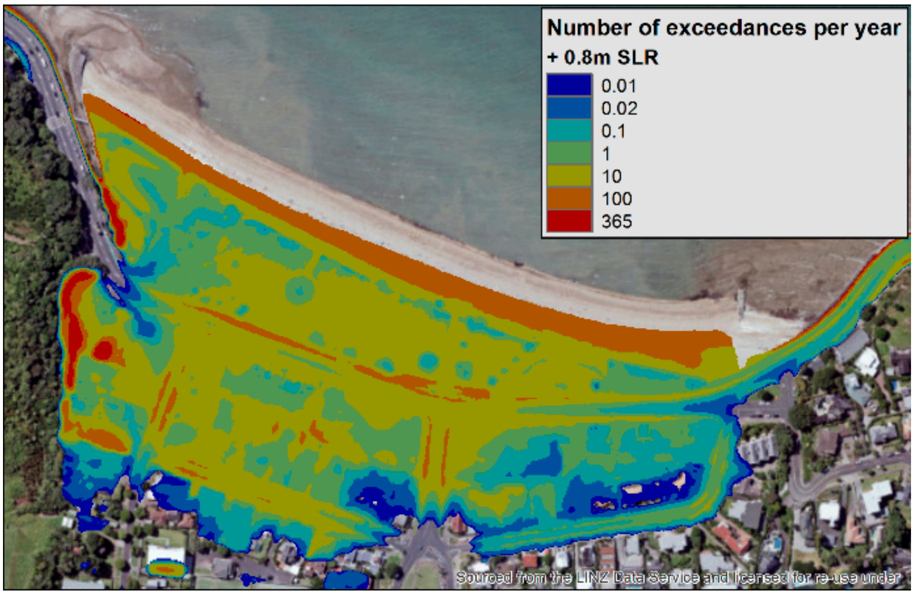

Figure 7. Frequency of inundation (exceedances per year) at Mission Bay, Auckland, for a 1% AEP storm-tide, at present-day MSL + 0.8 m SLR.

The final piece of the puzzle is to identify the likely timing of the various inundation scenarios mapped in Figure 6 and Figure 7, which can be achieved using Table 1.

Bracketed timeframes to reach a specific increment of SLR, from the earliest to latest time across the RCP2.6, RCP4.5, RCP8.5 and H^+ scenarios, are provided in Table 1 [source 9] to assist with the timing of decision points in the DAPP process. These timeframes can be used where particular SLR triggers or associated thresholds for frequency of inundation events have been established, based on vulnerability and risk assessments.

Table 1. Approximate years, from possible earliest to latest, when specific sea-level rise increments (metres above 1986–2005 baseline) could be reached for various projection scenarios of SLR for the

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wider New Zealand region. The earliest year listed is based on the RCP8.5 (83rd percentile) or H^{+} projection and the next three columns are based on the median projections of the RCP 8.5, 4.5 and 2.6 scenarios.

SLR (m)	RCP8.5 H^{+} (83%ile)	RCP8.5 (median)	RCP4.5 (median)	RCP2.6 (median)
0.3	2045	2050	2060	2070
0.4	2055	2065	2075	2090
0.5	2060	2075	2090	2110
0.6	2070	2085	2110	2130
0.7	2075	2090	2125	2155
0.8	2085	2100	2140	2175
0.9	2090	2110	2155	2200
1.0	2100	2115	2170	>2200
1.2	2110	2130	2200	>2200
1.5	2130	2160	>2200	>2200
1.8	2145	2180	>2200	>2200
1.9	2150	2195	>2200	>2200

6. Conclusions

Coastal inundation has occasionally caused damage, nuisance flooding or disruption in the past, but on the back of rising seas, will greatly increase in frequency, depth and consequence in the future. Coastal hazard assessments must provide more clarity in hazard-exposure information in a way that is clearly understood, to better assist decision-making and community engagement processes.

The dynamic adaptive pathways planning process involves the identification of trigger (decision) points, whereby communities decide ahead of time on courses of action or pathways once those decision points are reached. Coastal hazard assessments must therefore clearly assist communities and councils (in relation to levels of service) to decide what those decision points are, by providing alternative scenarios along with the likely time range for those scenarios. This requires a careful treatment of uncertainty, because there are different types of uncertainty that come into play when dealing with the long timeframes and creeping hazards associated with SLR. These sources of uncertainty must be carefully separated out and communicated transparently [9].

When undertaking coastal hazard assessment, there are four types of uncertainty that lead to different types of decisions: (i) little uncertainty; (ii) statistical uncertainty; (iii) scenario uncertainty; and, (iv) deep uncertainty.

We have outlined a framework for uncertainty identification and management when designing and undertaking coastal hazard assessments. The framework recognizes three types of decision: (i) accept; (ii) avoid; and (iii) adapt to coastal hazards, and it identifies the types of uncertainty that must be accounted for each decision type.

For short-lived, low-value, non-habitable assets at the coast, the hazard can largely be accepted; for high-value greenfields developments or major infrastructure the hazard can be avoided by accounting for deeply uncertain but potentially high SLR. However, the most pressing need and complexity comes from the increasing exposure for existing development that will need to progressively adapt as the sea rises, and which might be affected by relatively small SLR increments (and already may be experiencing increasing inundation events). To support the dynamic adaptation planning process, both statistical and scenario uncertainty need to be accounted for and be clearly separated.

A case study was used to show how coastal hazard exposure can be mapped for small increments of SLR. The SLR increments represent a range of plausible future scenarios, which can be

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superimposed on high storm-tide elevations for which there is an estimated statistical likelihood. The mapping of small SLR increments will be useful for adaptation planning, as it relates a gradually increasing inundation extent to gradually increasing SLR, and can inform communities and councils on when intolerable hazard exposure and risk may emerge (in relation to a SLR and event frequency trigger and using the bracketed time windows in Table 1).

Maps of coastal inundation typically show just the area of inundation, but we have demonstrated how these can be improved to also show both the depth and expected frequency of inundation. This extra information is useful for decision making, showing the degree of exposure, where that exposure occurs, and how much sea-level rise can be tolerated, which can enable more precise decision making.

When combined with information on the approximate bracketed timing of the incremental sea-level rise scenarios, the maps allow communities, stakeholders and councils to identify decision points and expected earliest time for the emergence of intolerable inundation risk. The actual progression of SLR towards those scenarios can then be monitored and reviewed.

Acknowledgments: The project was funded by the New Zealand Ministry of Business, Innovation and Employment under Strategic Investment Fund projects CAFS1703 and CAVA1704 of the National Institute of Water and Atmospheric Research. Sanjay Wadhwa produced the inundation maps. Aerial imagery sourced from LINZ Data Service and licensed for re-use under the Creative Commons Attribution 3.0 New Zealand license.

Author Contributions: Stephens and Bell conceived the mapping concepts, which were applied within a national guidance document on which all three authors collaborated [9]. Lawrence introduced us to Walkers work on uncertainty [10], to Haasnoots work on DAPP [16], and provided input to the development of Figure 2. Bell developed Table 1. Stephens wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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