Phase 2 Coastal Inundation Modelling

Development of an adaptation pathway methodology

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Author:	Damian Debski
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Jacobs New Zealand Limited

Level 8, 1 Grey Street
Wellington, 6143
PO Box 10-283
Wellington 6011
New Zealand
T +64 4 473 4265
F +64 4 473 3369
www.jacobs.com

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Summary

A methodology has been developed for defining an adaptation pathway for Kairaki and The Pines Beach based on an adaptation threshold of overtopping of the stopbank by a 5% AEP storm tide. This event has a similar probability of occurring over a planning period of 10 years as that of the 0.5% AEP event occurring over a period of 100 years. Signal and trigger levels can be defined as changes in mean sea level from the present-day level (or absolute mean sea level values) at which the 5% AEP storm tide approaches the adaptation threshold.

This adaptation threshold could be reached in 30 to 60 years' time, depending on how quickly sea level rises. This timescale could be compatible with a policy related to the use of relocatable structures in these areas. However, there is a risk of overtopping by events larger than the 5% AEP event (e.g. the 1% AEP) before the adaptation threshold is reached. Although the probability of such an event occurring may be lower than the accepted probability of overtopping in the planning timescale (e.g. 10 years), the consequences of this occurring may not be acceptable to the community.

Modelling of the inundation resulting from a 1% AEP storm tide (with 10% AEP fluvial flow) with sea level rise at the adaptation threshold value for the 5% AEP tide (0.29m) indicates a depth of flooding in Kairaki of up to around 1.5 m due to the confined nature of the floodplain. Flood depths in The Pines Beach are lower at around 0.2 m to 0.3 m, typically. Maximum water depths are deeper on the access route to the area (e.g. around 0.5 to 0.6 m at the junction of Beach Road and Dunns Avenue). This depth of water is not generally considered safe for evacuation by standard passenger vehicles (cars)[1]

Given the large depth of flooding that would occur in Kairaki in an exceedance event, adaptation pathways based on two alterative tidal event probabilities (2% AEP and 1% AEP) have also been considered. Under these options, adaptation thresholds could be reached in 20 to 40 years' time for a pathway based on a 2% AEP criteria, and in 20 to 30 years' time for a pathway based on a 1% AEP criteria. In the latter case the "signal" level would already be exceeded at present day and the 'trigger" level for implementation of the adaptation intervention could be met within 10 years. The reduced timescale to the adaptation threshold based on these criteria may not be acceptable in terms of a relocatable building policy.

These pathways are based on storm tide levels without any contribution to water level from fluvial flow in the Waimakariri river. Previous inundation modelling has shown that the effect of fluvial flow on water level is small for smaller tidal events (e.g. AEP greater than 1%) for which a small coincident fluvial flow is considered appropriate. For larger storm tide events (e.g. AEP 1% and smaller) with a larger coincident fluvial flow allowance, the additional increase in water level at Kairaki Creek means that trigger levels are reached more quickly. For an adaptation threshold based on overtopping by the 1% AEP storm tide with a coincident 10% AEP fluvial flow, the adaptation threshold would be reached in less than 10 years and both the "signal" and "adaptation" triggers would already be triggered at present day. Under this threshold criterion, a relocatable building policy is not considered appropriate.

Given the difference in the expected flood hazard in Kairaki and The Pines Beach for events which start to exceed the adaptation threshold, there may be merit in considering different adaptation pathways for each area.

[1] Section 7.2.4, Book 6: Flood Hydraulics, Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors)Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019 (ARR: A guide to flood estimation (au.s3-website-ap-southeast-2.amazonaws.com))

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to assess the extent of coastally driven flooding at the mouths of the Waimakariri and Ashley Rivers and investigate approaches to setting triggers for adaptation pathways in accordance with the scope of services set out in the contract between Jacobs and Waimakariri District Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources, including the Environment Canterbury river models of the Waimakariri, Kaiapoi and Ashley Rivers. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

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1. Introduction

Waimakariri District Council (WDC) is exploring options for flood risk management as part of the regeneration of the former red zone areas of The Pines Beach and Kairaki (Figure 1). These areas are exposed to four potential sources of flooding: i) localised flooding by direct runoff of heavy rain; ii) breakout of flow from the Ashley River during high flow in the river; iii) coastal inundation through overtopping of stopbanks during storm tides; and iv) elevated groundwater levels.

Figure 1 Location of The Pines Beach and Kairaki regeneration areas (indicative)

Under the Waimakariri Residential Red Zone Recovery Plan, only non-permanent (relocatable) buildings will be permitted in these areas. Flood risk to buildings is usually mitigated by requiring that floor levels are raised above flood levels. For habitable buildings, floor levels are usually set above the 1% or 0.5% Annual Exceedance Probability (AEP) flood level.

Under present day conditions, and once remaining improvements to stopbanks are complete, the highest flood levels in these areas are those arising from Ashley breakout flows. However, due to sea level rise, future flood levels from coastal flooding are significantly higher than those from Ashley breakouts and floor levels would need to be set a relatively high level (more than 1 m above ground level) for protection from the 1% or 0.5% AEP future coastal flood water level.

An alternative approach to managing flood risk would be to set floor levels above the Ashley breakout flood levels and to relocate structures once the risk from coastal flooding exceeds a specified threshold. A key consideration for this type of planning policy is whether the timescale before meeting any relocation threshold would provide a meaningful occupancy timeframe for structure owners.

This report provides, for discussion, a proposed methodology for specifying and applying criteria to trigger the relocation of buildings in these two areas in response to the risk of coastal inundation exceeding an acceptable threshold.

2. Coastal inundation pathways

Coastal inundation in the Waimakariri District has previously been simulated using a hydrodynamic model[2]. Figure 2 shows the previously simulated inundation extent for a 1% AEP storm tide under present day mean sea level in the Pines Beach and Kairaki area (prior to recent stopbank improvements). The inundation pathways are primarily overtopping of the stopbank along the true left bank of the Kairaki Creek together with localised overtopping of low points along the true left bank of the Waimakariri River downstream of the confluence with the Kairaki Creek, as shown in Figure 2.

A secondary pathway for inundation is through overtopping of the true right bank of the Ashley River at Waikuku during storm tides. However, due to the distance from the river, flooding from this source starts to occur for smaller probability storm tide events than flooding from Kairaki Creek which is the initial and primary source of coastal flooding.

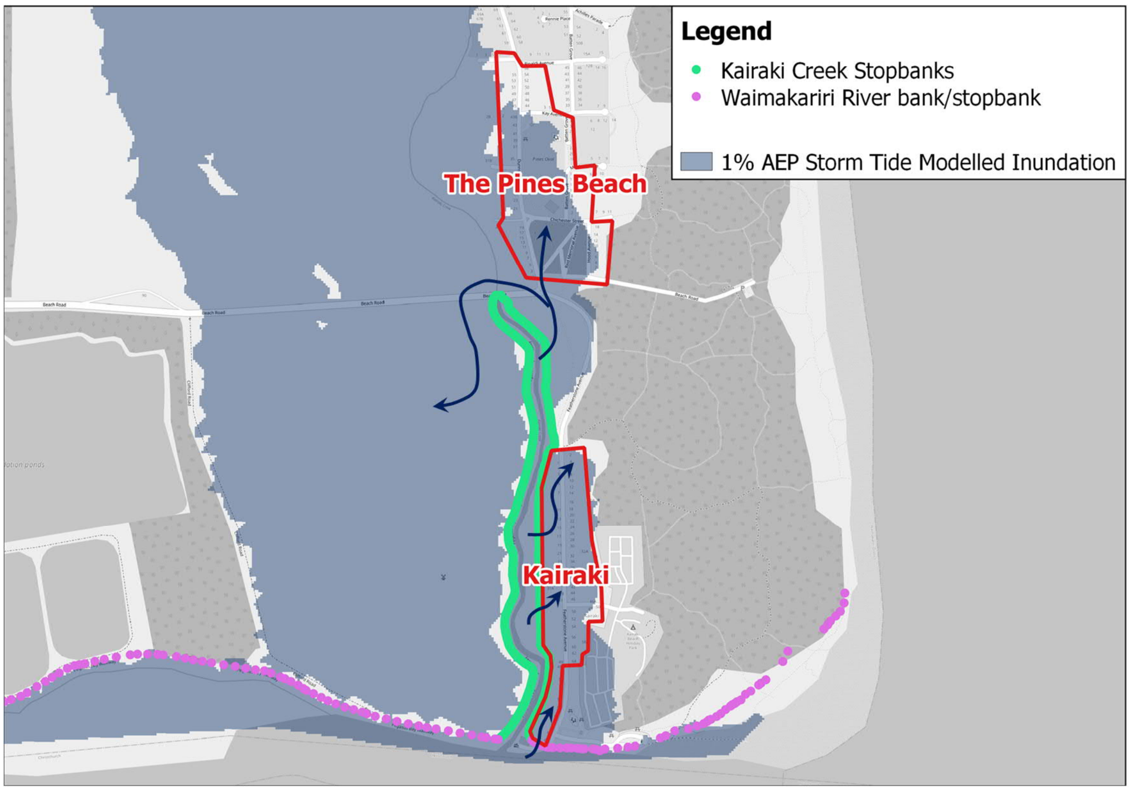

Figure 2 Modelled inundation pathways in the Kairaki and The Pines Beach regeneration areas

The inundation modelling was based on LiDAR survey data collected in 2014. The stopbanks along the Kairaki Creek and Waimakariri River have been upgraded since then. A recent (2019) as-built survey[3] of the Kairaki Creek stopbanks indicates a minimum crest level of 2.08 m to Lyttelton 1937 vertical datum (LVD-37) along the true left bank of Kairaki Creek, reducing to 2.01 mLVD-37 at the Beach Road crossing compared to a minimum crest level of around 1.9 mLVD-37 in the 2014 LiDAR survey. The minimum surveyed level of the true right bank in the 2019 survey is 2.76 mLVD-37, reducing to 1.98 mLVD-37 at the Beach Road crossing. The minimum level along the true left bank of the Waimakariri River downstream of the Kairaki Creek confluence in the 2019 survey is 2.40 mLVD-37 although the lowest levels are generally closer to 2.5 mLVD-37 (2.47m to 2.48m).

[2] Phase 2 Coastal Inundation Modelling - Final Study Report IZ105901-0000-NW-RPT-0001 | 2, Jacobs, 12 March 2020

[3] "Waimakariri River Stopbank As-Builts Nov 2019 Including Kaiapoi River and Kairaki Creek", Project No. 19346, Environment Canterbury, January 2020

It is understood[4] that the Kairaki Creek stopbanks will be made up to a design level of 2.8 mLVD-37 along the true right bank and 2.5 mLVD-37 along the true left bank and that the Beach Road crossing headwall will be raised to 2.8 mLVD-37.

2.1 Extreme water levels

Water levels in the mouth of the Waimakariri River and along the Kairaki Creek are tidally dominated. For the 2020 Coastal Inundation modelling, storm tide levels at the mouth of the Waimakariri River were defined from the analysis of Goring (2018)[5] for offshore tide levels and an allowance for wave setup in the river mouth of 0.25m, as summarised in Table 1.

Table 1 Storm tide levels

AEP	Storm tide level (mLVD-37)	
	Goring (2018)	Including wave setup (0.25m)
10%	1.894	2.144
5%	1.960	2.210
2%	2.046	2.296
1%	2.110	2.360
0.50%	2.174	2.424
0.20%	2.259	2.509

The hydrodynamic model simulations included both “tidal” events (low probability storm tide and high probability fluvial flow) and “fluvial” events (low probability fluvial flow and high probability storm tide). The simulation results showed that the water level at Kairaki Creek is higher for a tidal event of a given probability than for a fluvial event of the same probability (for probabilities greater than 0.2% AEP). The simulations also showed that for “tidal” events, the effect of the allowance for fluvial flow on the maximum water level at Kairaki Creek is relatively small – for the 1% AEP tidal event the water level is less than 0.1m above the storm tide level at the river mouth, and the difference in water levels reduces for higher probability tidal events (due to smaller fluvial flow) and with increasing mean sea level (higher storm tide level for a given probability).

[4] email correspondence with Chris Bacon, WDC, 13 January 2021
[5] Extreme Sea Levels at Christchurch Sites: EV1 Analysis, Mulgor Consulting Limited, 24 July 2018

3. Proposed methodology for trigger levels

Once remaining improvements have been completed, the stopbanks along the Waimakariri River and the Kairaki Creek will provide protection to Kairaki and The Pines Beach from storm tides to approximately the 0.5% AEP (without freeboard and assuming no fluvial effects) under present day mean sea level. Rising mean sea level will increase the exposure of these areas to coastal inundation.

An approach to designing trigger levels for Dynamic Adaptive Policy Pathways (DAPP) has been demonstrated by Stephens et al (2018)[6]. In this method, the source of flood hazard (rising sea level and storm tide levels) is measured over successive, set, monitoring and planning periods (10 years) and compared to pre-set “signal” (early warning), “trigger” (decision-point) and “adaptation threshold” levels which are defined as follows:

- the “signal” level gives a decision maker early warning of an impending “trigger”
- the “trigger” indicates the time when a decision needs to be made to change pathways for managing flood risk (e.g. to raise a stopbank or relocate a building). The trigger must provide sufficient lead time to adapt before the “adaptation-threshold” is reached
- the “adaptation threshold” is the time at which flood risk becomes unacceptable under the current pathway and is the time by which adaptation must be complete to avoid this risk.

By monitoring actual sea levels, the change to another pathway can be delayed if sea level rise is slower than expected or can be made sooner if sea level rise occurs more rapidly.

This approach can be adapted to specify and apply criteria to trigger the relocation of buildings in The Pines Beach and Kairaki regeneration areas once the probability of overtopping of the stopbanks becomes unacceptable. An alternative pathway to relocation, based on the same trigger levels, could be to further raise the stopbank crest level (for example). The process is illustrated in Figure 3.

The probability of the event for which overtopping during each successive planning and monitoring period is unacceptable could be defined through reference to flood mitigation requirements for permanent buildings. Typically, this will require protection from, for example, the 0.5% AEP flood over the lifetime of the building (e.g. 100 years). The probability of the 0.5% AEP event occurring at least once during a period of 100 years is approximately 39%. For a planning period of 10 years, there is a similar probability (40%) of the 5% AEP event occurring at least once within that period. For comparison, the probability of events of other magnitudes occurring over time periods of 10, 50 and 100 years is presented in Table 2[7].

Table 2 Probability of flood events of particular magnitudes occurring over a given time period

Annual exceedance probability (AEP) of flood event	10%	5%	4%	3%	2%	1%	0.5%
Probability event occurs at least once in a 10 year period	65%	$\boxed{40\%}$	34%	26%	18%	10%	5%
Probability event occurs at least once in a 50 year period	99%	92%	87%	78%	64%	39%	22%
Probability event occurs at least once in a 100 year period	100%	99%	98%	95%	87%	63%	$\boxed{39\%}$

On this basis, the adaptation threshold could be defined as the time at which the 5% AEP storm tide level exceeds the minimum stopbank level. Signal and trigger levels could be defined as changes in mean sea level from the present-day level (or absolute mean sea level values) at which the 5% AEP storm tide approaches the

[6] Developing signals to trigger adaptation to sea-level rise, Scott A Stephens, Robert G Bell, Judy Lawrence, Environmental Research Letters 13 (2018)
[7] See also, for example, https://www.ecan.govt.nz/your-region/your-environment/natural-hazards/floods/flood-probabilities/

adaptation threshold. This assumes that the effect of climate change on storm surge and wave setup are not significant, as is currently indicated by guidance on climate change effects[8][9].

The inundation resulting from overtopping of the stopbanks by storm tides which just start to exceed the adaptation threshold (i.e. a little less than 5% AEP) has not been modelled. However, available modelling of smaller probability events indicates that the resulting flood depths in such events may be relatively small (i.e. potentially below floor levels) and not all of the trigger area may be flooded due to the limited volume of water overtopping. From this point of view the adaptation threshold could be defined at a level above the stopbank crest level if a limited amount of overtopping at the selected frequency is acceptable to the community. However, if the stopbanks are not designed and constructed to withstand sustained overtopping flow there is a risk of breaching once overtopping occurs. This would result in significantly deeper and more widespread flooding and this risk may be unacceptable.

[8] Coastal Hazards and Climate Change, ME1341, MfE, December 2017
[9] UKCP18 Science Overview Executive Summary, Met Office, UK, January 2019

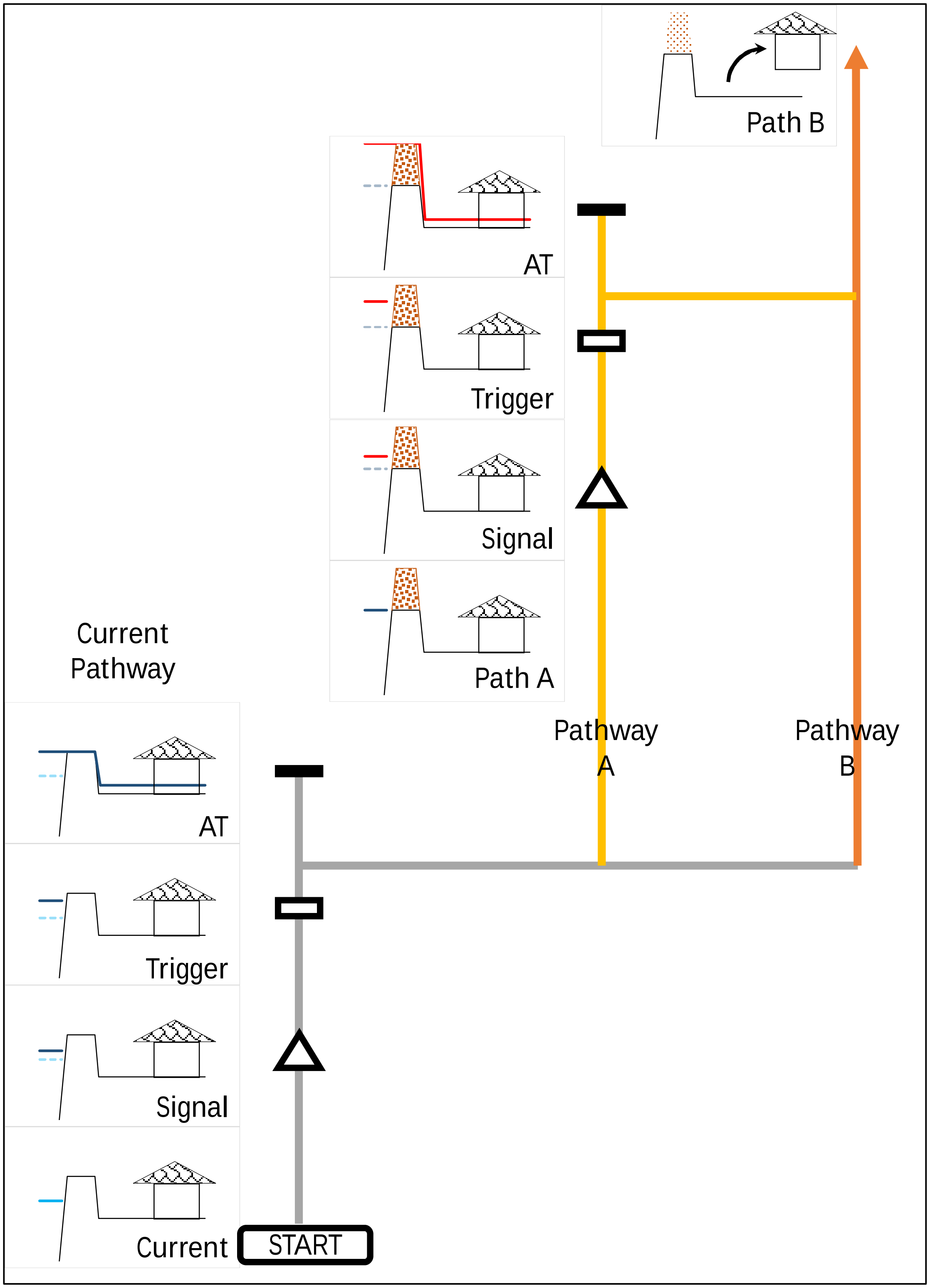

Figure 3 Proposed Dynamic Adaptive Pathways (AT=Adaptation Threshold)

4. Application of the proposed methodology

As described in Section 2, following remaining improvement works the minimum crest level of the stopbanks protecting The Pines Beach and Kairaki will be 2.5 mLVD-37.

For a 40% chance of overtopping within each 10-year monitoring and planning period, consider protection from the 5% AEP tidal event.

Suggested trigger conditions are:

"Signal": When the 5% AEP storm tide = 2.31 mLVD-37

"Adaptation Trigger": When the 5% AEP storm tide = 2.41 mLVD-37

"Adaptation Threshold (AT)": When the 5% AEP storm tide = 2.5 mLVD-37

Given a current estimate of the 5% AEP storm tide at Kairaki Creek of 2.21 mLVD-37, including wave setup allowance but excluding fluvial effects, and assuming stationarity of storm tide and wave setup relative to mean sea level:

Signal = 0.10 m rise in mean sea level above "present day" (2020)

Adaptation Trigger = 0.20 m rise in mean sea level above "present day" (2020)

Adaptation Threshold = 0.29 m rise in mean sea level above "present day" (2020)

Figure 4 illustrates the trigger levels and the 5% AEP water levels for four climate change scenarios (RCP2.6 M, RCP4.5 M, RCP8.5 M and RCP8.5 H+) based on current sea level rise guidance[10], referenced to 2020. Table 3 provides estimates of the indicative dates at which each of these three trigger levels may be exceeded or "activated" in each scenario. It should be noted that initial updated guidance on rates of future sea level rise were provided by IPCC in 2019 and a fuller update is expected in 2022. These updates have not been included in the values presented in Figure 4 and Table 3 which are intended to give an indicative illustration of the likely timescales for activation of the triggers. For these projections of sea level rise, the time interval between successive trigger levels is generally between 10 and 20 years. This suggests a 10-year cycle of monitoring and planning periods should provide an adequate lead time for implementing adaptation measures.

[10] Coastal Hazards and Climate Change, ME1341, MfE, December 2017

Table 3 Potential timescales for trigger activation

Trigger	Value (rise in mean sea level)	Indicative date of trigger being exceeded			
		RCP2.6 M	RCP4.5 M	RCP8.5 M	RCP8.5 H+
Signal	0.10 m	2040	2038	2037	2033
Adaptation Trigger	0.20 m	2062	2057	2051	2044
Adaptation Threshold	0.29 m	2080	2072	2062	2053

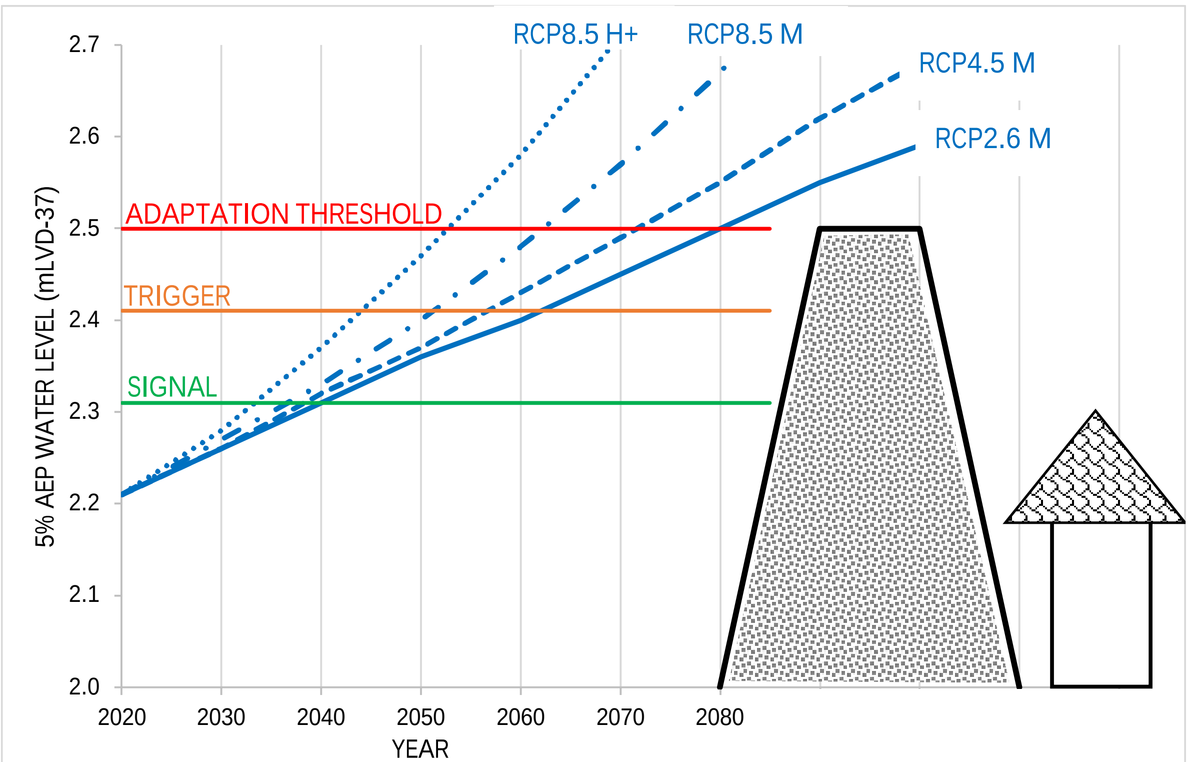

Figure 4 Proposed trigger levels and indicative projections of 5% AEP water levels for four climate change scenarios

5. Consequences of exceedance events

By adopting the adaptation methodology outlined above there is a risk of overtopping from events larger than the 5% AEP event (e.g. the 1% AEP) prior to the adaptation threshold being reached. Although the probability of such an event occurring may be lower than the accepted probability of overtopping in the planning timescale (10 years) the consequences of the event occurring may not be acceptable to the community.

In order to understand the consequences of an exceedance event, the flood model has been used to simulate a 1% AEP storm tide (combined with a 10% AEP fluvial flow) for an increase in mean sea level of 0.29m (the value at which the adaptation threshold is reached for a 5% AEP event). The flood model has been updated to include the design stopbank crest levels along Kairaki Creek: 2.5 mLVD-37 along the true left bank and 2.8 mLVD-37 along the true right bank and the Beach Road crossing.

Figure 5 shows the maximum water depths in the model simulation of this event. The peak water level at the mouth of Kairaki Creek (2.72 mLVD-37) exceeds the stopbank crest level along the true left bank of the creek resulting in flooding into Kairaki and north into The Pines Beach. The maximum water level attained in Kairaki is similar to the peak water level in the creek. This is because the floodplain area is confined by higher ground to the east and is relatively small compared to the length of stopbank and the volume of water overtopping the stopbank. In addition there is only a narrow overland flow path north towards The Pines. Maximum model depths in Kairaki are around 1.5 m. Flood depths are lower in The Pines (typically 0.2 m to 0.3 m) because less water flows into this area and it can spread out further over the large area of lower-lying land to the west of Kairaki Creek. Water depths are deeper on the access route to the area (e.g. around 0.5 to 0.6 m at the junction of Beach Road and Dunns Avenue). This depth of water is not generally considered safe for evacuation by standard passenger vehicles (cars)[11].

Given the large depth of flooding that would occur in Kairaki in an exceedance event ahead of reaching an adaptation threshold based on the 5% AEP storm tide, adaptation pathways based on two alterative threshold events (2% AEP and 1% AEP) have been considered.

[11] Section 7.2.4, Book 6: Flood Hydraulics, Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors)Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019 (ARR: A guide to flood estimation (au.s3-website-ap-southeast-2.amazonaws.com))

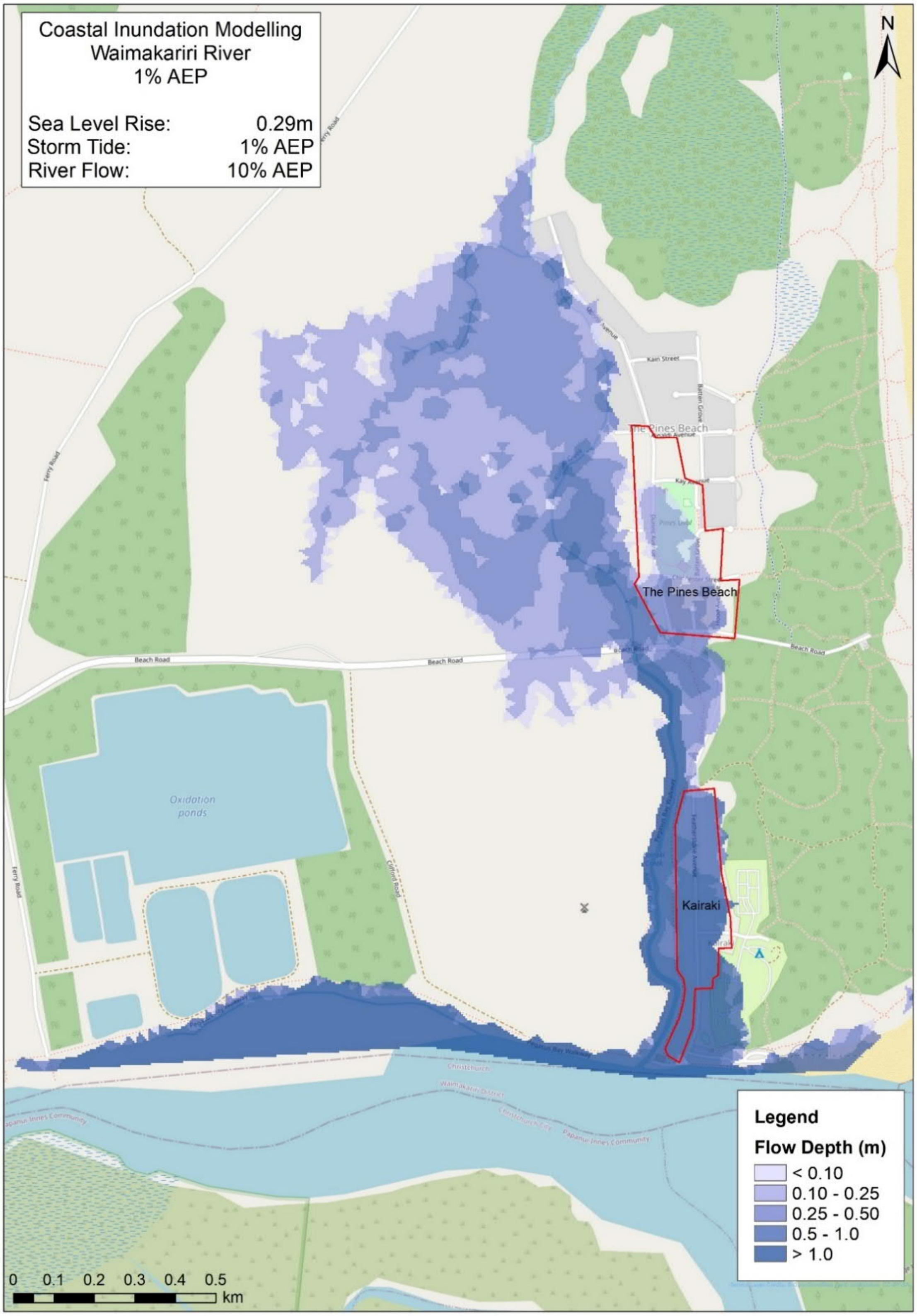

Figure 5 Model flood extent for 1% AEP storm tide and 0.29 m rise in mean sea level with design stopbank levels

6. Alternative adaptation thresholds

The methodology set out in Section 5 can be applied to alternative flood event probabilities as follows.

"2% Adaptation Threshold (AT)": When the 2% AEP storm tide = 2.5 mLVD-37 (stopbank crest level)

"1% Adaptation Threshold (AT)": When the 1% AEP storm tide = 2.5 mLVD-37 (stopbank crest level)

To illustrate these alternative pathways the "Signal" and "Adaptation Trigger" levels have been set at the same levels as for the 5% AEP Adaptation Threshold pathway, i.e.

"Signal": When the 2% AEP or 1% AEP storm tide = 2.31 mLVD-37

"Adaptation Trigger": When the 2% AEP or 1% AEP storm tide = 2.41 mLVD-37

Maintaining the same level interval between the triggers means that although the first trigger will be reached earlier, the time interval between triggers and threshold will be similar (approximately 10 years). Table 4 summarises the water levels for the three threshold strategies considered (5%, 2% and 1% AEP) and the corresponding mean sea level rises at each of the trigger levels. For the 1% AEP, levels allowing for fluvial contribution during a storm tide are also illustrated (1% AEP^{+FLUV}).

Table 4 Water levels and sea level rise trigger values for alternative adaptation threshold events

Threshold event	5% AEP	2% AEP	1% AEP	1% AEP^{+FLUV}
Storm tide level in 2020 (m LVD-37)	2.21	2.30	2.36	2.45
Sea level rise to Signal (2.31 mLVD-37)	0.10	0.01	already exceeded	already exceeded
Sea level rise to Adaptation Trigger (2.41 mLVD-37)	0.20	0.11	0.05	already exceeded
Sea level rise to Adaptation Threshold (2.5 mLVD-37)	0.29	0.20	0.14	0.05

Figure 6 illustrate the trigger levels and the storm tide event water levels for the 2% AEP, 1% AEP and 1% AEP event with fluvial allowance thresholds for the same four climate change scenarios (RCP2.6 M, RCP4.5 M, RCP8.5 M and RCP8.5 H+) considered in Figure 4 for the 5% AEP storm tide threshold. Tables 5, 6 and 7 provide estimates of the indicative dates at which each of these three trigger levels may be exceeded or "activated" in each scenario.

As shown in Figure 6 and Table 6, for the selected trigger level values the "Signal" trigger is already exceeded for the 1% AEP adaptation threshold scenario. Allowing for a fluvial contribution, the "Adaptation Trigger" is already exceeded for the 1% AEP threshold scenario.

Table 5 Potential timescales for trigger activation (2% AEP Adaptation Threshold)

Trigger	Value (rise in mean sea level)	Indicative date of trigger being exceeded			
		RCP2.6 M	RCP4.5 M	RCP8.5 M	RCP8.5 H+
Signal	0.01 m	2022	2022	2022	2021
Adaptation Trigger	0.11 m	2042	2040	2038	2034
Adaptation Threshold	0.20 m	2062	2057	2051	2044

Table 6 Potential timescales for trigger activation (1% AEP Adaptation Threshold)

Trigger	Value (rise in mean sea level)	Indicative date of trigger being exceeded			
		RCP2.6 M	RCP4.5 M	RCP8.5 M	RCP8.5 H+
Signal	n/a	ALREADY TRIGGERED			
Adaptation Trigger	0.05 m	2030	2030	2028	2027
Adaptation Threshold	0.14 m	2048	2046	2043	2038

Table 7 Potential timescales for trigger activation (1% AEP^{+FLUV} Adaptation Threshold)

Trigger	Value (rise in mean sea level)	Indicative date of trigger being exceeded			
		RCP2.6 M	RCP4.5 M	RCP8.5 M	RCP8.5 H+
Signal	n/a	ALREADY TRIGGERED			
Adaptation Trigger	n/a	ALREADY TRIGGERED			
Adaptation Threshold	0.05 m	2030	2030	2028	2027

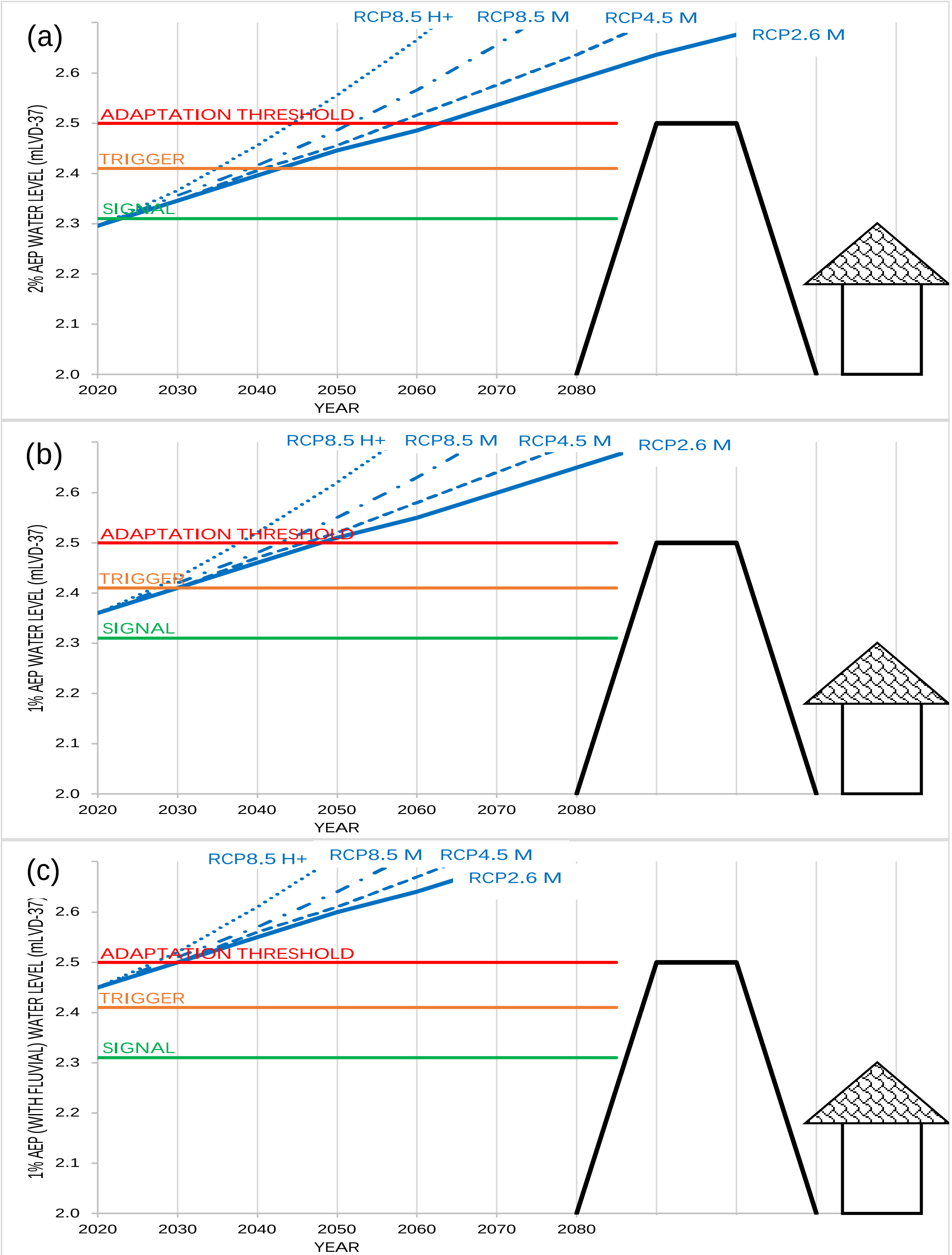

Figure 6 Proposed trigger levels and indicative projections of (a) 2% AEP water levels; (b) 1% AEP water levels; and (c) 1% AEP^{+FLUV} water levels for four climate change scenarios

7. Groundwater

The effect of a rise in mean sea level on groundwater levels and the potential for surface ponding from groundwater to contribute to coastal inundation was assessed in the Coastal Inundation Modelling project[12]. Groundwater levels were estimated for sea level rise of 0.5 m, 1.0 m, and 1.88 m.

Figure 7 shows the areas of surface ponding from groundwater which were included in the model simulation for 0.5 m rise in mean sea level. This sea level rise scenario is closest to (but slightly higher than) the sea level rise at the adaptation threshold for the 5% AEP storm tide (0.29 m, ref. Section 5 above). Figure 7 also shows the estimated depth of the groundwater surface below ground level for the 0.5 m sea level rise scenario.

Based on these estimates, surface ponding from groundwater is not predicted in either Kairaki or The Pines Beach regeneration areas at the time the 5% AEP storm tide adaptation threshold (or any of the other thresholds considered here) is reached. The depth to groundwater at this time is estimated to be approximately 0.5 m to 1.0 m below ground level in the majority of Kairaki and The Pines Beach.

[12] Phase 2 Coastal Inundation Modelling - Final Study Report IZ105901-0000-NW-RPT-0001 | 2, Jacobs, 12 March 2020

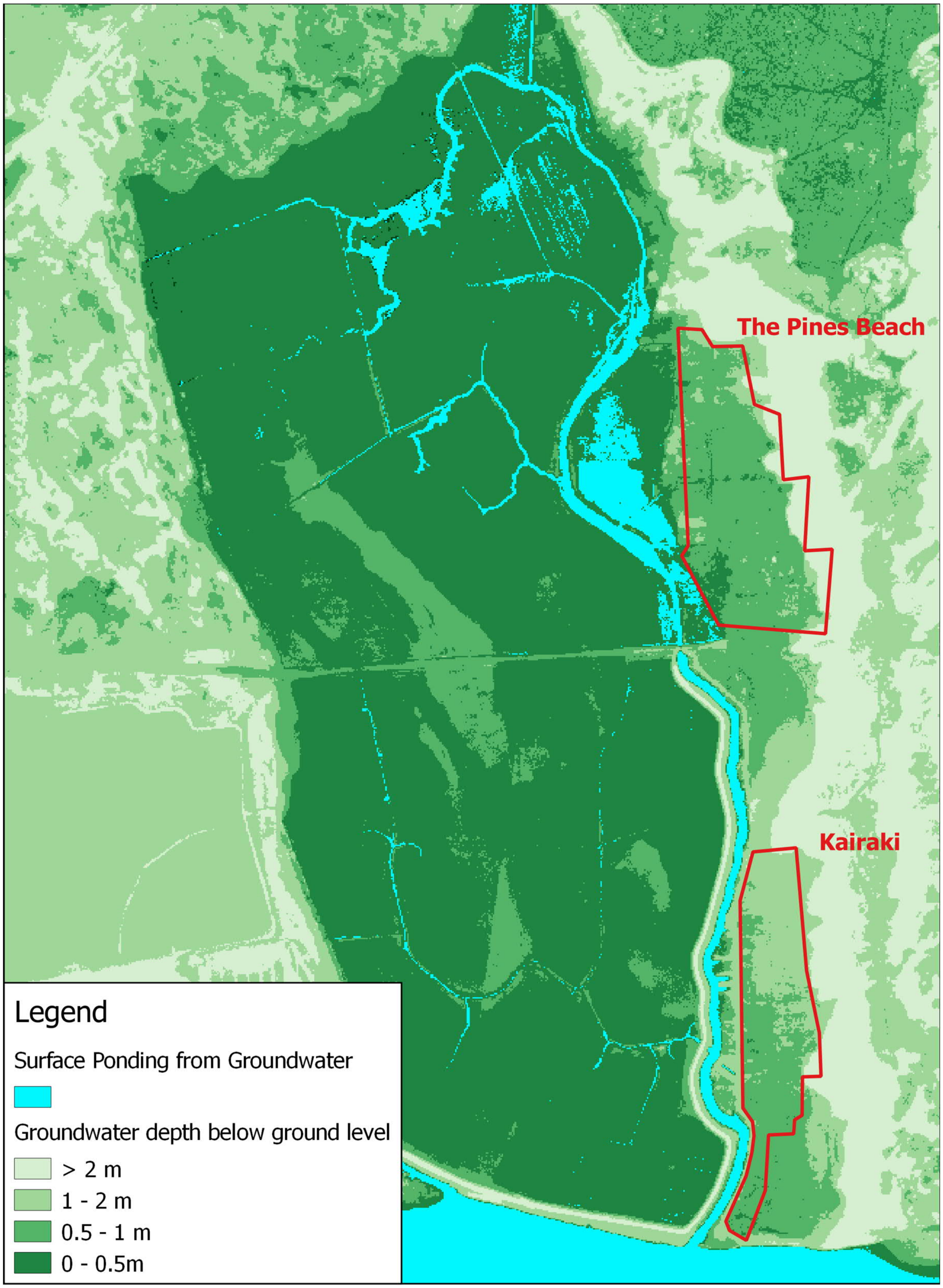

Figure 7 Estimated depth to groundwater and areas of surface ponding from elevated groundwater for 0.5 m rise in mean sea level