Proposed
Hurunui and Waiau River Regional Plan

And Proposed Plan Change 3 to the Canterbury Natural Resources Regional Plan

Section 42A Report
September 2012

Sediment transport and geomorphology

Prepared by

Darryl Murray Hicks

River and Coastal Geomorphologist

Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

1. Introduction

1.1 Author

1. My name is Darryl Murray Hicks. I am a Principal Scientist in Sediment Processes at the National Institute of Water and Atmospheric Research (NIWA). I have 27 years of experience at NIWA and pre-cursor organisations researching and consulting in the field of river and coastal sediment processes. For the past 15 years I have been involved with investigating the effects of existing and new hydro-power and irrigation schemes on downstream river channels and adjacent coasts. In this field, I have authored or co-authored numerous consulting reports and scientific publications and have provided evidence at hearings and to the Environment Court. Most recently, I have provided technical advice to the commissioners hearing the proposed Amended Rakaia River Water Conservation Order and the Transmission Gully Motorway Project.

2. Although this is a Council Hearing, I have read the Code of Conduct for Expert Witnesses contained in the Environment Court's Consolidated Practice Note dated 1 November 2011. I have complied with that Code when preparing my written statement of evidence and I agree to comply with it when I give any oral evidence.

3. The scope of my evidence relates to how the scenarios of water use proposed under the Hurunui and Waiau River Regional Plan (HWRRP) may impact on sediment transport and morphology in the mainstem river channels downstream from intake sites and also the river mouth behaviour and stability of the adjacent coast. I confirm that the issues addressed in this statement of evidence are within my area of expertise.

4. Key data on which I have relied are simulated flow records for the Hurunui and Waiau rivers for several flow allocation scenarios. These were developed and provided by Dr Jeff Smith at the Canterbury Regional Council. I have also used information developed in several previous reports prepared for the Canterbury Regional Council. Two key reports include a report by Measures and Hicks (2011), investigating the sedimentation and geomorphic effects of several alternative water-storage schemes in the Waitohi catchment, and a report by Snelder et al. (2011) investigating the effects of water-use scenarios in the Waiau River. Other literature or other material which I have used or relied upon in support of my opinions are referenced in the body of my evidence and are listed at the end.

5. I have not omitted to consider material facts known to me that might alter or detract from the opinions expressed.

1.2 Content of the officer’s report

6. This report is prepared under the provisions of section 42A of the Resource Management Act 1991 (RMA). Section 42A allows council officers to provide a report to the hearing commissioners on the proposed Hurunui and Waiau River Regional Plan and allows the commissioners to consider the report at the hearing.

1.3 Explanation of terms and coding used in the report

4.

CRC	Canterbury Regional Council or Environment Canterbury (ECan)
CWMS	Canterbury Water Management Strategy
HWRRP	Proposed Hurunui and Waiau River Regional Plan
L/s	Litres per second
m^3/s	Cumec (A measure of river flow. One (1) cumec is the equivalent to one (1) cubic metre per second or alternatively 1,000 L/s)

2. Scope

7. I have been asked by CRC to prepare evidence in relation to the effects on sediment transport and geomorphology of the water allocation that could occur in the Hurunui and Waiau Rivers under the proposed Hurunui and Waiau River Regional Plan (HWRRP). Specifically, this concerns the effects of plan implementation on sediment transport and morphology in the river channels downstream from intake sites, river-mouth behaviour, and stability of the adjacent coast. I have also been asked to comment on the assumptions and the uncertainties associated with the effects assessment.

3. Outline of evidence

8. The content of my evidence will be as follows :

- First I will describe the water-use scenarios that I will evaluate.
- Then, I will evaluate the effects of these scenarios on (i) braided channel processes, and (ii) river-mouth and coastal processes. For each of these two broad topics I will:
    - Provide some background description of the key processes that need to be considered, explain how these can be affected by changes to a river's flow regime and what consequences can ensue, and link these with specific objectives in the HWRRP.
    - Describe the methods I used to quantify these effects.
    - Compare the effects predicted for various scenarios of water allocation.
- Lastly, I will draw conclusions about how each scenario might achieve the geomorphic objectives set out in the HWRRP and comment on mitigation options.

4. Scenarios

9. The scenarios of water allocation that I consider are detailed in the evidence of Dr Snelder. In brief they are:

For the Hurunui River:

- A Status Quo allocation with existing takes
- Scenario 1: an A-block allocation of 7 m^3/s
- Scenario 2: an A-block allocation of 7 m^3/s and a B-block allocation of 10 m^3/s
- Scenario 3: an A-block allocation of 7 m^3/s, a B-block allocation of 10 m^3/s, and a seasonally varying C-block allocation, with a winter maximum of 33 m^3/s
- Scenario 4: an A-block allocation of 7 m^3/s, a B-block allocation of 10 m^3/s, and an all-year C-block allocation of 33 m^3/s.

For the Waiau River:

- Scenario 1: an A-block allocation of 18 m^3/s
- Scenario 2: an A-block allocation of 35 m^3/s
- Scenario 3: an A-block allocation of 71 m^3/s
- Scenario 4: an A-block allocation of 18 m^3/s, a gap of 2 m^3/s, and a B-block allocation 0f 11 m^3/s.
- Scenario 5: an A-block allocation of 18 m^3/s, a gap of 2 m^3/s, and a B-block allocation of 53 m^3/s.

10. Each scenario has been represented as a record of daily mean water discharge at two references sites: Hurunui at Mandamus and Waiau at Marble Point. These simulated records were supplied by Dr Jeff Smith from The Canterbury Regional Council. As detailed by Dr Snelder, they were generated by subtracting allocations from a Natural flow record, providing minimum flow rules were satisfied. The Natural flow record was also generated by Dr Smith and was based on the gauged flow records at these two sites. The Hurunui simulations cover the 52-year period from January 1960 to December 2011. The Waiau simulations cover the approximately 42-year period from October 1967 to September 2009.

11. Collectively for each river, these scenarios cover a spectrum of allocation from the low and mid-high range bands of river flow. From a river geomorphology perspective, it is the takes from the mid-high flow ranges (B and C-blocks) that are expected to have effects, since mid-high flows are required to entrain channel bed material and scour riparian vegetation. On the other hand, river mouth behaviour reflects the interplay of river and coastal

forces, and this is impacted by changes both at the high and low end of the flow range, thus effects there might be expected over all scenarios.

5. Braided channel processes

5.1 Key processes

12. Both the Hurunui and Waiau Rivers are braided for substantial proportions of their run from the nominal extraction sites to the sea. Maintaining the physical characteristics of these braided reaches is important because these characteristics underpin the in-stream and terrestrial riparian habitat.

13. There are several factors that need to be considered. Firstly, there is the pattern of braids and associated distributions of water depth, velocity, and substrate that – for a given water discharge in the river - determine the quality and quantity of potential habitat for fauna (e.g. fish, invertebrates, birds) and for fish and jet-boat navigation. With these, the challenge is to determine whether an altered flow regime on the existing morphology will continue to provide adequate physical habitat. These aspects are being addressed by Mr Duncan, but a fundamental assumption of the IFIM approach that he applies is that the time-averaged characteristics of the channel size and morphology will not change as a consequence of the flow regime change.

14. The second consideration, then, is to assess whether the underlying channel size and the intensity of braiding might change – for example, if the braidplain width narrows on average and if the channel planform pattern becomes less braided or even changes to a single-thread channel. This can happen potentially if floods and freshes becomes less energetic or more intermittent or both due to harvesting of water to off-channel storage. Braided channels such as those of the Hurunui and Waiau are formed and maintained by active transport of their gravelly bed-material during floods and freshes. If these events are large enough and occur often enough, the rivers are able to naturally maintain their channel size and form against the encroachment of woody vegetation. They do this by eroding gravel from braid banks and beds and depositing it on bars; in the process, riverbed vegetation is scoured. Shifting the balance by reducing floods allows the woody vegetation to crowd down the banks and establish on islands. If, for example, several years were to pass between floods competent to scour gravel and riverbed vegetation, the vegetation can become sufficiently dense and woody that the braiding process is stifled. As a consequence, braiding intensity (that is average number of braids) can decrease and average channel width can decrease. Indeed, it is now recognised in the scientific literature that river braiding is constrained by woody riparian vegetation, and in instances where dams and upstream storage have reduced flood frequency, naturally braided rivers have been driven to a less braided state. Examples include the Platte River in the United States and the lower Waitaki River in South Canterbury; both remain braided by virtue of regularly-applied artificial vegetation control (for example, spraying or bulldozers).

15. As well as inducing a feedback effect on channel morphology, the flood-frequency versus vegetation balance also impacts on terrestrial braided riverbed habitat, particularly for wading birds in regard to space for breeding, foraging, and predator awareness. This particular issue is addressed in Mr Duncan’s evidence.

16. The "channel maintenance" function of the flow regime is covered by Objective 6d and Policy 6.2d of the HWRRP: *…woody vegetation is managed to provide for bird habitat, natural channel and bed forming processes …*.

17. A third, closely-related consideration is the frequency at which the surface of the braided riverbed is "turned-over" by flood events. As well as keeping woody vegetation at bay, the process of gravel transport, and the shifting and formation of new braids and bars, "freshens" braided riverbed substrate (by flushing periphyton, sand, and mud-grade sediment from the gravel framework) and creates the dynamic behaviour and form that typifies an active braided river. This flushing occurs at two levels. "Surface flushing" occurs when silt or sand draped above the cobbly bed-surface layer is removed. "Deep flushing" involves removal of fine sediment from beneath this surface layer due to the mobilisation of the surface cobbles. The latter requires a higher river flow and occurs less often.

18. This "bed maintenance" function of the flow regime is covered by Objective 3c of the HWRRP: *…ensuring flow variability is maintained and that flows between 1.5 and 3 times the median flow required to flush periphyton and mobilise gravel and reset the bed of the mainstem of the Hurunui and Waiau Rivers are not adversely affected*. There is a close link between bed mobility and periphyton removal, which is addressed in detail in the evidence of Dr Snelder.

19. A fourth consideration is change in gravel bedload transport capacity along alluvial reaches – that is, the long-term average rate at which the river is capable of moving its gravelly bedload. This provides a measure of the geomorphic "work" that the river can do in maintaining a dynamically braiding channel pattern. It also determines continuity of coastal gravel delivery. I will return to this coastal effect later. I focus on alluvial reaches because whereas non-alluvial (that is, bedrock- or boulder-floored) reaches exist where the river is steep enough to have more capacity to move bedload than is available to be transported, alluvial reaches (by definition) have a ready supply of bedload in their bed and banks and so the transport of bedload through them is limited only by the capacity of the flow to move this material. Thus, alluvial reaches are more sensitive to a change in the flow regime than are non-alluvial reaches.

20. This "bedload transport continuity" function relates to Objective 6d (*…maintaining existing geomorphic and sediment transport processes*) and Policy 6.2 of the HWRRP (as listed above in paragraph 16).

21. I note an important distinction between the bedload transport and bed maintenance functions. Although both involve the mobilisation of channel bed material, the bed maintenance function only requires transient bed mobilisation (just long enough to flush away fine sediment), whereas the bedload continuity function requires that the transport events continue long enough to transfer a certain mass of gravel. Thus, for example, "harvesting" flood recessions into off-channel storage reservoirs may have no impact on the frequency of bed disturbance, but it can cause a major reduction in the annual average bedload transport rate.

5.2 Analysis approach

22. In regard to these second and third considerations (paragraphs 14 and 17), the effects of a proposed flow regime change can be evaluated by assessing the change in the frequency distribution of floods, including those competent to scour riverbed vegetation and to “surface flush” and “deep flush” the channel beds, and assessing the change in long-term average gravel-transporting capacity of the river.

23. The mean annual flood discharge is widely regarded in the river geomorphology literature as indexing natural channel-forming and maintenance processes (such as controlling encroachment of woody riparian vegetation). A reduction in the size of the mean annual flood (or, equivalently, an increase in the average time between floods of the same size or larger) will, in an average sense, permit riparian vegetation to establish lower down banks and spread further across islands, thus leading to a reduction in overall channel size and, in the case of braided riverbeds, a likely reduction in the intensity of braiding. Accordingly, I have looked at how the mean annual flood would change under the various water-use scenarios supplied.

24. Similarly, increases in the time interval between events competent to entrain the riverbed surface-material portend a greater build-up, on average, of fine sediment on and within the cobbly substrate. I have investigated this across the water-use scenarios by applying sediment-entrainment theory to calculate the frequency at which channel beds would be mobilised. For this, the approach for both rivers was to map the bed shear stress (that is, current drag force per unit area of river bed) over a representative braided reach for a range of discharges using a 2-dimensional hydrodynamic model. The same model and representative braided reaches (near SH7 Bridge on the Hurunui and near Mouse Point on the Waiau) were used by Mr Duncan for his analysis of in-stream habitat.

25. The threshold shear stresses for “surface flushing” and “deep flushing” were calculated using dimensionless threshold stress values developed by Milhous (1998) and required data on the size-grading of the bed-surface material. In both rivers, I used reach-averaged gradings of the bed-surface material for this purpose. Milhous’s dimensionless threshold stress values are 0.021 and 0.035 for “surface flushing” and “deep flushing”, respectively. As a sensitivity exercise, the Hurunui calculations were repeated using a larger threshold value of 0. 052 for “deep flushing” as used recently by Gaeuman et al. (2009) for the Trinity River in the US. A flushing event was defined as one in which at least 50% of the bed inundated by the natural median flow would experience a shear stress exceeding the threshold stress. This criterion focuses interest on the quality of the substrate inundated at baseflows.

26. I have used analyses undertaken by my NIWA colleagues Mr Richard Measures and Mr Maurice Duncan to assess changes in gravel transport capacity under the various water-use scenarios in both rivers. In both cases, the calculations of gravel bedload transport capacity were based on spatially-varying shear stress maps generated by the 2-dimensional hydrodynamic models described above. These were used to develop “rating” relationships between bedload transport capacity and water discharge. These ratings were then combined with the discharge-frequency tables from the flow scenarios to calculate the annual average bedload transport capacity for each river and scenario.

27. Mr Duncan's analysis for the Waiau at Mouse Point braided reach (reported in Snelder et al., 2011) used Wong and Parker's (2006) revised version of the traditional Meyer-Peter and Muller bedload transport formula with a single, representative gravel size. Mr Measure's analysis for the Hurunui River and SH7 Bridge (described in Measures and Hicks 2011) used the Gaeuman et al. (2009) version of the more sophisticated Wilcock-Crowe formula, which requires a full representative size grading of the bed-surface material.

28. As a sensitivity exercise, and to establish consistency between the Hurunui and Waiau results, we repeated the Hurunui calculations using the Wong and Parker's (2006) version of the Meyer-Peter and Muller formula.

5.3 Scenario comparisons – Hurunui River

29. The results of my analysis of the potential geomorphic effects of the Hurunui water-use scenarios are summarised on Figures 1 and 2. Figure 1a shows the relative decline in the magnitude of the mean annual flood discharge (based on daily mean discharge values) from the Natural regime value of 365 m^3/s. This reduces progressively as B-block and then C-block water is taken. Even so, the reduction is only by 14% for the most extreme scenario, Scenario 4.

30. What effect would this reduction in mean annual flood have on channel size? "Hydraulic geometry" relations for braided rivers indicate that the braidplain width is related to mean annual flood discharge to the power of approximately 0.5. This means that a 14% reduction in mean annual flood size should cause a 7% reduction in braidplain width (that is, in the case of the Hurunui River downstream from SH7 Bridge a reduction of about 42 m over an existing width of about 600 m). In my opinion, this is not a substantial reduction because the width of a braided riverbed typically varies in a downstream direction and over a multi-year basis by as much or more than this.

31. Another way of viewing this is to assess how the recurrence interval of the natural, 365 m^3/s, flood changes with the scenarios (the recurrence interval, or return period, of a given-sized flood is the average time between floods of size equal to or greater that the given size). Under the natural regime, a 365 m^3/s flood has a recurrence interval of 2.3 years. Under the most extreme Scenario 4 it increases to approximately 3 years. If this increase had been to, say, 6 years that would indicate a much longer period between floods during which woody weeds could establish on the braidplain. However, the 0.7 year increase calculated indicates only a marginal advantage to weed establishment.

32. I conclude that by virtue of only relatively small shifts in the magnitude-frequency distributions of flood events, the Hurunui water-use scenarios would be unlikely to cause substantial change in braidplain morphological characteristics. Rather, I would expect to see only a relatively small reduction in braidplain width, even under the most extreme scenario that uses C-block water all year round.

33. Figure 1b compares the average frequency (in days per year) when the flows would be competent to "surface flush" the base-flow braids. This shows that as B- and particularly as C-block water is progressively taken, this frequency reduces substantially from the Status Quo scenario (that is from 253 to 53

days per year). In essence, the extraction of mid-range flows would hinder the river from clearing silt and sand deposited on relatively low velocity regions of its base-flow channels during the tails of freshes and floods.

34. Figure 1c compares the average frequency (events per year) when “deep flushing” would occur. The blue bars show the results using the Milhous threshold criterion while the red bars are for the Gaeuman et al. (2009) criterion. Figure 1d compares the relative changes in “deep flushing” frequency. Together, these plots show that while the frequency of flushing (in terms of events per year) is sensitive to the threshold criterion used, the relative effects of the water-use scenarios are relatively insensitive to the threshold criterion. Taking the Milhous threshold, the frequency of flushing would reduce from 14 times per year (for the Natural and Status Quo regimes) to 8.4 times per year for the most extreme Scenario 4. Taking the higher threshold of Gaeuman et al., the frequency of flushing would reduce from about 11 times per year to 6 times per year. Thus with either threshold, the increasing takes of B- and C-block water would reduce the frequency of bed turnover.

35. In some years the time gaps between flushing events will be longer than the time-averaged values shown in Figures 1c and 1d. Figure 2 compares histograms showing the counts of all time-gaps between deep flushing events over the 52-year simulation period (for the case of the Gaeuman entrainment threshold). This shows that as well as causing an increase in the average time gap between “deep flushing” events, the use of B- and C-block water spreads the distribution towards longer gaps. For example, under the Natural and Status Quo regimes and Scenario 1 the longest gap between flushing events would be less than 320 days, but it would be 514 days under the most extreme Scenario 4. To keep things in perspective, the count of long time-gaps remains small relative to the total, thus the effects of the B- and C-block takes would be felt mainly in a few “dry” years.

36. I conclude that the progressively increasing takes of B- and C-block water will reduce the frequencies at which fine sediment will be flushed from above and within the surface cobble layer of the base-flow channels in the Hurunui’s braided reach.

37. Figure 1e compares the long-term average bedload transport capacity of the water-use scenarios relative to the Natural regime. The red bars show the results using the Gaeuman et al. bedload formula while the blue bars are for the revised Meyer-Peter and Muller bedload formula. There is minimal difference between the formulae results. They both show a progressive reduction in bedload transport capacity as B- and C-block water is taken. Under the most extreme Scenario 4, the reduction exceeds 50% of the Natural and Status Quo capacities. This indicates that the river will have less capacity to do “geomorphic work” moving gravel.

38. There will be two main implications of this. Firstly, the dynamic braiding behaviour will slow down – the river should still actively braid, but not as energetically, which is as was indicated by the analysis of change in flood frequency. Secondly, the slow-down of gravel transport will have effects at the upstream and downstream boundaries. Upstream, gravel can be expected to accumulate in the channel in the vicinity of the water takes. This will occur because the flows passing the diversion site have less transport capacity than the flows arriving. The deposit grows both up- and downstream from the

diversion site until a new equilibrium bed profile is developed. The downstream bed grows steeper so that the river can eventually transport the supplied bedload with the diminished flood-flows. The bed upstream rises in order to maintain the original gradient and transport capacity. Such an adjustment may require decades or even centuries to equilibrate and may require mechanical intervention to maintain extraction operations. Downstream, the rate of delivery of bedload to the river mouth will slow down, which can contribute to erosion of the adjacent coast. I assess this later in my evidence.

5.5 Scenario comparisons – Waiau River

39. The results of my analysis of the potential geomorphic effects of the Waiau water-use scenarios are summarised on Figures 3 and 4. Figure 3a shows the relative decline in the magnitude of the mean annual flood discharge from the natural-regime value of 670 m^3/s. This reduces by 10.5% at most for Scenario 3 and Scenario 5, with an associated 5.3% reduction in braidplain width (which amounts to a 36 m reduction in the 690 m width of the braidplain at Mouse Point). Under these two scenarios, the return period of the natural mean annual flood would increase from 2.3 to 2.6 years, which indicates only a marginal advantage for woody weed establishment. I conclude that by virtue of only relatively small shifts in the magnitude-frequency distributions of flood events, even the more extreme of the Waiau scenarios would be unlikely to cause substantial change in braidplain morphological characteristics.

40. Figure 3b compares the average frequency (in days per year) when the flows would be competent to “surface flush” the base-flow braids. This shows that as A- and B-block water is progressively taken, this frequency reduces substantially from the Natural regime (that is from 117 to 39 days per year). Thus, under the more extreme takes, the river would flush fine sediment from the channel-bed surface considerably less often than under the natural case.

41. Figure 3c compares the average frequency (events per year) when “deep flushing” would occur. Figure 3d compares the relative changes in “deep flushing” frequency. The frequency of deep flushing would reduce from 10 times per year on average for the natural scenarios to just under 7 times per year for the most extreme Scenarios 3 and 5. This is not a major reduction.

42. Figure 4 compares histograms showing the counts of the time gaps between deep flushing events over the 42-year simulation period. This shows that as the take increases there are more and longer very-long gaps between flushing events. For example, there are more gaps in the 200-350 day range under Scenarios 3 and 5. Even so, this skewing is not large, and the time gap never exceeds one year for any scenario. Also, the count of long time gaps remains small relative to the total, thus the effects of the increased takes would be felt only in the occasional “dry” years.

43. I conclude that the larger takes of A- and B-block water will induce some reductions in the frequencies at which fine sediment will be flushed from above and within the surface cobble layer of the base-flow channels in the Waiau’s braided reach. However, this flushing would still occur relatively often during the year, and there would be no years without at least one deep flush.

44. Figure 3e compares the long-term average bedload transport capacity of the Waiau water-use scenarios relative to the Natural regime. It shows a

progressive reduction in bedload transport capacity as the A and B takes increase. The maximum reduction is to 41% of the natural bedload capacity with Scenarios 3 and 5. This indicates that the river will have less capacity to do “geomorphic work” moving gravel and the rate of dynamic braiding behaviour will slow down. I note that the scenarios have been calculated assuming that takes would continue during flood flows. If they were to be halted (for example to avoid sediment entry to the irrigation network) then the effects on bedload transport capacity would not be as severe as I indicate above.

45. As with the Hurunui case, the slow-down of gravel transport will induce bed-level changes around the take sites and the rate of delivery of bedload to the river mouth will slow down.

6. River-mouth and coastal processes

6.1 Key processes

Mouth closure and dynamics

46. The Hurunui and Waiau River mouths are typical hapua-type river mouths. Hapua occur on wave dominated coasts with sloping or cliffed backshores, and are characterised by shore-parallel, elongate lagoons fronted by a sandy-gravel barrier and an outlet channel through the barrier that exhibits variable form and location in response to river and coastal conditions. Hart (2009) identified five characteristic morphological states of hapua. As illustrated on Figure 5, these range from a wide outlet centred on the river valley and cut during river floods, a narrowed mouth that has migrated alongshore from the river valley, a migrated mouth than has an extended (and usually constricted) outlet channel, a closed outlet, and an outlet that has formed by breaching during coastal storms. River floods obviously determine the occurrence of the first state. The narrowed, migrated mouths tend to appear during periods of moderate waves and river flows, when the river outflow is able, more or less, to clear beach sediment from the outflow channel at about the same rate as waves deposit it (migration occurs when the river cuts one bank while waves build-out the opposite one). An extended and constricted outlet is forced when the wave deposition starts to dominate and build a bar across the outlet. Outlet closure results when the wave deposition of gravel wins over outflow scour, and often occurs during coastal storms. Closure can be transitory, lasting only as long as the lagoon fills and spills over the barrier – which may only require a few hours during a river fresh or flood – but a closed state may persist if the river is at baseflow and freshwater seepage through the barrier matches (or exceeds) the inflow from the river.

47. The mouth state exerts a major influence on hapua water levels and their range of tidal variation. A wide, river-aligned mouth allows the lagoon water level to connect directly with the tide in the ocean, thus the lagoon mean level is close to that of the sea and its range is close to the ocean tidal range. With an extended/constricted outlet, the lagoon tends to be perched high in order to provide enough hydraulic “head” for the outflow to overcome drag along the outlet channel; this also damps the tidal range in the lagoon.

48. A mouth that is closed for days to weeks impacts on fish migration between the river and the ocean, lagoon size and water level, and so lagoon habitat. A mouth on the verge of transient closure, or even with an extended and

constricted outlet, can cause backshore flooding and restrict human access due to the perched average lagoon level.

49. As river baseflows reduce, and the dominance of waves over river outflows increases, the likelihood increases that the outlet will adopt an extended state and experience unstable behaviour, including transient closure. With even lower river flows, the risk increases of a stable closure event, even without a coastal storm. In either an extended-constricted state or a closed state, the time gap between freshes and floods determines how long it will be before the river can create a wide breach again.

50. Thus, at least three things need to be investigated when assessing the impacts of river flow regime change on river mouth behaviour. The first is the incidence of river baseflows less than the threshold flow for a stable closure situation. The second is the incidence of baseflows associated with an extended-constricted outlet morphology. The third is the duration of baseflow periods between floods and freshes, since this will determine how prolonged these two states will typically be.

51. For the Hurunui case, drawing on the work of Smith (1995), Hart (1999) reported that closure would occur at outflows less than 15 m^3/s while a migrating outlet occurred at flows above 45 m^3/s (which implies that an extended/constricted mouth is most likely in the flow range 15-45 m^3/s). For the Waiau case, a closure threshold of 15 m^3/s has also been suggested, based on Mosley (1994). I have assumed that flows in the range 15-45 m^3/s also render an extended/constricted state most likely at the Waiau mouth.

52. River mouth behaviour is covered under Objective 2f of the HWRRP: *...river mouth opening of the Hurunui River, and maintaining an open river mouth in the Waiau River, to provide for the migration of native fish and salmonid species and the collection of mahinga kai by tangata whenua*.

Coastal stability

53. The coasts adjacent to the Hurunui and Waiau River mouths (located on Figure 6) are characterised mainly by rocky shore or cliff-backed mixed-sand-and-gravel barrier beaches. Barrier-fronted lagoons and narrow coastal backshores occur immediately adjacent to the river mouths, while rare sandy or mixed sand and gravel beaches occur in the partial wave-shelter of headlands (such as at Gore Bay). These beach and barrier systems are nourished by the sandy-gravel bedload of the rivers, while the high energy, predominantly southerly wave climate moves the beach material both north and south on occasion but predominantly north. The beaches nourished by the Hurunui River give way to a rocky shore between Gore Bay and the Waiau mouth. The Waiau River nourishes the mainly cliff-backed beach that runs north past the Conway River mouth to Amuri Bluff (Figure 6).

54. A study of shoreline shifts from historical aerial photographs by Worthington (1991) indicated that for the period between 1950/55 and 1988 the shore between Napenape and the Hurunui mouth was generally quasi-stable to accreting, while the Gore Bay shore was eroding. Beach profile data collected at Gore Bay by The Canterbury Regional Council since 1993 indicate that most of the shore there has been quasi-stable since 1993, albeit subject to short term spates of erosion and recovery and some net accretion at the south end. Overall, it appears that Gore Bay may experience multi-decadal cycles but is probably quasi-stable overall.

55. Thus under the present regime the sediment budget for the beaches adjacent to the Hurunui mouth, including Gore Bay, appears to be in a state of quasi-balance, with the dominant supplies of beach sediment from the Hurunui River offset by losses due to abrasion and net northward wave-driven longshore transport. These beaches are therefore potentially vulnerable to any reduction in the river's delivery of bed material.

56. Worthington's (1991) study showed also that the cliff-backed shore north of the Waiau mouth is already in a state of long-term retreat, with average erosion rates over the 1950 to 1988 epoch varying alongshore between 0.3 and 0.7 metres per year. Thus this retreat could be expected to accelerate after a significant reduction in bedload delivery from the Waiau River.

57. This "coastal bedload transport continuity" function relates to the HWRRP's Objective 6d (…*maintaining existing geomorphic and sediment transport processes*) and Policy 6.2 (…*sediment supply from the headwaters to the sea is maintained by flow events*).

6.2 Analysis approach

Mouth closure and dynamics

58. Based on the above, for both rivers I have analysed the flow scenarios to compare:

- The incidence and duration of events when the river flows at the mouths were less than the closure threshold of 15 m^3/s.

- The incidence and duration of events when the river flows at the mouths were less than the 45 m^3/s threshold assumed above for the change from extended-constricted to migrating behaviour.

- The duration of the time gaps between freshes/floods. For this exercise, I have chosen a fresh to be any event exceeding a daily mean discharge of 70 m^3/s for the Hurunui and 100 m^3/s for the Waiau.

59. I first needed to adjust the flow scenarios to convert then to flows at the river mouths. This is particularly important for the Hurunui, where tributaries entering below the Mandamus reference site contribute approximately 26% of the natural average flow to the river mouth. It is less so for the Waiau, where tributaries downstream of Marble Point contribute approximately 15% of the flow at the mouth. In both cases, my approach was to estimate the tributary inflows, then add these to the scenario flows at the Mandamus and Marble Point reference sites.

60. I used two approaches for estimating the daily mean lower Hurunui tributary flows, and I compared the results as a sensitivity exercise. The first approach used a simple, regression-derived scaling relation between flows at the Mandamus and State Highway 1 Bridge recorders (the SH1 Bridge site is close enough to the mouth that it provides a reasonable proxy for the mouth flows). This was developed by Facer-Gabites (2004, as appended in Smith and Gabites, 2011) using data from periods of overlapping record at the two sites. The relation indicates that the flow at SH1 equals 1.26 times the flow at Mandamus plus 0.13 m^3/s, which means that the tributary flows should equal 0.26 times the Mandamus flows plus 0.13 m^3/s.

61. The complication with this approach, though, is that it does not allow that the lower Hurunui catchment experiences a different climate from the upper catchment. The upper and lower catchments often experience different weather systems, while the flow at Mandamus is also affected by the storage effect of Lake Sumner. Thus while the scaling relation may be correct on a long-term average basis, on a day-by-day basis the relationship is erratic. I therefore used an alternative approach that scaled the tributary flows off the flow record of the Stanton River at the Cheddar Valley site. While the Stanton is actually a tributary of the lower Waiau River (entering downstream from Marble Point), its flow record is the only long-term, quality record available for any catchment in the coastal sections of either the greater Waiau or Hurunui catchments. Accordingly, I scaled the lower Hurunui tributary daily mean flows off the Stanton daily mean flows by using the ratio of their respective long-term average mean flows (using the Facer-Gabites relation to estimate the mean inflow from the tributaries). Because the Stanton flow record only began in January 1968, I limited my comparison of the Hurunui water-use scenarios to the 44-year period between 1968 and 2011.

62. For the Waiau, I simply estimated the tributary inflows between Marble Point and the mouth using the regression relation developed by Smith (2010). This was based on comparing gauged flows at the mouth with the flows at Marble Point for flows less than the median flow. The relation predicts that the tributary daily mean inflows equal 0.047 times the flow at Mandamus minus 0.24 m^3/s. I did not consider it necessary to use the scaled-Stanton record for the Waiau, since the lower tributary average flow contribution is substantially less for the Waiau compared to the Hurunui.

Coastal stability

63. I assessed the impacts of the water allocation scenarios on coastal stability by assessing the change in bedload delivery to the mouths of the Hurunui and Waiau Rivers. I have not been able to directly calculate this because I have no detailed hydraulic data from the river mouths (and obtaining these data would not be a trivial or cheap undertaking). However, I consider it reasonable to assume that the proportional changes in bedload delivery to the mouths will be much the same as the proportional changes in bedload transport capacity calculated at the braided reaches further upstream (that is, at SH7 Bridge on the Hurunui and at Mouse Point on the Waiau).

64. I also assume that because their bedload comprises greywacke gravel, which is significantly more abrasion-resistant than the softer, younger sedimentary rocks that are being eroded from the Hurunui-Waiau coast, these rivers are the major sources of sediment to the local beach gravel budgets. Thus reduced supplies of their gravel are likely to have a significant impact on the beach sediment budgets and thus on coastal stability.

6.3 Scenario comparisons – Hurunui River mouth & coast

65. The results of my analysis of the potential effects of the Hurunui water-use scenarios on the Hurunui mouth behaviour are summarised on Figures 7 to 9.

66. Figure 7 compares amongst scenarios the number and duration of potential closure events at the Hurunui mouth over the 1968-2011 period. A potential closure event is a period when the flows at the mouth fall below 15 m^3/s (I say “potential” here because whether the mouth actually closes or not at these flows will depend on the concurrent wave conditions). The two graphs are for

the different ways of estimating the lower Hurunui tributary flows. The top graph is based on use of the Facer-Gabites relation. It shows a low number of closure events (17 in total over 44 years), many lasting only one to several days, and much the same distribution of closure durations for each scenario. In other words, it suggests no significant impact of any scenario on the likelihood of mouth closure. This arises because the minimum residual flows at Mandamus that are allowed for in the scenarios are always increased by 25% using the Facer-Gabites relation, hence there are few instances of mouth flows falling below 15 m^3/s for any scenario.

67. In contrast, the lower graph, derived using the Stanton record to estimate the lower Hurunui tributary flows, shows substantially more potential closure events, with many lasting more than several days. However, with Scenarios 1 and 2 there would not be many more events than under the Status Quo regime, while the closure event count would actually reduce with Scenarios 3 and 4. The latter outcome appears to be simply because Scenarios 3 and 4 assume increased minimum flows. I take the view that these results, utilising the Stanton record, should be the more reliable of the two approaches (for the reasons given in paragraph 61), and I focus now on following through with this set of results based on use of the Stanton record.

68. Figure 8 shows the frequency distributions by water-use scenario of flows at the Hurunui mouth, focusing on the low-flow range less than 100 m^3/s. The flows have been estimated using the Stanton-scaling approach. The percentage of time the flow is in the 10-15 m^3/s band confirms the above findings about closure likelihood. Looking now at the 15-45 m^3/s range, which is the range assumed for greater likelihood of an extended-constricted outlet channel, Scenario 2 and moreso Scenarios 3 and 4 all occupy significantly more time in this range compared to the status quo. Thus I conclude that under these scenarios the mouth would tend towards more unstable behaviour, with perched lagoon levels and transient closure expected to be more common.

69. Figure 9 compares the count by duration of baseflow periods between freshes and floods at the Hurunui mouth for the water-use scenarios. There is little difference amongst the scenarios. I conclude that none of the water-use scenarios will significantly impact on the ability of the Hurunui River to breach a new outlet if and when a closure event occurs.

70. In regard to bedload delivery to the Hurunui coast, Figure 1e indicates a progressive reduction in bedload delivery to the coast as increasing amounts of B and C-block water are taken. With Scenario 4, the bedload transport capacity reduces to less than half of the natural and status quo values. This portends a significant deficit to the coastal sediment budget and the likelihood that the adjacent shore will change from a state of quasi-equilibrium to one of retreat on the adjacent barrier, the beach at Manuka Bay, and the Gore Bay shore while the shore re-equilibrates to the reduced supply.

6.5 Scenario comparisons – Waiau River mouth & coast

71. My analysis showed no potential closure event (that is, a period when the flow is less than 15 m^3/s) at the Waiau mouth under any scenario. This arises simply because the scenarios allow for a minimum residual flow downstream

of Marble Point of 20 m^3/s while the minimum natural daily mean flow over the simulation period was 19 m^3/s.

72. Figure 10 compares the low-range flow frequency distributions by scenario at the Waiau mouth. It shows that, compared to the natural case, all water-use scenarios occupy more time in the band between 20 and 30 m^3/s. This flags a greater likelihood of an extended-constricted outlet channel and more unstable mouth behaviour, including perched lagoon levels and transient closure. This would be moreso with Scenarios 3 and 5.

73. Figure 11 compares the count by duration of baseflow periods between freshes and floods at the Waiau mouth for the water-use scenarios. There is no substantial difference between any scenario and the natural case. I conclude that none of the water-use scenarios will significantly impact on the ability of the Waiau River to breach a new outlet in the unlikely event of its mouth closing.

74. In regard to bedload delivery to the Waiau coast, Figure 3e indicates a progressive reduction in bedload delivery to the coast as increasing amounts of water are taken. The greatest reduction, to 41% of the natural value, occurs with Scenarios 3 and 5. This portends a significant deficit to the coastal sediment budget and the likelihood that coastal erosion will accelerate along the shore between the Waiau mouth and Haumuri Bluffs.

75. Again, I add the caution that the scenarios have been calculated assuming that takes would continue during flood flows, thus the above assessments of effects on coastal stability should be regarded as upper limits.

7 Significance of effects

76. To summarise and assess the relative significance of the various water-use scenarios on geomorphic functions, I have used the same style of “scenario evaluation tables” that are detailed in the evidence of Mr Norton. These tables capture my expectations of the extent to which the relevant HWRRP objectives and policies will be achieved. In building my tables, I have endeavoured to follow the same logic as my colleagues[1] who cover other environmental issues. This is so that my findings can be integrated with theirs in a consistent way.

77. In summarising my findings, I have categorised the effects of each water-use scenario on a scale of likelihood that the geomorphic functioning of the natural regime would be delivered by the given scenario. To do this I have had to make subjective definitions of the likelihood categories. I show these definitions in Table 1. For example, considering the channel maintenance function, I have assumed that a scenario would “almost certainly” achieve the functioning of the natural flow regime if the mean annual flood discharge was 95-100% of the natural mean annual flood; it would “probably” achieve this if the proportion was 90-94%; it would “possibly” achieve this if the proportion was 85-89%; but it would be “unlikely” if the proportion was less than 85%.

78. My “scenario evaluation tables” so developed for the Hurunui and Waiau Rivers are shown as Tables 2 and 3, respectively. For the Hurunui (Table 2),

---

[1] Ned Norton, Ton Snelder, Maurice Duncan, Don Jellyman, Ken Hughey

the progressive increase in the use of B- and C-block water across Scenarios 1 to 4 slows the river down in its ability to do geomorphic work, including delivering bedload to the coast, flushing fine sediment and turning over its bed, and maintaining its braided planform and average width. The HWRRP objectives "unlikely" to be achieved (that is, the red boxes in Table 2) are those relating to bedload transport and bed flushing/turnover. At variance to this general trend, the use of C-block water (Scenarios 3 and 4) creates a lesser likelihood of river mouth closure than do the uses of just A- or A and B-block water (Scenarios 1 and 3); however, all water-use scenarios would render the mouth more prone to an extended-constricted state and associated unstable behaviour.

79. With regard to the Hurunui River mouth, I note that the colour-coding and likelihood classification (in the *River mouth opening* row of Table 2) would change substantially if the Status Quo regime was chosen as the reference condition instead of the Natural regime. In that case, the likelihoods of matching or exceeding the Status Quo functionality at the Hurunui mouth would be Almost certainly, Probably, Probably, Probably for Scenarios 1 through 4, respectively.

80. For the Waiau (Table 3), the greatest effects on geomorphic work-rate, including delivering bedload to the coast, flushing fine sediment and turning over its bed, and maintaining braided planform and width occur with the largest takes, irrespective of whether these are operated as A- or B-block takes. Again, the objectives that are "unlikely" to be achieved are those relating to bedload transport and bed flushing/turnover. At the Waiau mouth, the HWRRP requirement for a minimum flow of 20 m^3/s in all scenarios protects the mouth from closure, but all but Scenario 1 would render the mouth more prone to an extended-constricted state and unstable behaviour.

81. From a pragmatic viewpoint, these geomorphic effects still need to be transformed into environmental risk. For example, the coastal erosion risk associated with the reduced delivery of gravel to the coast depends on the assets exposed to the potential erosion. In my view, the shore at Gore Bay (just north of the Hurunui mouth) is more vulnerable to reduced bedload because it is currently quasi-stable and built-up, whereas the shore north of the Waiau mouth is already eroding and relatively undeveloped. However, a detailed valuation of the coastal risk has not yet been undertaken. In similar fashion, the reduced frequency of riverbed flushing needs to be weighted by its significance to in-stream habitat and biota. And so on for channel maintenance flows, natural vegetation control, and bird habitat. These environmental weightings are taken up in other evidence by my colleagues[1].

82. Some final comments relate to uncertainty. As I have explained through my evidence, I have made a number of assumptions and estimates, notably in regard to thresholds such as the discharge required to maintain an open river mouth and the shear stress required to entrain river bed material. For the river mouth analysis, additional uncertainty accrues from the approach to adjust the scenario flows for the discharge added by tributaries in the coastal ranges. Further uncertainty arises from input data, such as the representativeness of the gravel sizes used to evaluate the bed flushing.

83. Where practical, I have evaluated the level of uncertainty using quantitative sensitivity analyses – that is, repeating calculations using alternative methods or thresholds. In some cases, for example with bed flushing thresholds, I find

that the relative effects of the scenarios are consistent. In other cases, for example the method for estimating tributary flows, I have justified my preference for a given approach. Beyond these measures, the approach of adopting a qualitative categorisation of effects by “likelihood of achieving the HWRRP objectives” (that is, the “Almost certainly” to ”Unlikely” scale) acknowledges that there is remnant uncertainty.

8 Mitigation

84. In regards to the effect of water-use on the processes captured above under “geomorphic work-rate”, as I have noted already the simulated discharge records developed for the scenarios assume that the takes would continue during freshes and floods (thus ‘trimming’ the flood peaks by the take amount and also harvesting discharge from the event recessions). The effects could be mitigated (potentially to the level of almost certainly meeting HWRRP objectives) with flood bypass rules. For example, Meridian Energy’s proposed North Bank Tunnel Project on the lower Waitaki River includes a rule to bypass floods exceeding 900 m^3/s for 48 hours. Moreover, in practice irrigation water abstraction is often shut-down during freshes and floods (above a certain discharge) to avoid taking excessive quantities of sediment into the distribution network.

85. Mouth closure events can be mitigated by artificial breaching with a mechanical excavator (or “digger”).

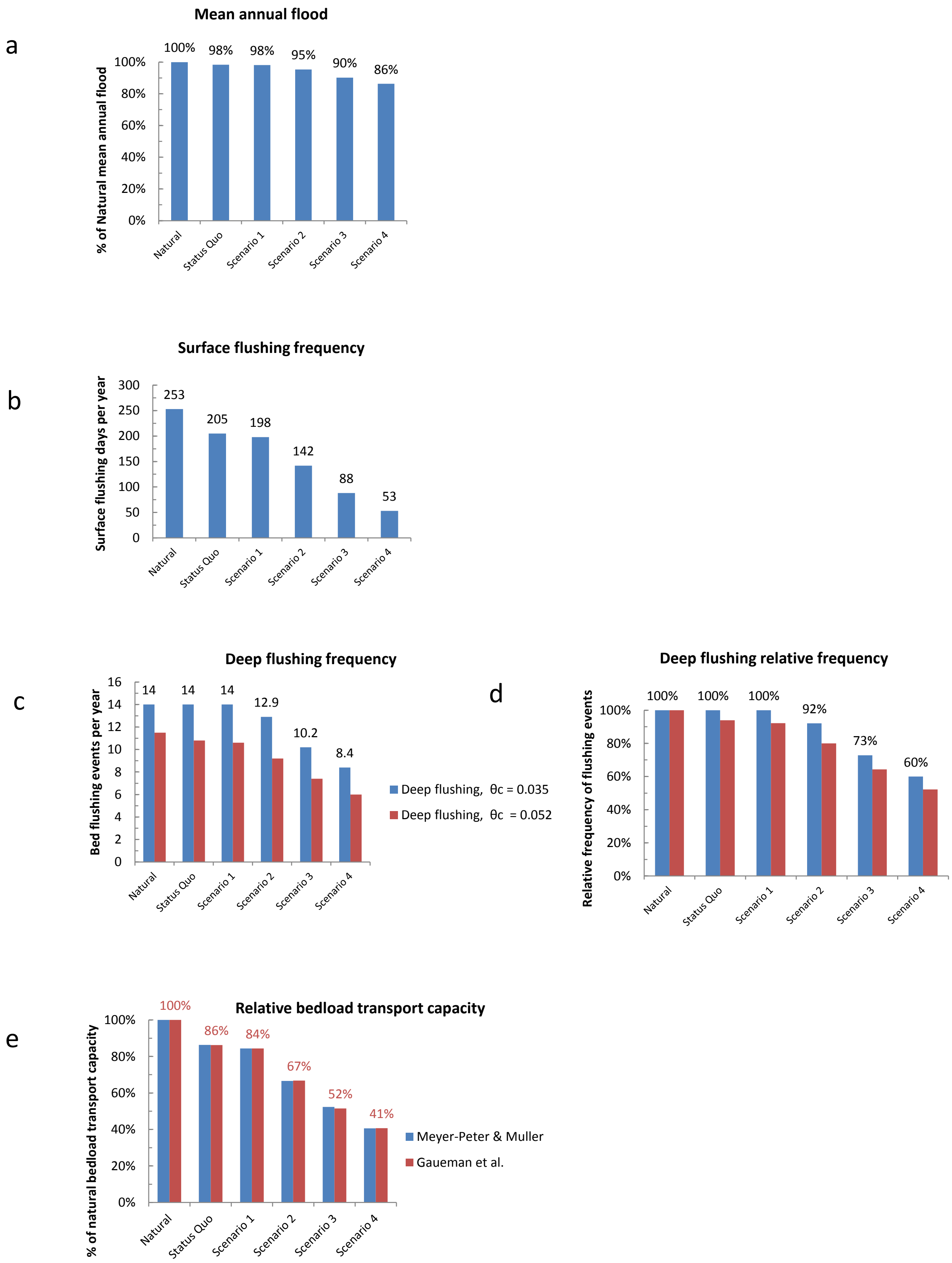

Figure 1: Comparison of effects of Hurunui water-use scenarios on (a) mean annual flood size, (b) frequency of bed surface flushing, (c) and (d) frequency of bed deep flushing, (e) bedload transport capacity.

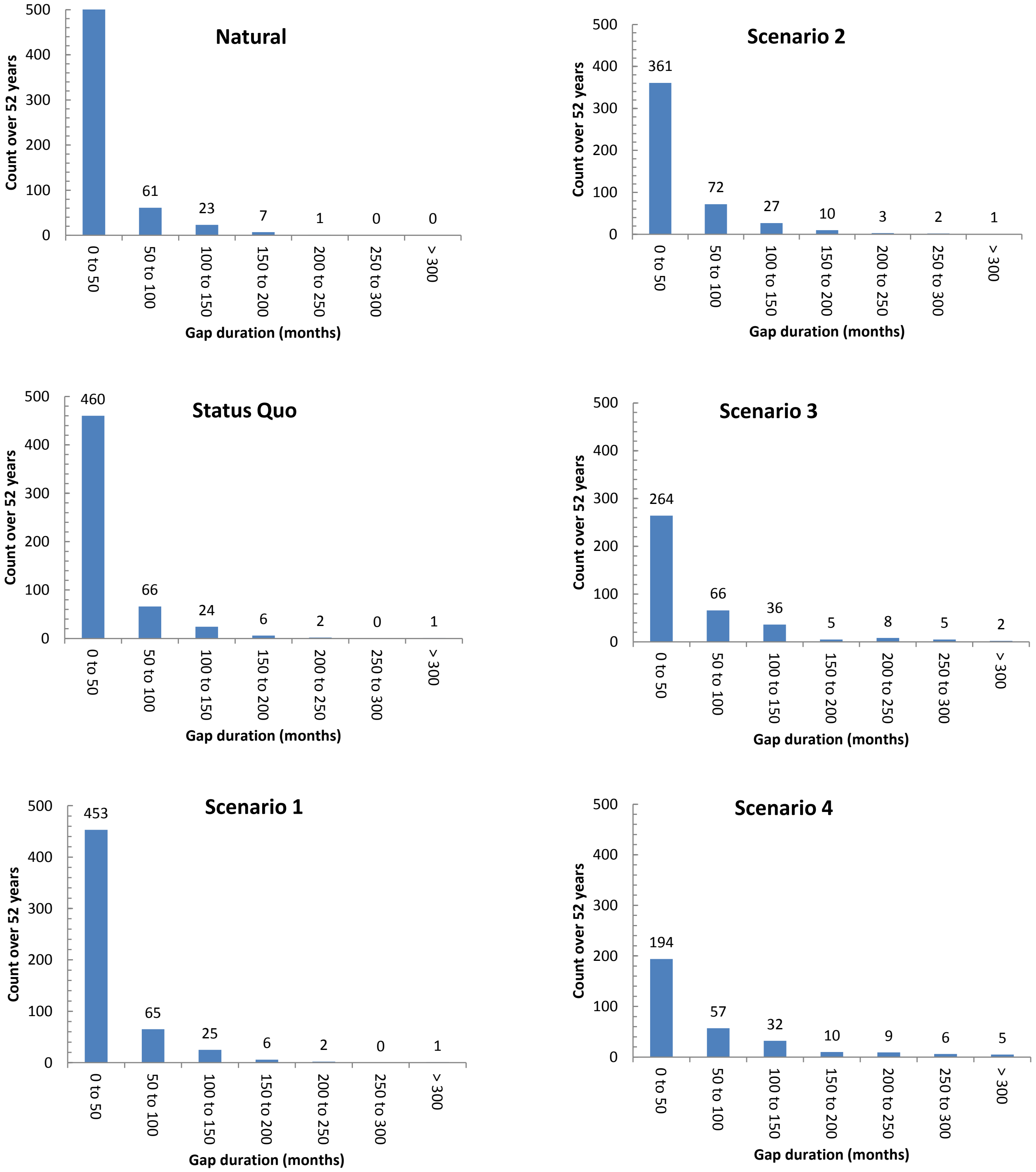

Figure 2: Frequency distributions of the time-gap between deep flushing events in the Hurunui at SH7 braided reach for water-use scenarios (assuming a dimensionless threshold stress of 0.052).

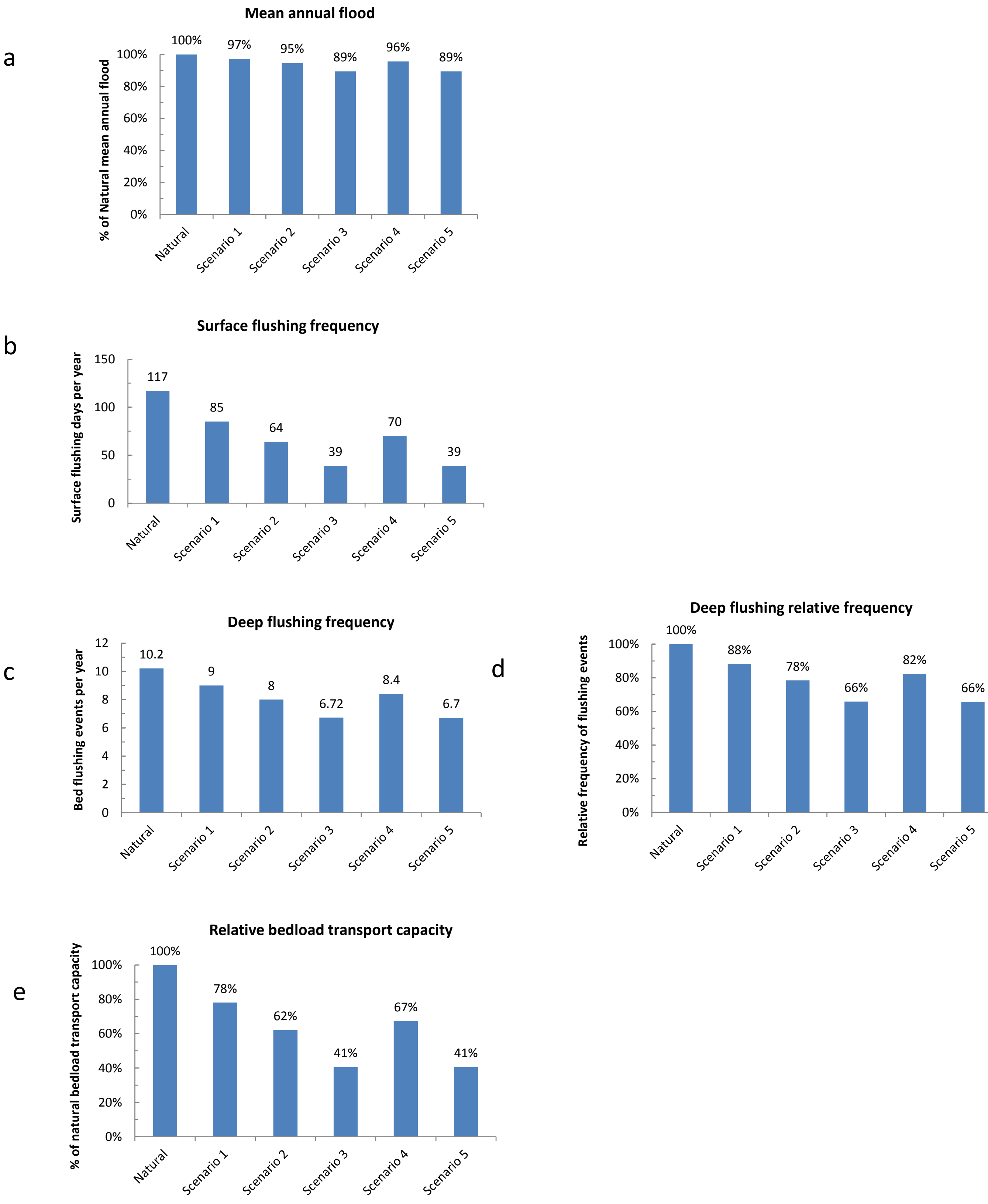

Figure 3: Comparison of effects of Waiau water-use scenarios on (a) mean annual flood size, (b) frequency of bed surface flushing, (c) and (d) frequency of bed deep flushing, (e) bedload transport capacity.

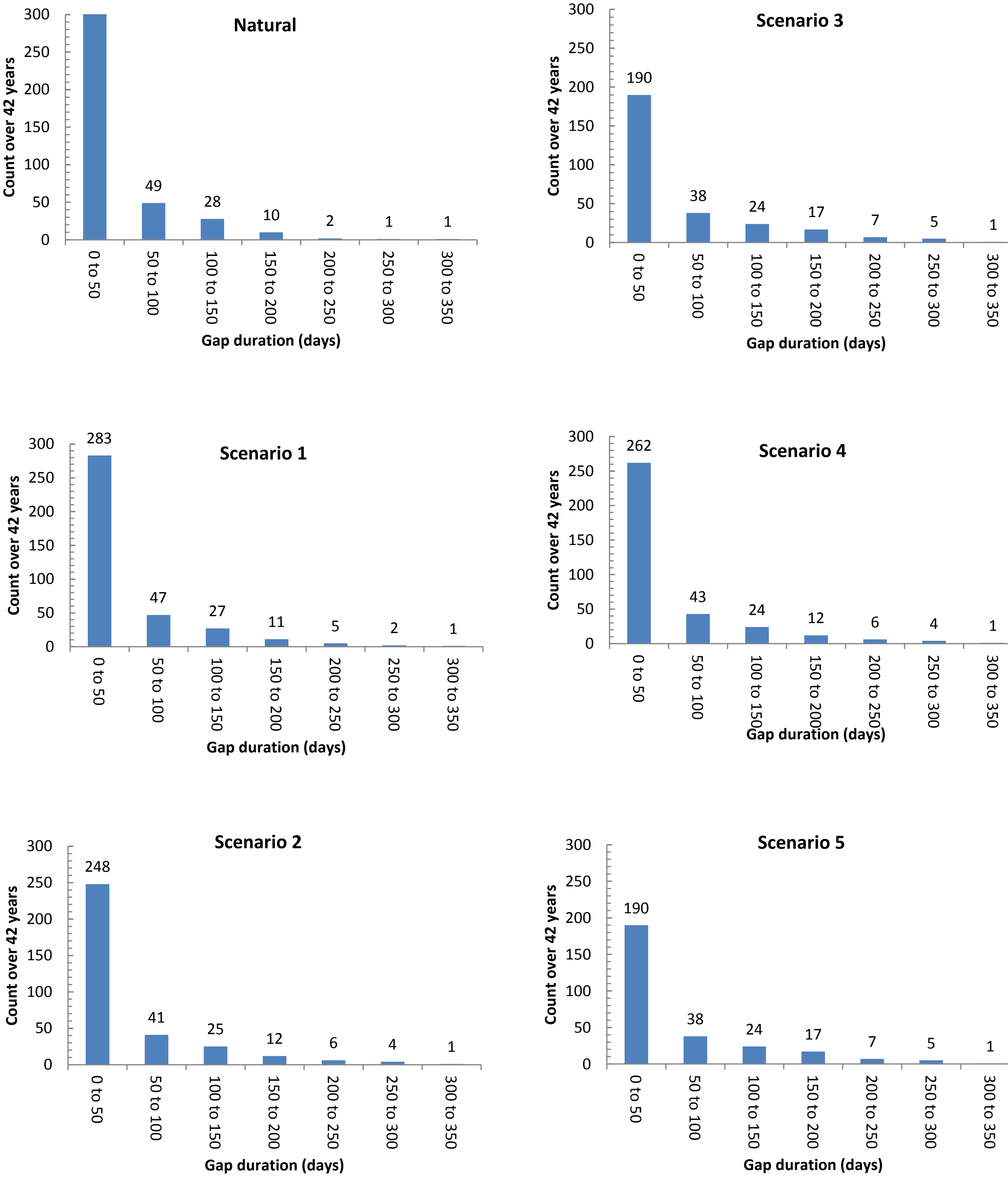

Figure 4: Frequency distributions of the time-gap between deep flushing events in the Waiau at Mouse Point braided reach for water-use scenarios.

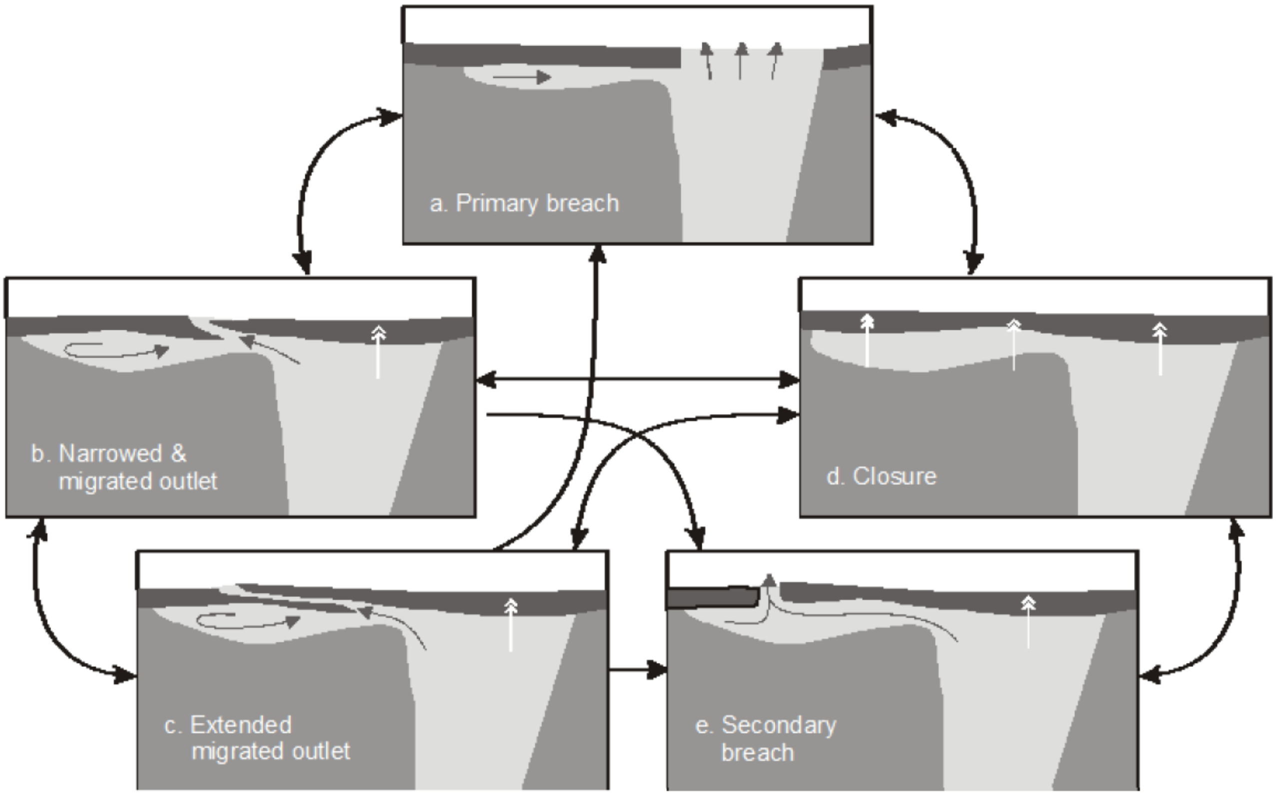

Figure 5: Hapua morphological states, from Hart (2009).

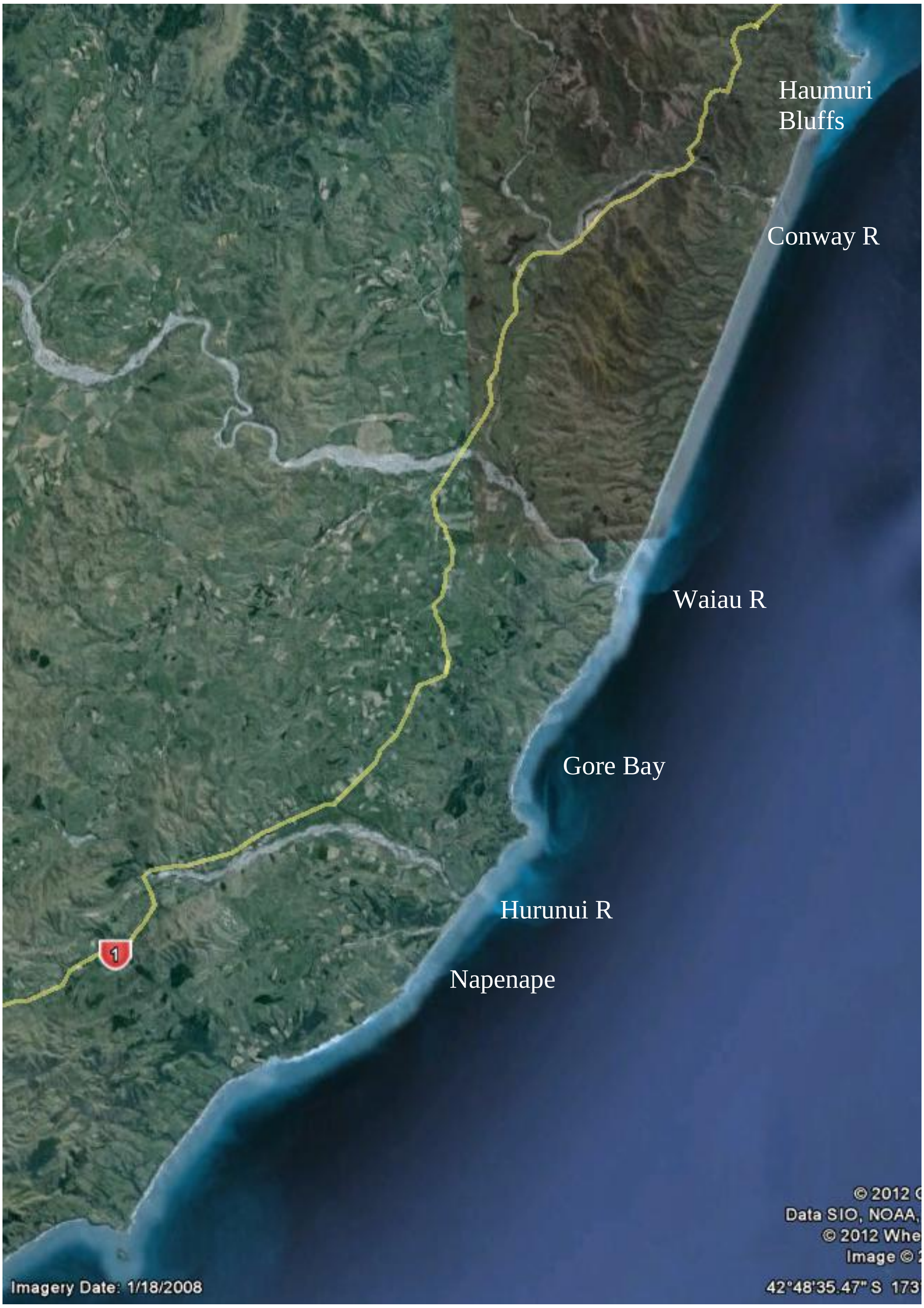

Figure 6: Satellite image of the Hurunui-Waiau coast, from Google Earth.

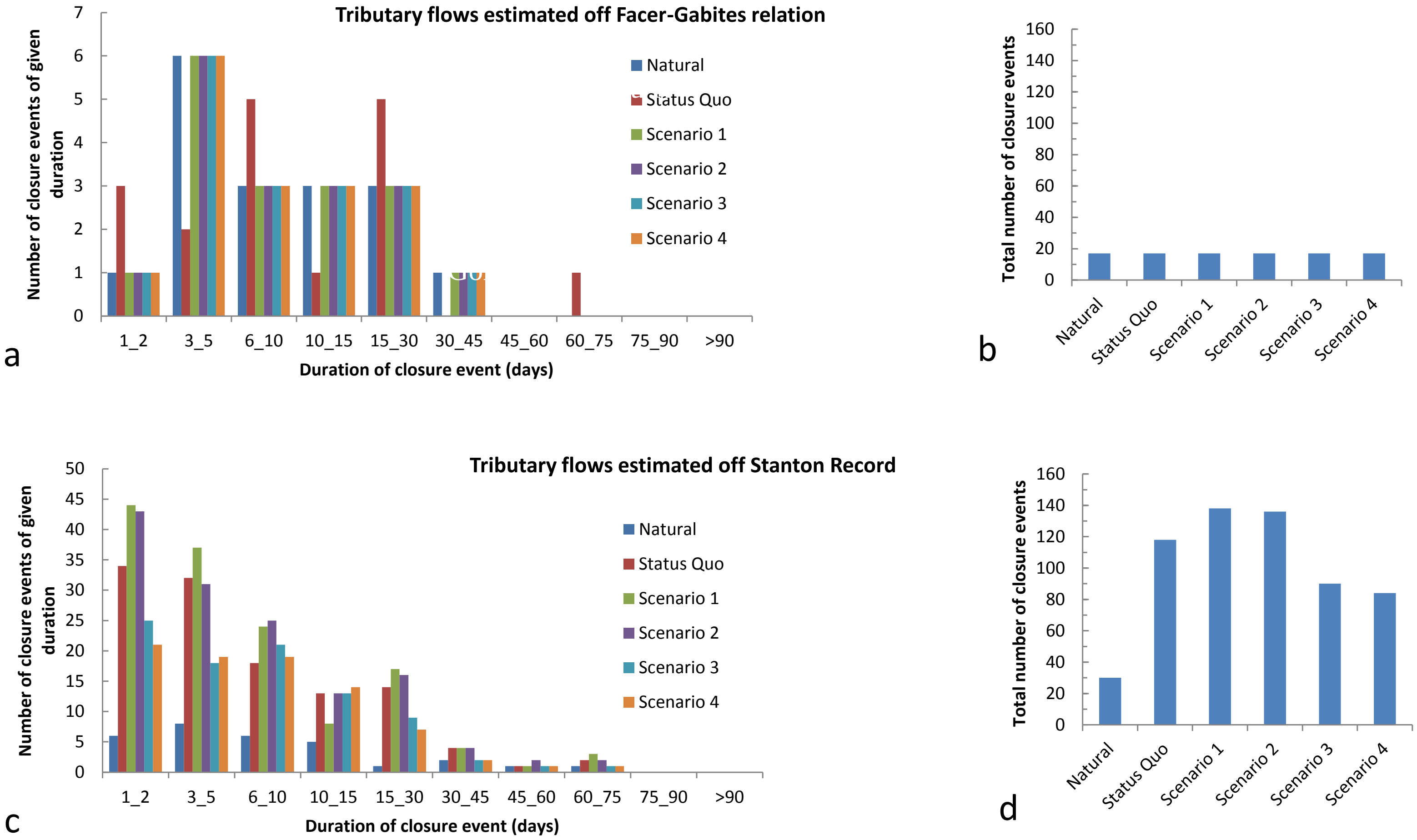

Figure 7: Count, for each flow scenario, of potential closure events (river flows < 15 m^3/s) at the Hurunui River mouth over the period 1968-2011, distributed by event duration and in total. a) and b) use Facer-Gabites relation to estimate lower Hurunui tributary flows; c) and d) scale tributary inflows off Stanton River record.

Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

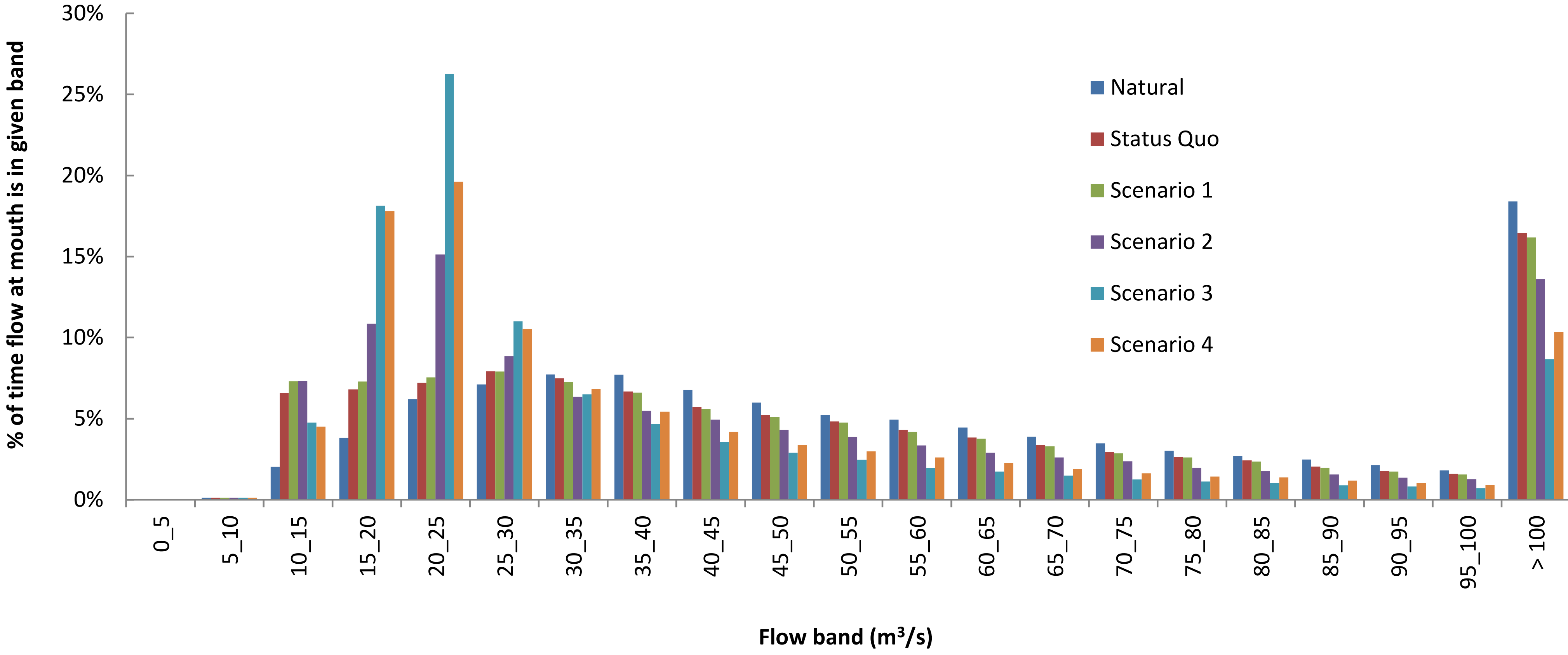

Figure 8: Frequency distributions by water-use scenario for the Hurunui mouth flow. The mouth flows have been estimated by scaling tributary inflows off the
record.

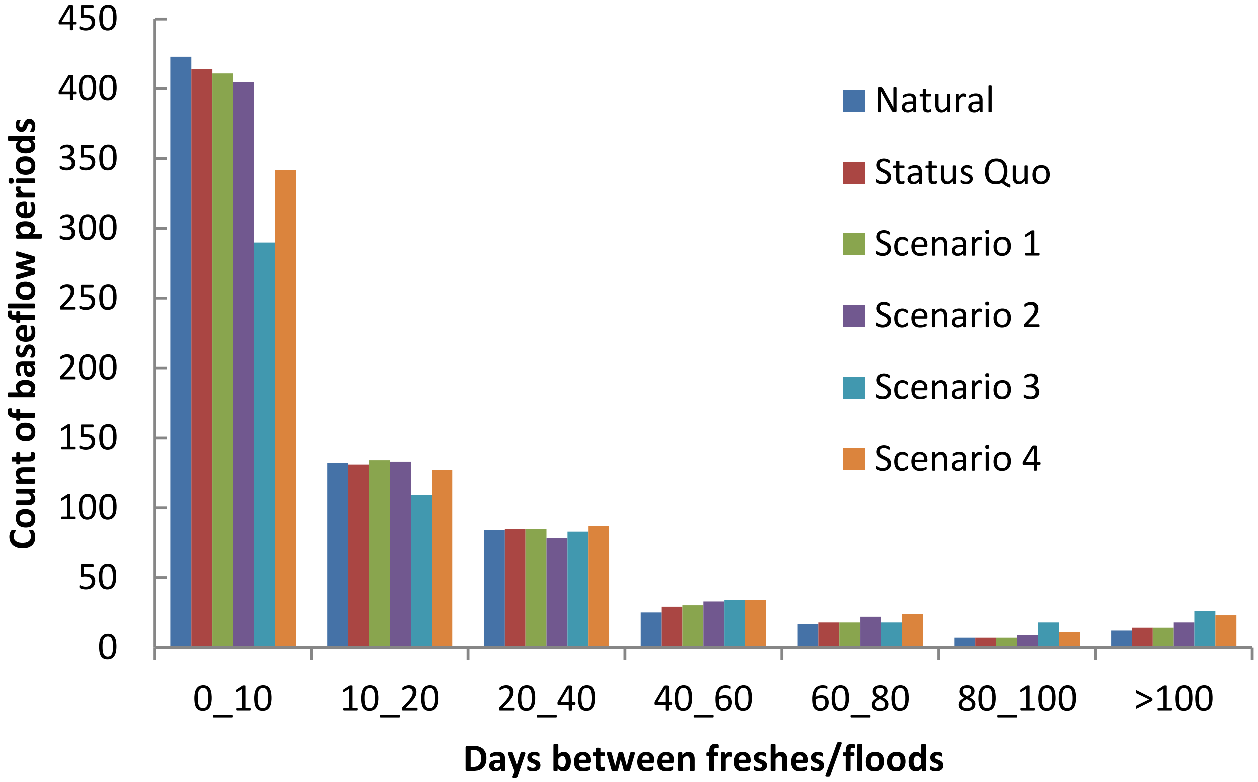

Figure 9: Count by duration of baseflow periods between freshes and floods at the Hurunui mouth for the water-use scenarios. The flow threshold assumed for a fresh is 70 m^3/s. The record spans 1968 to 2011, and the lower tributary flows are estimated with the Stanton-scaling approach.

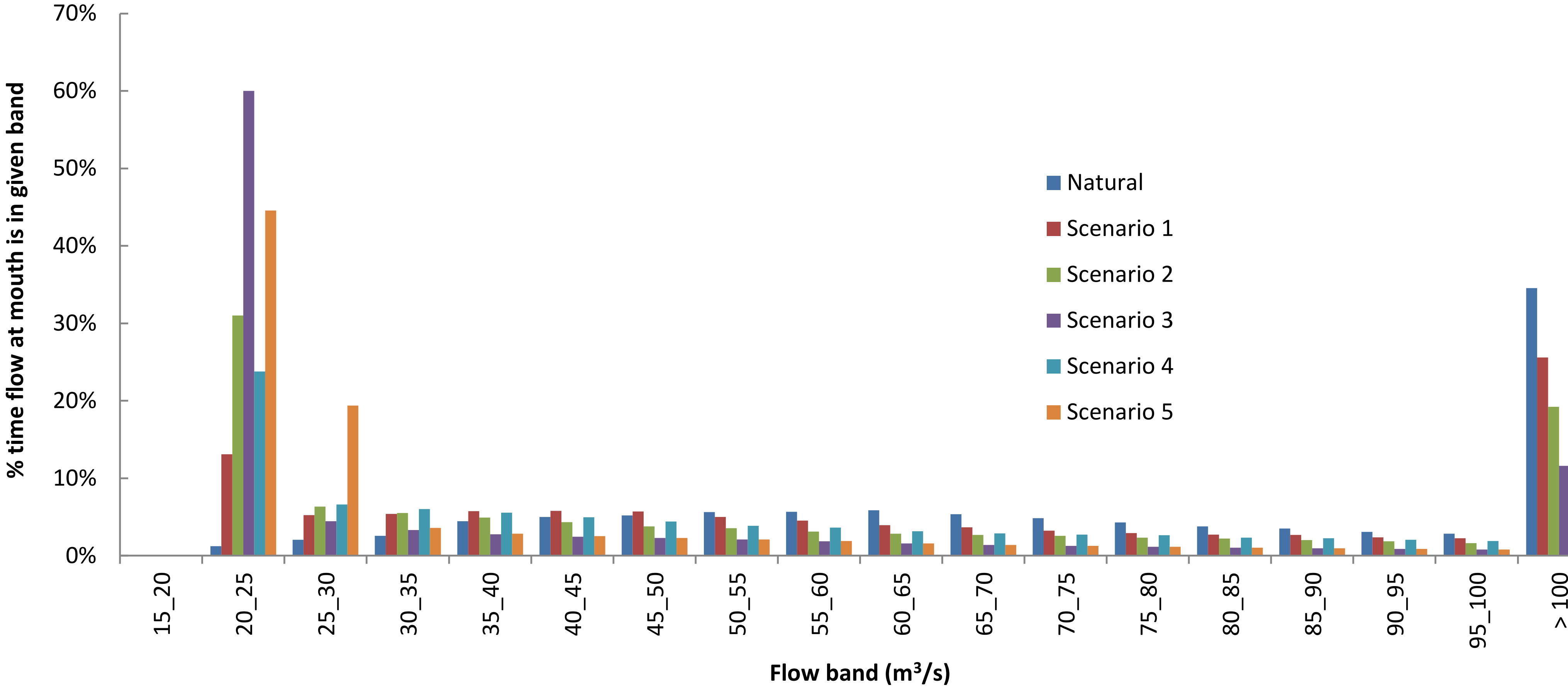

Figure 10: Frequency distributions by water-use scenario for the Waiau mouth flow.

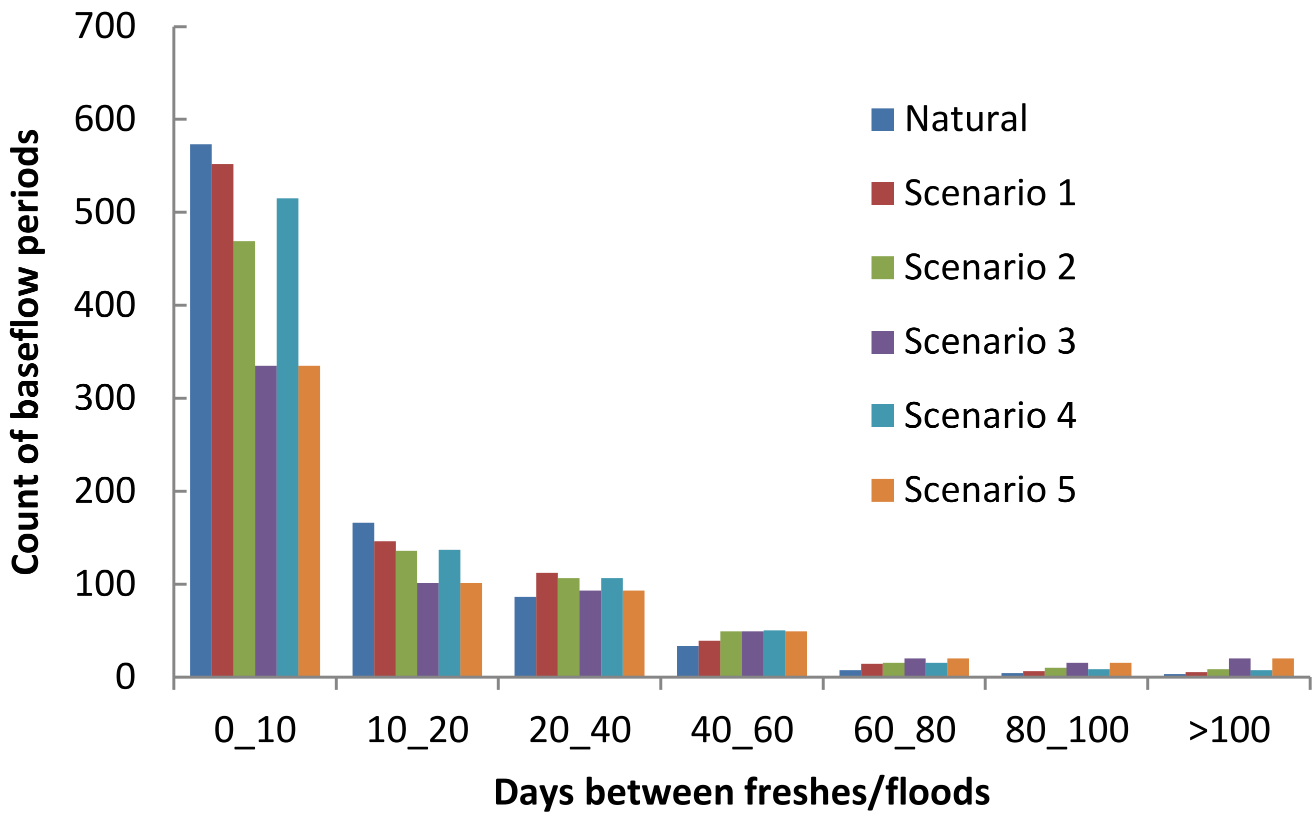

Figure 11: Count by duration of baseflow periods between freshes and floods at the Waiau mouth for the water-use scenarios. The flow threshold assumed for a fresh is 100 m^3/s.

Table 1. Definitions of likelihood categories in terms of achieving objectives of the HWRRP.

ACHIEVES…	Likelihood category definitions			
	Almost certainly	**Probably**	**Possibly**	**Unlikely**
Bedload transport (Gravel transfer through storage reaches, coastal gravel delivery) *HWRRP Objective 6d*	Mean annual bedload 90-100% natural bedload	Mean annual bedload 80-90% natural bedload	Mean annual bedload 65-80% natural bedload	Mean annual bedload <65% natural bedload
River mouth opening (Opening maintained, no less stability) *HWRRP Objectives 2f, 3e*	Closure frequency 1-2 times natural, no change in frequency of extended-constricted outlet state	Closure frequency 1-2 times natural, extended-constricted more often	Closure frequency 2-4 times natural, extended-constricted more often	Closure frequency >4 times natural, extended-constricted more often
Channel maintenance (riverbed vegetation naturally controlled, channel size & form maintained) *HWRRP Objective 6d*	Mean annual flood 95-100% natural	Mean annual flood 90-94% natural	Mean annual flood 85-89% natural	Mean annual flood <85% natural
Fine sediment flushing (surficial sediment flushed, armour intact) *HWRRP Objective 3c*	Flushing frequency 85-100% of natural	Flushing frequency 70-85% of natural	Flushing frequency 55-70% of natural	Flushing frequency <55% of natural
Bed turnover (deep flushing – surface layer mobilised) *HWRRP Objective 3c*	Flushing frequency85-100% of natural	Flushing frequency 70-85% of natural	Flushing frequency 55-70% of natural	Flushing frequency <55% of natural

Table 2. Likelihood of achieving HWRRP geomorphic objectives for Hurunui River mainstem, river-mouth and coast under water-allocation scenarios. Definitions of likelihood categories are given in Table 1.

ACHIEVES…	**Scenarios…**					
	Natural	**Status Quo**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Bedload transport (Gravel transfer through storage reaches, coastal gravel delivery) *HWRRP Objective 6d*	Almost Certainly	Probably	Probably	Possibly	Unlikely	Unlikely
River mouth opening (Opening maintained, no less stability) *HWRRP Objectives 2f, 3e*	Almost Certainly	Possibly	Unlikely	Unlikely	Possibly	Possibly
Channel maintenance (riverbed vegetation naturally controlled, channel size & form maintained) *HWRRP Objective 6d*	Almost Certainly	Almost Certainly	Almost Certainly	Almost Certainly	Probably	Possibly
Fine sediment flushing (surficial sediment flushed, armour intact) *HWRRP Objective 3c*	Almost Certainly	Probably	Probably	Possibly	Unlikely	Unlikely
Bed turnover (deep flushing – surface layer mobilised) *HWRRP Objective 3c*	Almost Certainly	Almost Certainly	Almost Certainly	Probably	Possibly	Unlikely

Table 3. Likelihood of achieving HWRRP geomorphic objectives for Waiau River mainstem, river-mouth and coast under water-allocation scenarios. Definitions of likelihood categories are given in Table 1.

ACHIEVES…	**Scenarios…**					
	Natural	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Bedload transport (Gravel transfer through storage reaches, coastal gravel delivery) *HWRRP Objective 6d*	Almost Certainly	Possibly	Unlikely	Unlikely	Possibly	Unlikely
River mouth opening (Opening maintained, no less stability) *HWRRP Objectives 2f, 3e*	Almost Certainly	Almost Certainly	Probably	Probably	Probably	Probably
Channel maintenance (riverbed vegetation naturally controlled, channel size & form maintained) *HWRRP Objective 6d*	Almost Certainly	Almost Certainly	Almost Certainly	Possibly	Probably	Possibly
Fine sediment flushing (surficial sediment flushed, armour intact) *HWRRP Objective 3c*	Almost Certainly	Probably	Possibly	Unlikely	Possibly	Unlikely
Bed turnover (deep flushing – surface layer mobilised) *HWRRP Objective 3c*	Almost Certainly	Almost Certainly	Probably	Possibly	Probably	Possibly

D M Hicks

24 September 2012

References

Duncan, M. & Shankar, U. (2004). *Hurunui River habitat 2-D modelling.* NIWA Client Report CHC2004-011, prepared for Environment Canterbury, April 2004.

Gaeuman, D., Andrews, E. D., Krause, A., & Smith, W. (2009). Predicting fractional bed load transport rates: Application of the Wilcock-Crowe equations to a regulated gravel bed river. *Water Resources Research, 45*.

Golder Associates. (2010). *Conway River ecology and hydrology investigations.* Report No. 0978110120.

Hart, D. E. (2007). River-mouth lagoon dynamics on mixed sand and gravel barrier coasts. *Journal of Coastal Research*(50), 927-931.

Hart, D. E. (2009). Morhpodynamics of non-estuarine rivermouth lagoons on high energy coasts. *Journal of Coastal Research*(56), 1355-1359.

Kirk, R. M. (1991). River-beach interaction on mixed sand and gravel coasts: a geomorphic model for water resources planning. *Applied Geomorphology, 11*, 267-287.

Measures, R. & Hicks, M. (2011). *Geomorphic effects on the Hurunui River of the Waitohi water storage schemes.* NIWA Client Report CHC2011-112, prepared for Environment Canterbury, October 2011.

Milhous, R. (1998). Modelling of instream flow needs: the link between sediment and aquatic habitat. *Regulated Rivers:Research & Management*, 79-94.

Mosley, P. (2004). *Waiau River: instream values and flow regime*. Environment Canterbury Technical Report R04/02.

Smith, J. (2010). *Waiau River hydrological information*. Environment Canterbury Report No. U10/11, November 2010.

Smith, J. & Gabites, S. (2011). *Hurunui River hydrological information*. Environment Canterbury Report No. R11/53, September 2011.

Snelder, T., Booker, D., Jellyman, D., Bonnett, M., & Duncan, M. (2011). *Waiau River mid-range flows evaluation*. NIWA Client Report CHC2011-084, prepared for Environment Canterbury, June 2011.

Todd, D. J. (1992). River mouth and coastal processes of the Ashburton River mouth. In T. Dons, & D. Stringer (Eds.), *Natural Resources of the Ashburton River and Catchment* (pp. 208-234). Canterbury Regional Council Report 92(36).

Wong, M., & G. Parker (2006). Reanalysis and correction of bed load relation of Meyer-Peter and Muller using their own database. *Journal of Hydraulic Engineering* 132: 1159–1168.

Worthington, A. (1991). *Assessment of coastal erosion potential Rakaia River to Conway River.* Canterbury Regional Council Publication No. R90/12.