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Taihoro Nukurangi

Assessment of the potential effects of dams on selected South Canterbury rivers on sediment movement and coastal nourishment

NIWA Client Report:CHC01/81
Project No: ENC01511
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Maurice J. Duncan
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Prepared for

Environment Canterbury

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Reviewed by: *Approved for release by:*

Graeme Smart Ross Woods

Executive Summary

1. With the continuing pressure on water resources in Canterbury, primarily for irrigation, there is serious consideration being given to damming major rivers to provide storage of high flows for later release for irrigation. This report was commissioned by Environment Canterbury to examine the effects of proposed dams on the Rakaia, Ashburton and Rangitata Rivers on riverbed sediment movement and habitat and, in particular, on the coastal sediment budget.

2. The geomorphic setting is one of high uplift rates and high rainfalls in the mountain headwaters of the major South Canterbury Rivers, resulting in relatively high rates of sediment delivery to the rivers. In addition, the relatively unconsolidated beds and banks of the plains sections of the rivers allow the rivers to source and move large quantities of bed material.

3. The Rangitata River bed downstream of the gorge appears to be degrading slowly because of the steep slope of the river bed increases its transport capacity. The Ashburton River is predominantly degrading due to gravel extraction for industrial and stop banking purposes in the mid section of the plains and to coastal retreat near the coast. One section of the North Branch is rapidly aggrading due to a reduction in bed slope. The Rakaia River appears to be in equilibrium, although the lower section has intense braiding features characteristic of aggradation and in common with the other two rivers there is probably long term degradation in the reach approaching the coast due to coastal retreat.

4. Large quantities of bed material are transported to the coast where they are readily moved alongshore to the north by the predominant southerly swell. Such is the capacity of the wave energy to move sediment that the coast is retreating at an average of 0.68 m/y between the Opihi River and Birdlings Flat (Gibb 1978). It would appear that rivers supply a significant proportion of the total supply of sediment to this coast, although eroding cliffs are the largest source.

5. Damming the rivers will cut off the bedload supply. Immediately below the dam, the riverbed can be expected to degrade and coarsen and the river planform will tend to meander rather than braid. Without bed destabilising floods, dry bars will vegetate. Further downstream, the effects will be delayed as the river gains bedload from its bed and banks. The dry bars may still vegetate unless there are natural or managed floods.

6. The general tendency for degradation will be moderated by a reduction in sediment transport capacity associated with dam-induced changes in the flow regime, which will include both reduced flood peaks and outflow rates. Where gravel extraction occurs in riverbed, degradation may be enhanced because of reduced bedload transport into the extraction reach.

7. The reduced flow regime of the dammed rivers will result in a reduced supply of bed material to the coast, even if bed-material is recovered from the riverbed and banks. The effect of the reduced river sediment input on increasing coastal erosion will vary, depending on the river size in relation to the existing contribution from coastal erosion.

8. There are large uncertainties in many components of the coastal sediment budget. Recent wave climate data offer the opportunity to better model longshore transport and so reduce some of these uncertainties.

9. Damming will inhibit fish migration and mitigation measures need to be put in place.

10. The lower and more stable flows downstream of dams may encourage suspended sediment to settle and improve benthic productivity. Flushing flows are likely to be required to mobilise fine sediment and remove nuisance algal growths.

11. Before dam filling, the area to be flooded and the bed down stream of the dam need to be surveyed and photographed (using vertical aerial photographs). This will allow calculation of rates of sediment accumulation in lake deltas and will provide baseline information that can be used to provide a comparison with five-yearly surveys carried out to monitor bed changes.

13. There is no bed level information that can be used to check bed-level changes on the Rangitata or Rakaia Rivers. A system of low level monitoring needs to be established to gather this basic data.

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1 INTRODUCTION

With the continuing pressure on water resources in Canterbury, primarily for irrigation, there is serious consideration being given to damming major rivers to provide storage of high flows for later release for irrigation. The issue considered in this report is the effect of proposed dams on riverbed sediment movement, in-channel hazards and habitat, and, in particular, on the coastal sediment budget.

The purpose of the report is to provide material on which Environment Canterbury can base policy related to the damming of the large Canterbury rivers. That is, to flag where dams could pose a problem and to present an overview of present aggradation/degradation trends.

This report focuses on the main South Canterbury rivers: the Rakaia, the Ashburton and the Rangitata (Figure 1). Future reports will consider other segments of the Canterbury coast. It updates Hicks' (1998) report entitled "Sediment budgets for the Canterbury coast – a review, with particular reference to the importance of river sediment", including new information on the above rivers from cross-section surveys and reports by Healey (1997), Hudson (2000a,b), Flatman (1997), and Patterson (2000). These reports allow any degradation due to future dams to be put into a geological perspective.

The report also outlines, conceptually, the expected geomorphic response of rivers to dams, to flow regime and to sediment transport regime changes, and is supported where possible with reference to existing examples (e.g. of how a braided river behaves when it is in a degradational phase). For each of the three rivers, an estimate is made of the downstream effects of the dams on the river morphology and on sediment delivery to the coast. Information gaps are identified.

2 GEOMORPHIC SETTING AND CURRENT TRENDS

New Zealand lies astride the boundary between the Pacific and Australian tectonic plates (Walcott 1984). The Alpine Fault marks the boundary between these plates, and there is lateral movement and uplift along the fault. The Southern Alps "backbone" of Canterbury is being pushed up as the Pacific plate moves below the Australian plate.

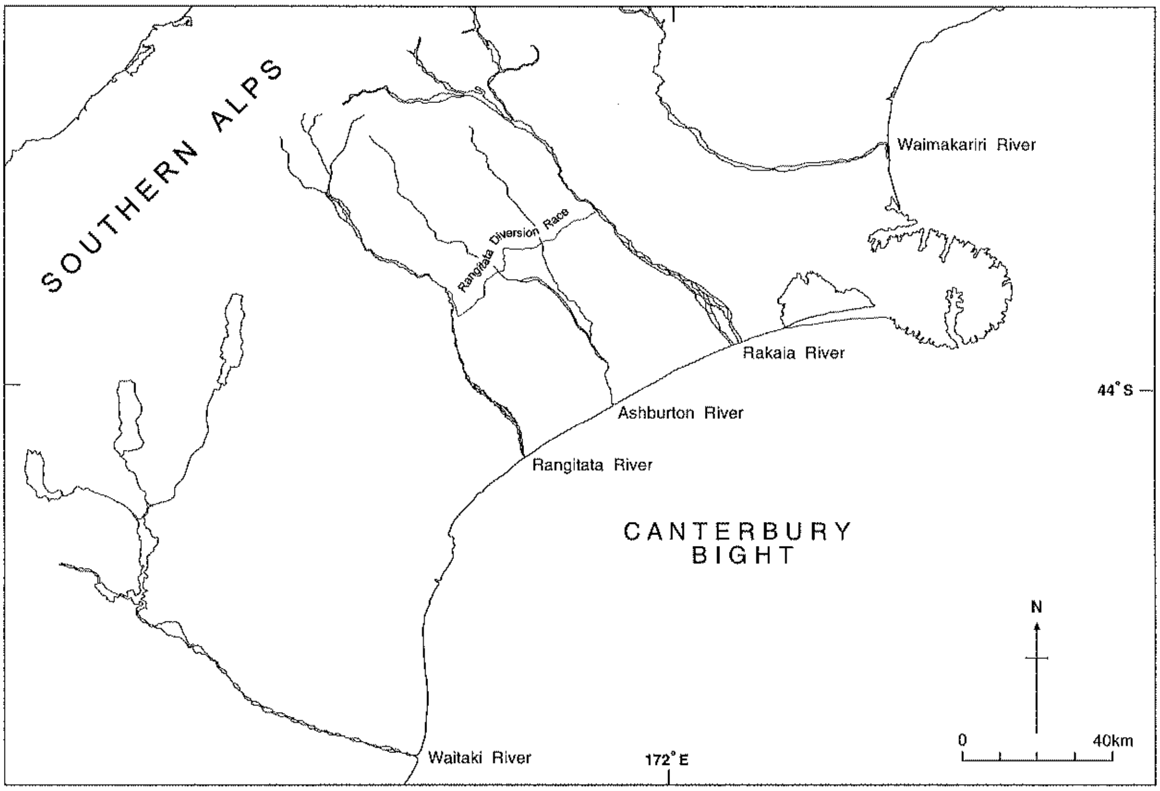

Figure 1: Location diagram for the major South Canterbury rivers.

Current rates of uplift may be as high as 15 mm/y near the Alpine Fault and decrease eastward (Wellman 1979). The basins and ranges of the eastern Southern Alps are uplifting 0.5-3 mm/y and eroding 0.1-0.5 mm/y. In the eastern front ranges, uplift and erosion are about equal at about 0.2mm/y (Whitehouse and Pearce 1992). The Southern Alps are probably about two million years old, mountains to the east such as the Puketeraki Range perhaps one million years old, the foothills younger again and embryonic hills such as Burnt Hills are just starting to be pushed up. The rivers draining the Alps have been able to keep pace with the uplift and have cut through the eastern mountains and hills as they have been thrust up. Along the upper part of the Plains abutting the foothill ranges, ongoing drag-uplift and incision of the river gorges is probably occurring concurrently. In contrast, the rest of the plains appear to be either tectonically stable or slowly subsiding (Wellman, 1979, as reported by Carson, 1984).

The axis of the mountains lies more or less normal to the prevailing moisture laden north-westerly winds, resulting in high rainfall, particularly just to the west of the main divide. The combination of high rainfall and high uplift rates appears to be the dominant control of basin sediment yield. On the western side of the Alps some of these yields are extremely high, equivalent to a lowering of the ground surface by as much as 11 mm/y (Griffiths and McSaveney 1983).

These mountains were affected by many glacial periods over the last several million years, creating the glaciated landscape obvious in the Canterbury mountains. During the Otiran Glaciation, the last major cold period that ended about 14,000 years ago, there were multiple advances of the large valley glaciers of the South Island. In Canterbury they extended to the mountain fronts overlooking the Canterbury Plains. Sea level was some 120 m lower at this time. The Plains are formed from a line of coalescing glacial outwash fans. Along the South Canterbury coast, the toes of these fans are being eroded under the influence of the modern, higher sea level. This coastal retreat is causing the rivers to steepen as they approach the sea, and the steepening process contributes to the rivers' sediment yield to the sea.

2.1 Rangitata River

The Rangitata River has its source high in the Southern Alps. Immediately downstream it has filled a glacially-enlarged trough that ends at a greywacke gorge, roughly corresponding to the Pleistocene glacial limits (Speight 1941). Downstream of the gorge an entrenched reach exists where the river has cut down through the Pleistocene outwash fans that form the Plains.

According to Carson (1984), the ongoing incision at rates of >3 mm/y immediately downstream of the gorge is consistent with the tectonic uplift of the plains or the sudden increase in transport capacity associated with the abrupt increase in valley floor gradient downstream of the gorge. Surface bed material coming from above the gorge has a median particle size of 20 mm (which may be rapidly reduced as it is moved through the gorge). The gorge acts as a control due to the slower erosion of the bedrock.

Immediately downstream from the gorge, the river slope steepens and the channel meanders. Here, too, the river is still down-cutting rapidly, so its floodplain is relatively narrow and sinuous, and large quantities of gravel are acquired from undercutting of the tall (50 m) cliffs of outwash gravels (Carson 1984). Hicks (1998) suggests that the bedload at Klondyke is about 360 kt/y. The increase in bed slope (from 0.0017 above the gorge to 0.0053 below the gorge increases the competence of the river to move sediment of larger size and this is reflected in the median particle size of 100 mm immediately downstream of the gorge. This cobbly-bouldery material is likely a lag deposit, left from lateral erosion of the glacial deposits after the fines have been transported downstream, and the bedload probably overpasses in an under-supplied situation.

The river abruptly braids where it is joined by the Lynn Stream, which contributes large amounts of sediment. Braiding continues to the sea, although upstream of State

Highway 1 the braiding is less intense. The river is incised all the way to the sea: the terrace height above the river is lowest 7-8 km from the coast (Healey 1997); entrenchment increases again from there to the sea, where the terrace level is about 8 m above the bed. This increased entrenchment as the river moves seaward implies that the river is down-cutting in response to coastal retreat, and this down-cutting will be contributing sediment to the coast. With coastal retreat of 0.34 m/y (Gibb 1979), and assuming no change to the nick point 8 km from the coast, a fairway width of 850 m, and a bulk density of 1.8 t/m^3, then the river should be adding 14.1 kt/y to the coastal budget from this source. The same figures suggest a down-cutting rate at the coast of approximately 2.3 mm/yr, reducing upstream.

There are no contemporary records (e.g. surveyed cross-sections) to confirm whether or not and where the Rangitata River is aggrading or degrading. However, we may infer that the bed level at the State Highway 1 Bridge has been stable because OPUS Consultants and their predecessors have not needed to survey the bed level to check on rates of bed level change that might threaten the safety of the highway or railway bridges. There is no trend in the bed-level at the water-level recorder at Klondyke between August 1979 and September 2000.

2.2 Ashburton River

The Ashburton River has its source in the mountains to the east of the main divide (Figure 1) and in the ranges and mountains abutting the Canterbury Plains. The South Branch also flows through a glacially enlarged valley and rock gorge before emerging onto the Plains, where it is joined by several gravel bedded tributaries. The South Branch is entrenched where it leaves the gorge and is predominantly single threaded until Mt Somers, where it becomes braided. The entrenchment diminishes downstream, ceasing about 6 km downstream of the State Highway 1 Bridge (Hudson 2000). From there to the sea the river becomes entrenched again, until at the coast the right bank is 20 m above the river. Again, this latter entrenchment is attributed to coastline retreat (Hudson 2000a).

The braided section of the South Branch, and the mainstem down to the sea, are heavily modified by stopbanking, narrowing, and gravel mining (for stopbanking, industrial, and road building purposes). Cross-section surveys indicate that the mainstem has been degrading all the way to the sea. In the Ashburton area this degradation has been due to gravel mining, but within 10 km of the coast the degradation appears to result from the natural response to coastal retreat (Hudson 2000a).

In the North Branch Ashburton River, rapid (11 cm/y) aggradation is occurring in the Blands Reach area as a result of the combined effects of an abrupt reduction in gradient and artificial channel narrowing (which has "squeezed" the natural aggradation that was occurring in this reach due to the slope decrease). Upstream of Thompson's Track Bridge, the river has been narrowed from an active bed over 500 m wide to less than 200 m, while downstream of the river has been narrowed from 350m to 85m (Springer 1981). Very little bedload is transported from the North Branch into the mainstem Ashburton River (Hudson 2000a).

Given the industrial demand for gravel, the degradational trend in the South Branch and mainstem Ashburton River is likely to continue, although it may be managed to minimise this trend. An alternative source of industrial gravel is likely to be the aggradational reach of the North Branch.

2.3 The Rakaia River

Like all the large Canterbury rivers, the Rakaia has its source in the main axis of the Southern Alps, traverses an infilled glacial valley and exits onto the plain via a narrow, sinuous rock-bound gorge. Unlike the Rangitata, the continuity of the long profile across the gorge implies no major increase in bedload transport capacity as it enters the Plains (Carson 1984). The braided nature of the river upstream of the gorge continues downstream of the gorge with little change in median particle size (30-40 mm diameter).

The Rakaia River is entrenched until a few kilometres downstream of the State Highway 1 Bridge. Immediately downstream of the gorge, the tops of the gravel terraces are over 100 m above the riverbed. Like the Ashburton River (and probably for the same reason), it becomes entrenched again in the last 10 kilometres towards the coast. Braiding is most intense where the river is at the same level as the plains. By comparison with the Rangitata River, the Rakaia River has a much wider floodplain (1.5 to 2 km) in its entrenched section.

There are no contemporary records to indicate whether or not and where the Rakaia River is aggrading or degrading. However, the bed level at the State Highway 1 Bridge may be inferred to be stable on the basis that OPUS Consultants and their predecessors have not needed to survey the bed level to check on the safety of the bridge. There is no trend in the bed-level at the water-level recorder at the Gorge between 1958 and 1981 (when gaugings ceased) or at the Fighting Hill site since 1979.

There is no compelling evidence to suggest that Rakaia River profile is not at or close to an equilibrium profile, at least over historical time scales. This is qualified with the observation that intense braiding of the lower river is indicative of aggradation, and that the relatively rapid coastal retreat is likely to cause some degradation in the lowest reaches in the long term. The terrace height at the mouth (8m), combined with the coastal retreat rate (0.15 m/y, mean of rates at North and South and South Rakaia Huts reported by Gibb 1979), suggest a long-term degradation rate at the coast of approximately 0.8 mm/y, which to all intents and purposes may be considered stable.

3 REVIEW OF PREVIOUS REPORTS

3.1 Summary of the findings of the Hicks (1998) report

Hicks critically reviewed the literature about river sediment supplies to the Canterbury coast and littoral budgets of the Canterbury coast. The work included reviews of measurements and estimates of suspended (Table 1) and bedload (Table 2) as well as consideration of the littoral budgets (Table 3) of sections of the Canterbury coast. This was followed by short sections on the effects of existing and future hydro-dams and irrigation works on coastal sediment budgets and further work.

He noted that many of the estimates need revisiting, particularly in the light of new methods and longer records.

Hicks gathered bedload estimates determined from either erosion 'ratings', cross-section surveys, or formulae. He was then able to calculate bedload: suspended load ratios. They raged from 2.2% to 28.6% and averaged 12.7% when the low Waimakariri value from near the coast is excluded. It would appear that Griffiths and Glasby's (1985) commonly used value of 3% is too low and would impact on many coastal budgets made to date.

3.2 Review of Hudson's (2000a,b) reports on the Ashburton River

Hudson (2000a, b) was retained by ECAN to review a proposal by ECAN to excavate bed material from a reach of the North Branch Ashburton River, because aggradation there has reduced the flood carrying capacity of the river. He evaluates the proposal (Hudson 2000a) in terms of the current situation and the effects of the proposal on headward erosion, downstream degradation, coastal erosion, and channel and bank stability. In Hudson (2000b) he critically reviews the proposal.

Hudson makes use of the extensive set of cross-section data in both branches of the Ashburton River as a basis for his evaluations, and in doing so covers much of the ground needed to evaluate the effect of damming of the South Branch of the Ashburton River.

These mountains were affected by many glacial periods over the last several million years, creating the glaciated landscape obvious in the Canterbury mountains. During the Otiran Glaciation, the last major cold period that ended about 14,000 years ago, there were multiple advances of the large valley glaciers of the South Island. In Canterbury they extended to the mountain fronts overlooking the Canterbury Plains. Sea level was some 120 m lower at this time. The Plains are formed from a line of coalescing glacial outwash fans. Along the South Canterbury coast, the toes of these fans are being eroded under the influence of the modern, higher sea level. This coastal retreat is causing the rivers to steepen as they approach the sea, and the steepening process contributes to the rivers' sediment yield to the sea.

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Table 1: Specific suspended sediment loads ($t/km^2/y$) and loads (t*1000/y) (italics) at gauging sites in Canterbury rivers, all estimated by the sediment rating method. The ×/÷ values with Hicks' estimates show the 95% confidence interval factorial error (from Hicks 1998).

River	Griffiths (1981)	Thompson and Adams (1979) and Adams (1980)	Hicks (unpublished)	Others
Clarence at Jollies	-	320	142 ×/÷ 2.2	-
		141	*62*	
Waiau at Marble Point	1300	1850	1171 ×/÷ 1.45	-
	2574	*3663*	*2319*	
Hurunui at Mandamus	-	1140	507 ×/÷ 2.4	-
		1208	*537*	
Waimakariri at SH Br.	1669	1540	989 ×/÷ 1.7	-
	5357	*4943*	*3175*	
Rakaia at Gorge	1641	3320	1691 ×/÷ 1.66	-
	4332	*8765*	*4464*	
Ashburton at Mt Somers	574	110	136 ×/÷ 4.4	-
	309	*59*	*73*	
Rangitata at Klondyke		1750	-	616
		2557		*900*
				(Scarf, in Waugh, 1983)
Orari	-	-	-	54
				283
				(de Joux, 1980)

Table 2: Bedloads in Canterbury rivers (kt/yr). Yields are to coast unless indicated otherwise (from Hicks 1998).

River	Adams (1980)	Griffiths and Glasby (1985)	Others
Clarence	540	106	
Hapuku	86		
Kowhai	14		
Kahautara	46		
Conway	70	17	
Waiau	143	113	
Hurunui	165	71	
Waipara	25	14	
Ashley	10	35	
*Waimakariri	156	179	115 (Griffiths 1979)
*Waimakariri at Crossbank	391		401 (Griffiths 1979)
Rakaia	466	144	
Ashburton	73	45	
Rangitata	281	50	
Orari	27	20	
Orari at Silverton	64		64 (Cuff 1981)
Opihi	67	71	
Opihi upstream Opuha	29		29 (Cuff 1974)
Opuha upstream Opihi	39		43 (Cuff 1974)
Paraeora	31	9.5	
Waihao	15	9.8	
Waitaki	178	34	
Lower Waitaki (pre dams)			221-288 (MWD 1982)
Lower Waitaki (post dams)			112-179 (MWD 1982)

* Gravel bedload does not reach the coast

Table 3: Summary of littoral sediment budget estimates by various authors for segments of the Canterbury Bight. Figures are bulk volumes in kt /yr (assuming 1.8 t/m^3) Refer to Hicks (1998) for discussion on values (or gaps) flagged with a question mark.

	Benn (1987) Washdyke-Opihi R	Hicks (1994) Smithfield-Orari R	Rheinen-Hamill (1995) Orari R – Rakaia R	Kelk (1974) and Kirk et al. (1977) Ashburton Mth	Kirk (1983) Rakaia Mth	Gibb and Adams (1982) Canterbury Bight
River bedload	0	0	185	79	144	910
(% of sum of river and cliff supply)	(0%)	(0%)	(26%)	(39%)		(51%)
Cliff/barrier erosion	0	54	463	122	45	889
Longshore drift in	0	0	54	?	180?	110 pre 1875 0 post 1875
*Longshore drift out	-11	-36	-306	?	180?	0
Backshore accretion	0	0	0	-34	-115 or 0	-140
Abrasion	-52	-18	-396	0	-59 (included in offshore losses)	-176
(m^3/m/yr)	(2.4)	(0.8)	(2.8)			(7.2)
Offshore losses	0	0	0	-131	-859	0
Storage gains	-58	0	0	36	-605 to -490	0

Negative values of the Storage Gain term imply a net loss of sediment from the area for which the budget was calculated, either by longshore transport to the north or by abrasion.

With regard to the North Branch Ashburton River, Hudson notes that even though large quantities (54 kt/y) of bed material were removed from Blands Reach for stopbanking and industrial uses, the mean bed level still rose by 1.27 m from 1937 to 1983 and by a further 1.73 m or so since 1983. The deposition at Blands Reach appears to be caused primarily by a reduction in bed slope, from 1.2% for the 15 km long reach below the Gorge to 0.5% from Shearers Crossing to the South Branch confluence. Hudson quotes Connell (1988) on the source of the sediment "*...about 80% of the shingle is derived from the upper catchment area with the remaining 20% coming from the river above Blands Reach to the gorge*." Immediately downstream of Blands Reach, from 1982 to 1997, bed levels remained stable despite 116 kt (10 kt/y) of gravel extraction, indicating that this amount of gravel was passing through Blands Reach. Between there and the confluence with the South Branch, there has been degradation of 10 kt/y over the same period. Hudson attributed this to headward erosion from the mainstem Ashburton River, which had degraded due to gravel extraction.

In the South Branch Ashburton River there has been significant degradation (>1719 kt from 1961 to 1997). This extends at least 22 km upstream from the confluence with the North Branch. This amounts to about 1.4 m lowering of the bed level at the confluence (km 21) and tapering to zero at km 43 (upstream) from 1937 to 1997. Much of this degradation is attributed to headward erosion from gravel extraction in the main stem from the confluence downstream to below the State Highway 1 bridge, but there was also gravel extraction for stopbank construction in the 1930s and 1940s.

Gravel extraction from the mainstem Ashburton River was 1823 kt from 1961 to 1997. Hudson estimates that the bedload inputs into the mainstem Ashburton River from the North and South Branches are small (sediment budgets suggest up to ~21.6 to 27 kt/y).

At the coast, Hudson notes "*In mid Canterbury, at the mouth of the Ashburton River current retreat ranges from 0.26 to 1.09 m/y (Flatman 1997).*" This retreat induces steepening of the river long profile and degradation of the river upstream. This steepening is evident on Hudson's plots to about 10 km from the coast.

Hudson comprehensively reviews the contribution of the Ashburton River to the coastal sediment budget. As listed by Hudson, the Ashburton river's bedload inputs to the coast have been variously estimated as:

- 79 kt/y (Kirk, Owens and Kelk 1977) based on estimating the residual of a coastal sediment budget and cliff erosion surveys.
- 73 kt/y (Adams 1980) based on a simplified Einstein-Brown bedload formula and flow duration curve.

- ~45 kt/y (Griffiths and Gasby 1985) assuming bedload was equal to 3% of the suspended load.
- ~97 - 124 kt/y (Hudson 2000a) from cross-section surveys and gravel extraction records.

Hudson's (2000a) lower estimate of ~ 97 kt/y (equivalent to 54,000 m^3/y assuming a bulk density of 1.8 t/m^3) was based on his sediment budget analysis of the river channel, and equals the difference between the total surveyed degradation (120,000 m^3/y) and the recorded gravel extraction volume (66,000 m^3/yr)[1]. This figure assumes that all the current bedload to the sea comes only from degradation of the mainstem Ashburton River due to the coastal retreat effect, with none entering the mainstem from the two branches. In fact, Hudson estimated that ~21.6 to 27 kt/y bedload is input to the mainstem Ashburton River from the North and South Branches, and his upper bound estimate assumes that this passes to the coast. From a sediment budgeting view-point, this larger figure is more sensible.

Hudson then summarises the components of the Ashburton coastal sediment budget over a 7500 m coastal segment as follows:

- *"Net northward longshore drift: 72 (Flatman 1997) to 180 kt/y (Kirk 1991).*
- *Cliff erosion: 122 kt/y (Kirk, Owens and Kelk 1977) to 198 kt/y (Hudson 2000a).*
- *River bedload inputs: 97 kt/y, possibly as high as 124 kt/y (Hudson 2000a).*
- *Net foreshore loss: 131 kt/y (Kirk, Owens and Kelk 1977): 437 kt/y (Kirk, 1991).*
- *Washover to lagoon: Taken as 10% of the gross foreshore loss (Kirk 1991), thus 14.4 kt/y (Kirk, Owens and Kelk 1977) and 49 kt/y(Hudson 2000a).*
- *Abrasion loss: 44.6 kt/y for the 7.5 km coastal cell of the Ashburton coast (Adams 1978).*

For the budget estimate developed here, the river input of 97 kt/y provides 9.7% of the coastal sediment budget with 180 kt/y of net longshore drift and 10.8% at 73 kt/y net longshore drift. Even if the river input load were dramatically reduced (say to half the

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[1] We note that if anything this sediment outflow figure may be over-estimated since gravel extraction records invariably tend to be underestimated.

current input of 97 kt/y) the percentage contribution would be reduced to 5.5% at 180 kt/y of net longshore drift and to 5.7 % at 73 kt/y net longshore drift."

Hudson concludes that the coastal processes dwarf the Ashburton River inputs, thus any reduction in bedload yield is unlikely to have a large effect on coastal processes. We note that Hicks (1998) has been critical of many of the estimates above and of the interpretations taken from various manipulations of the numbers.

To Hudson's 198 kt/y for cliff erosion, we suggest that 45 kt/y should be added for the sub-tidal portion of cliff retreat (7500 x 0.74 x 5*0.9*1.8) (assuming a sub-tidal beach height of 5 m, coarse sediment fraction of 0.9, bulk density of 1.8 t/m^3, and coastal retreat rate of 0.74 m/y). If we include Flatman's figure of 72 kt/y of littoral drift from the south and Hudson's river input of 124 kt/y, then the total supply of sediment to this coast is 439 kt/y. The river input amounts to 28% of this total. Most significant is that the bulk of the Ashburton River sediment yield to the coast appears to be sourced from the lower Plains, and so would not be trapped in dams at the gorges.

3.3 Review of Healey's thesis on "An investigation of the flood risk and erosion mitigation on the Rangitata River at Klondyke"

Healey (1997) conducted an investigation of flood risk and erosion mitigation on the Rangitata River at Klondyke for a Master of Engineering thesis. The most relevant section for this report is the chapter on the "Physical Environment". He comprehensively reviews the literature on the geomorphology of the Canterbury Plains as it relates to the Rangitata River. He reports on current and historical surveys in the area of the Rangitata Diversion Race (RDR) Intake, and on the differences in sediment size distributions throughout the main stem. Several series of vertical aerial photographs of the Klondyke Reach were examined for evidence of bank erosion. The section on the geological setting contains information on the coastal erosion at the Rangitata River mouth and long profile of the river and the adjacent terrace surfaces. There is also a section on the effect of the RDR abstraction on sediment movement downstream of the intake. He used the equations of Bagnold (1980), Einstein-Brown (1950), Schoklitsch (1962) and Smart (1984) to estimate bedload transport at the Intake bend with and without a constant water abstraction of 30.7 m^3/s. The calculated bedload transport capacities varied an order of magnitude from 559 to 6179 kt/y, but the proportional reduction in transport capacity after the constant abstraction was relatively consistent and ranged from 26% to 36%.

3.4 Comment on Nickolas's ongoing work in the Rakaia River headwaters

Nicholas (pers. com.) has been working in the Harper-Avoca catchment. The work involves 2D flow and sediment transport modelling and storage changes over periods of a few decades to centuries. Basher (pers. com.) at Landcare has been helping with some aspects, particularly with relative dating of fan and floodplain surfaces. He has also done other work recently developing a method for estimating bedload yield in braided rivers that is based on a revision of the Murray-Paola model (Murray and Paola 1994).

Nickolas's work may be reasonably relevant, at least on a conceptual basis to the dam effects question, and so the papers should be reviewed when they are published.

3.5 Comment on Collins work on the Ashburton River

Daniel Collins, while employed by ECAN, assembled a spreadsheet of the Ashburton River surveys and calculated most of the information that Hudson used, but without any interpretation. On the advice of ECAN staff, most prominence has been given to Hudson's results.

3.6 Summary of the findings of Thompson et al. (1997)

This report looks at the likely effects of prolonged low flow on the morphology of the lower Waitaki River. Since 1953 flooding in the Waitaki River has been controlled by dams, and a series aerial photographs first taken in 1943 allow the morphological changes as a result of the damming to be assessed. Since the damming, the fraction of the time that the flows exceed 1250 m^3/s has decreased ten fold. Thompson et al. (1997) considered flows of 1250 m^3/s would be required to prevent narrowing of the fairway and to destabilize terrestrial vegetation in the river bed to conserve the river bed character. Thompson et al. (1997) calculated that flows of 1250 m^3/s have reduced four fold in frequency, and have decreased ten fold in duration, of occurrence since dam building. In 1943 the river bed was bare of vegetation, windswept, and up to 2 km wide, with one or two main braids and extensive areas of shifting gravel bars and channels. The river bed had scattered willow trees and numerous more or less temporary islands vegetated to varying degrees with grass and exotic scrub. By 1997 the river had a much more well-defined fairway, with a fairly constant width of about 0.5 km. The fairway of relatively unvegetated bars and islands was occupied by one or two main braids and 3-5 minor braids. (Note: The authors have observed that by July 2001 these islands were well vegetated with tall exotic scrub down to the 500 m^3/s water level). The number of braids does not appear to have changed since damming, but backwater channels were much less common. In general there has been a substantial narrowing of the river bed and the braids are more stable. There is now tall woodland outside of the fairway. On the fairway the islands are usually vegetated with scrub, except after large floods.

Thompson et al. (1997) conclude that the residual flow regime has two major detrimental effects: the accumulation of underwater silt and periphyton and the covering of bare gravel on islands and river margins with dense terrestrial vegetation. They recommend deliberate "flood" releases to counter these detrimental effects.

3.7 Review of Flatman's thesis on "Cliff erosion and coastal change, mid Canterbury"

Flatman (1997) studied the components of coastal sediment budget for the portion of the mid Canterbury coast between the Rangitatata River and Wakanui Creek, about 5 km north of the Ashburton River mouth. The thesis adds to the data on cliff erosion with the analysis of 25 cliff and beach profiles more or less evenly spaced along the 32 km study reach. Most of the profiles were established by ECAN in 1981 and were resurveyed 9-10 times over the following 15 years. Erosion rates varied from 0.03 to 1.09 m/y and averaged 0.43 m/y and are within the range of rates reported by others e.g. Gibb (1978). There was a trend for increasing rates of cliff recession from south to north (at 0.02 m/y/km), although the erosion rate was highly variable from one station to the next. Quantities of material eroded differ from recession rates as the cliffs vary in height from about 8 m in the south to about 21 m in the north of the study reach. Volumetric rates of erosion estimated by Flatman range from 0.4 kt/km/y to 39 kt/km/y, total 411 kt/y for the reach and also generally increase from south to north. He does not account for the 4-6 m of sub-tidal gravel between mean sea level and the flat nearshore bed composed of sand that must erode at the same long-term rate as the cliffs. This portion would add 124 kt/y for the reach, assuming a 5 m high nearshore gravel face.

He also calculated net longshore sediment transport rates at the Ashburton River mouth based on the "longshore component of wave energy flux" approach and four months of wave height and wave approach angle observations, arriving at a figure of of 73 kt/y northward. This estimate was lower than others reported and may reflect the short duration and season of the observations. Also, the estimate is highly dependent on the choice of coefficient used in the calculation.

His estimate of bedload delivery to the coast (45 kt/y) is based on 3% of the suspended sediment load. This may be an underestimate as Hicks (1998) has estimated bedloads to be 4 - 26% of the suspended sediment load in Canterbury rivers. In addition, Flatman's estimate of bedload is less than half Hudson's (2000a) more soundly based estimate (97-124 kt/y).

To close the sediment budget, Flatman proposed that the sediment inputs were balanced by losses to northward longshore transport and abrasion. He estimated that 76.8% of the input sediment was lost to abrasion, using Gibb and Adams (1982) approach (although it is not clear exactly how he did this calculation), with the residual being lost alongshore.

3.8 Review of Paterson's thesis " River mouth processes and Morphodynamics on a mixed sand-gravel beach"

Patterson (2000) analysed time-lapse video images of the Ashburton River mouth plus data on lagoon water levels, tides, and waves in a study of the processes of mouth migration. He also investigated an acoustic instrument to measure longshore sediment transport. The study provided some measurements and relationships between mouth migration rate, wave conditions, and river flow rate. The presence of 'raised banks' that appear to be more stable than the rest of the barrier beach influenced the location of the mouth. Extreme wave climate and flood events were the most significant factors defining the observed patterns.

4 THE EXPECTED GEOMORPHIC RESPONSE OF RIVERS TO DAMS

Dams cut off the sediment supply and change the downstream flow regime, in particular, by reducing the number of freshes and smaller floods that naturally move most of the bedload. Water abstraction from irrigation dams also results in flow reduction that further reduces the potential for bedload transport.

4.1 Changes to the flow regime

The purpose of irrigation dams is to store flood waters for later release for irrigation. The consequence of this is that the magnitude, duration and frequency of floods is reduced. Mid-range flows may well be reduced, and lows flows could be reduced or enhanced depending on resource consent conditions. There will also be reduction in mean flow due to the abstraction for irrigation. While the largest floods move the most sediment per flood, it is the more frequent freshes that move the most sediment because they occur more often than very large floods (Davies 1988). It is these smaller floods that are mostly captured by dams. All these factors lead to a reduction in the sediment transporting capacity of a river. Hydro-electric power dams or irrigation dams with hydro-electricity components often have quite unnatural outflows, e.g., daily cycles to match electricity demand. Furthermore, such flow regimes often change in response to the electricity market.

4.2 Changes to morphology immediately downstream of dams

Dams cut off the sediment supply of coarse, bed-material grade sediment to the river downstream.[2] The usual response of a river is for the bed to degrade and to coarsen immediately downstream of the dam as the river attempts to restore its bed-material load and armours its bed in the process. The changed flow regime with reduced magnitude and frequency of flooding in combination with degradation often leads to narrowing of the channel and invasion of the bed by vegetation (Thompson et al. 1997).

Braided rivers work differently from single-thread channels in that much of the supply comes from erosion of the banks of braids rather than the bed, so classical degradation and armouring of a bed may be delayed while the braids and bars get worked over. In an unmodified braided river, degrading reaches are characterised by coarse bed material, more stable channels, more incised channels and a greater range in the elevation between the thalwegs of channels and the tops of bars than in aggrading reaches. However, in a modified system, the ultimate combined effects of the degradation process, flood regime change, and vegetation encroachment may be a profound change in the morphology, e.g., from braiding to meandering.

4.3 Changes to morphology further downstream

Further downstream, the river will change more slowly and will lag the upstream changes, due to the recovery of at least part of its sediment load from the degradation process upstream. Moreover, braided reaches will find a ready supply of bed-material in their bed and banks. In addition, tributaries will add further inflows of sediment and water to transport the sediment. Thus the bed form may change less away from the dam, although invasion of the bed by vegetation may still occur.

Changes may also occur at river mouths. With reduced flood flows, the balance between the energy of the river and the sea alters. Barrier beaches that seal-off river mouths are more likely to form and persist. The effects will range from less frequent bursting of the barrier beach opposite the river for the larger rivers (e.g. Rangitata and Rakaia Rivers), and hence more prolonged times with highly skewed outlet configurations, to longer closures of river mouths for smaller rivers (e.g. Ashburton River). The mouths of the Rakaia and Rangitata Rivers are currently kept open by frequent freshes as well as occasional large floods. If these freshes were to be captured by dams then the mouths are more likely to close (Dr G Goring, NIWA pers. comm.).

[2] Sluice gates, if installed, are only effective at restoring this supply after substantial infilling of the reservoir has occurred, since the bed-material deposits on a delta at the top end of the reservoir.

4.4 Actual changes

Whether or not the bed degrades after damming depends on the competency of the residual flows to erode the bed, the capacity of the river to transport the sediment away, and the ability of the sediments to form an armour layer which prevents further erosion (Kellerhals 1982).

Degradation may occur slowly because of the reduced frequency of competent flows. In most rivers, sediment transport is supply limited, with armouring reducing the supply from the bed. In many cases a reduced flow may not necessarily result in less sediment movement because the reduced flow may still be able to transport all the available sediment. For example, Healey (1997) reports that even though abstraction of water by the Rangitata Diversion Race reduces the capacity of the river to move sediment by 29% to 36%, the river is still capable of moving five to six times the amount of sediment that is being supplied.

In braided gravel bed rivers, sediment supply and armouring are less likely to limit sediment transport (at least initially), especially in naturally aggrading reaches which are poorly armoured compared to degrading reaches such a those studied by Healey (1997). This is because braided rivers get much of their bedload from attacking banks rather than obtaining it from the bed.

4.5 Aggradation at tributary confluences

The effect of tributaries will depend on the relative loads and flows arriving at the confluence from the tributary and main river. Tributaries may effectively offset the loss in sediment load due to damming, or, if they supply too much or too coarse sediment for the altered flow regime in the mainstem to transport away, aggradation may occur (Kellerhals 1982). An aggrading tributary fan may force the river against the opposing bank causing erosion of the bank.

4.6 Type of flow regime

Even though the total flow may be reduced by abstraction for irrigation, the use of the dam for hydropower purposes, especially for peak power, can result in a higher median flow than before damming. Having a greater proportion of the flow in the high range may activate the channel, increase sediment transport capacity and cause the downstream river to widen and straighten.

4.7 Monitoring

Any morphological changes in rivers downstream of dams may take some time to become apparent and there is a downstream lag as any adjustment advances as a "wave". It is therefore essential that the bed morphology, planform, and grain size distribution (including the sand fraction) are carefully quantified before dam construction starts and that these parameters are monitored on a regular basis (say every 5 years) until they stabilise. Monitoring all the way to the sea is required. The arrangements for such monitoring and archiving of the results have to be structured in such a way that the work is done properly and that it will continue even if personnel and institutions (both dam owners and regulators) change. It is our experience that compliance in these matters can be haphazard and checks are not made by regulators that the conditions of water rights are strictly adhered to, and that monitoring work is properly done. Aerial photos at an appropriate scale are very useful, and the aerial photography companies have excellent archives. Information on grain size distributions tends to get lost unless published. These days an aerial laser survey can be used to capture the morphology. Bench marks for cross-section surveys are often lost, or difficult to re-establish, and so the order of the errors between surveys is such as to bring into doubt the value of the surveys. Location of bench marks by GPS co-ordinates may now overcome such difficulties, as long as the co-ordinates are properly archived.

One of the very best ways to monitor long-term bedload transport is to measure (survey) the increase in size of deltas where rivers enter still water such as lakes. The building of new irrigation (or hydro) dams offers an excellent opportunity to estimate bedload transport in the river being dammed. Thus the beds of any proposed lakes should be surveyed accurately before filling so there is a base against which the rate of bedload deposition can be measured.

5 COMMENT OF THE ECOLOGICAL EFFECTS

Dams physically prevent the movement of migrating fish. Fish passes need to be incorporated in dam design. Consideration needs to be given to passage for upstream migration of adult salmon, elvers and lamprey, and downstream migration of juvenile salmon and adult eels.

If there are more stable flows downstream of dams, this will allow periphyton to grow and community composition is likely to change from, for example, diatoms to filamentous algae (Biggs et al. 2001), and benthic invertebrate community composition is also likely to change. The river may well be more productive without the constant flooding characteristic of most Canterbury rivers. However, in the absence of floods, releases of flows of about 5 times the previous flow may be needed every three months to remove nuisance growths of algae and accumulations of fine sediment (Biggs and Close 1989). Such moderate flushing flows would probably remove accumulated silt, sand and periphyton and so cleanse the gravel bars without mobilising the armoured surface and destablising the channel pattern.

Any change in flow regime is likely to affect the character of the river. For example the riverbed's response to reduced flooding is likely to be encroachment of scrub vegetation and maybe willows onto the less frequently flooded areas, as has happened in the lower Waitaki River (Thompson et al. 1997). As well as altering their natural character, the exposed bars will no longer be suitable resting and nesting areas for birds such as wrybill plover, oyster catchers and black-backed gulls. To mitigate against the change in character it may be necessary for "flood" flows to be released periodically to mobilise the whole fairway. Thompson et al. (1997) recommend for the Waitaki River flushing flows of 600 m^3/s every month and bar destabilising flows 1250 m^3/s for 3 days every 3 years. These flows correspond to events that reoccur several times per year and every 3 years , respectively. The 600 m^3/s is presumed to be 5 times the pre-existing flow of 120 m^3/s recommended by Biggs and Close (1989) to flush periphyton but the paper does not say so. The monthly frequency is required to prevent periphyton growth reaching "nuisance" levels that can occur within 4-6 weeks. Thompson et al. (1977) argued that a flow of 1250 m^3/s provided a velocity of 2.8 m/s (sufficient to mobilise a packed (armoured) bed where the d_{90} was 0.083 m) over 17% of the bed and assumed that would be sufficient to destabilise the bed. The duration of three days would restore the duration of flows of that magnitude to that occurring since damming. That may be enough to retain the current (modified) character of the bed, but whether it would restore the bed of the pre-dam state is unknown.

6 THE OPUHA RIVER DAM: A CASE EXAMPLE

There is a Canterbury example of the effect on flows of damming for irrigation. The Opuha Dam is about 12 km upstream of the Skipton water-level recorder site and there are no significant tributaries between the two locations. The Opuha Dam in South Canterbury was assumed to start filling from 1 January 1998. Because of the short record since the dam was filled, the post damming data may be not be typical, but the differences are so marked that they must be indicative. It appears that the minimum, median and mean flows are similar for the pre-dam and post-filling periods, but the post-filling period maximum flow is less than half of the pre-dam mean annual flood. Table 4 shows flow statistics before and after damming. Caution should be used in interpreting the table as the pre-dam record is much longer than the filling and post filling records. In addition the reduction in peak discharge will depend on how empty the reservoir is at the time of the flood.

If it is not already being done, we recommend that deposition in this reservoir and morphological change in the river downstream of the dam be monitored – so this stands as a case example for future dams.

Table 4: Flow statistics from the Opuha River at Skipton before and after the building of the Opuha dam for irrigation storage. The dates are indicative.

Record dates	Situation	Minimum (m^3/s)	Median (m^3/s)	Mean (m^3/s)	Mean annual flood (m^3/s)
16-7-63 to 1-2-98	Pre-dam	1.0	6.6	9.58	267
2-2-98 to 1-12-98	Filling	1.0	2.3	3.49	15.1
1-12-98 to1-7-01	Post filling	0.8	7.7	8.90	106

7 THE EFFECT OF DAMMING ON EACH OF THE THREE RIVERS

The purpose of this section is to speculate on the hydrological effect of damming the Rakaia, Ashburton, and Rangitata Rivers for irrigation abstraction, the resultant effects on sediment transport and beach nourishment, and the factors taken into consideration.

7.1 The Rakaia River

7.1.1.1 The effect of damming on river morphology and processes

The assumption is that any dam would be in the vicinity of the Gorge. An abstraction of 60 m^3/s is assumed on the basis that it is about one third of the mean flow and is thus a similar proportion of the mean flow to the abstraction from the Rangitata River. It could also be assumed that the largest floods would only be slightly attenuated, but the more frequent floods and freshes would be severely reduced in magnitude and volume. The magnitude of the minimum residual flow is immaterial to this discussion as low flows have no material effect on gross bedload transport even though the bed may continue to move at quite low flows.

Such a dam would cut off the sediment supply from upstream.[3] There are no tributaries downstream to add sediment to the river. However, the gravel terraces downstream of the gorge are over 100 m above the river bed which is 1.5 – 2 km wide. Thus there is a large potential source of bed material but only a fraction of the rivers power would ever bear on these banks. The Rangitata Diversion Race adds up to 31

[3] While in principle sluice gates could allow sediment to be passed during floods, passing gravel through from the top end of the reservoir would require a severe and prolonged draw-down – at least until the reservoir filled and the gravel depositional front was closer to the dam.

m^3/s from April to September when flows are naturally low, and this additional flow is unlikely to add significantly to the transporting power of the river.

Griffiths and Glasby (1985) suggest that the Rakaia River transports about 144 kt/y of bedload. Adams (1980) suggested 466 kt/y. Bedload can also be estimated from Hicks' (1998) estimate of suspended sediment load of 4,464 kt/y and assuming 13% bedload (mean % from Table 4 of Hicks (1998) excluding the lower Waimakariri) gives a bedload of 580 kt/y.

Davies (1988) suggests that a constant diversion of 70 m^3/s would reduce the bedload capacity of the Rakaia by 20%. Since a dam would also attenuate floods, we therefore - in the absence of any detailed investigation - assume that an irrigation dam operation on the river would reduce the bedload transport capacity by about 30%.

The Rakaia currently gets its bedload from the mountains, the braided reaches upstream of the gorge, the cliffs immediately upstream of the gorge, and the bed of the river from the Gorge to about State Highway 1. As discussed in section 3, downstream of SH1 Bridge the form of the bed suggests that it is aggrading, while there may be some slight degradation near the coast. With the advent of a dam (without sluice gates) at the Gorge the upstream sources of sediment would be cut off. The bed and banks downstream represent a large source of sediment and would be able to supply the river all the sediment it needs, especially as its competency will have been reduced.

If the river was to lower its current bed level by 1 m for the reach between the Gorge and the SH1 Bridge (40 km by 1.5 km), that would supply gravel for over 266 years assuming the Hicks (1998) estimate of current bedload and a reduction of this by 30% caused by the damming. ((1,500*40,000*1)/(322,000*0.7))[4]. The process of down cutting through the most recent Pleistocene fans has been going for 10 000 to 15 000 years and yet there is little sign of armouring of the bed. This is attributed to the way braided rivers move sediment by eroding the banks of the braids rather than by eroding the bed as is more prevalent in single thread streams. It is possible that the diminished bedload capacity of the river will cause a change towards a less intensely braided form, with more incised channels characteristic of degrading beds. Such more stable channels are likely to develop coarse armoured beds. The more stable bed in general is likely to be encroached by vegetation in a similar manner to that of the Waitaki River bed, despite the occasional effects of large floods.

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[4] A bulk density of 1.8 t/m^3 has been assumed.

7.1.2 The effect of damming on coastal nourishment by the Rakaia River

After damming of the river, the coast will receive the reduced amount of bedload as estimated for the river (580 kt/y *0.7 = 406 kt/y) - as a result of the reduced capacity of the river to transport it rather than because of a limit in the supply. The usual way of estimating the effects of such a reduced supply on coastal stability is by a coastal sediment budget analysis. Kirk (1983) has made estimates of the components of the coastal sediment budget, but Hicks (1998) questioned the veracity of these estimates.

The situation remains that the quantities of the various components are not known with any certainty, except for the amount contributed by cliff retreat, which was estimated by Kirk (1983) to be 46 kt/y for a 10 km long study reach (of which 4 km is lagoon without cliffs). The littoral drift in the Rakaia region is not well known, let alone how much beach material is gained or lost per unit shoreline length by longshore gradients in the littoral drift. Similarly, the loss rate of barrier beach sediment by abrasion is very uncertain, since previous investigators have tended to close their coastal sediment budgets by assigning to abrasion the difference between all other gains and losses (with all their accumulated uncertainties). What becomes clear when the Canterbury Bight littoral cell is viewed in its entirety (e.g. Gibb and Adams, 1982, Hicks, 1998) is that Kaitoriti Spit is the only sink for beach gravel, and historically that accounts for only a small fraction of the sediment supplied from rivers and cliff erosion. Thus the bulk of this supply must be ground-up by abrasion processes as it is scrubbed alongshore by waves.

What is also clear is that dams on the rivers will not effect the littoral drift regime nor the rate of abrasion of the beach sediment (unless there is a significant difference in the abrasion rates of gravel sourced from cliffs and from rivers). On this basis, we would expect any reduction in the river sediment supply to be offset by accelerated cliff erosion. So, for this study, for the purpose of assessing the impact of dams on coastal stability, we consider the best approach is to forget about trying to close the coastal budget and to simply estimate what a reduced river sediment supply translates to in terms of additional coastal erosion[5].

As discussed previously, the amount of bedload being delivered by the Rakaia to the sea is estimated to be between 144 kt/y and 580 kt/y. The absence of an obvious delta

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[5] Inherent in this approach is the assumption that cliff erosion will keep pace, supplying new material to the barrier beach in balance with the longshore transport potential of the waves to transport it alongshore or to abrade it away. If the cliff erosion lags, then the outcome would be a loss of the beach at the cliff toe, which could be expected to cause an increased rate of cliff failure since the beach, when present, buttresses the cliff. In this sense, the cliff erosion will tend to be self-regulating. Relatively short-term observations (e.g. Flatman, 1997) indicate that such processes operate continually, with talus from cliff failure accumulating on the back-beach until the beach is attacked by storm waves.

indicates that this quantity is being smeared alongshore by waves and/or abraided relatively quickly. Probably, the barrier of gravel at the mouth is the equivalent of a delta, albeit a long buffer of gravel. Maps and aerial photographs of the coastline do show a seaward bump at the Rakaia mouth. Gibb (1978) noted an average accretion of the coastline of 0.34 m/y just to the south west of the Rakaia mouth between 1942 and 1976, while just to the northeast of the river mouth there was erosion of the coastline of 0.66 m/y. This pattern is suggestive of a temporary phase of sediment storage around the river mouth.

As regards cliff erosion in the Rakaia area, Kirk (1983) reports mean recession rates of the lagoon of 0.6 m/y, north of the lagoon of 0.90-0.97 m/y, and an average for a 10 km reach centred on the river mouth of 1.06 m/y. His computed cliff sediment supply from this 10 km reach amounts to approximately 47,000 t/y (assuming a bulk density of 1.8 t/m^3). On the basis of these figures, the Rakaia bedload input to the coastal sediment budget appears to be substantial, so any reduction is likely to have a significant affect on coastal retreat.

If the Rakaia's bedload input was reduced by 30 % due to damming, we assume that the cliffs and sub-tidal face would be eroded at a greater rate to provide a similar amount of material, i.e., the average rate of coastal erosion of 1.06 m/y would increase by a maximum of 1.305 m/y to 2.366 m/y. As discussed above, this estimate is based on the assumption of the reduction of sediment transport due to the dam and the material from the cliffs will be as easy to transport and erode as the less consolidated river sourced bedload. This qualification also applies to the estimates of accelerate erosion of coastal erosion for the Ashburton and Rangitata River coastal reaches.

We note that the above estimate of increased erosion rates is keyed to the 10 km shore length used by Kirk in his study – a longer span of shore would reduce the estimated retreat rate, a shorter span would increase it. Establishing the length of coast expected to respond to a reduced supply of river bedload is tricky, since a supply deficit does not tend to be recovered uniformly along a shore but is focussed initially at the updrift end (as observed at Washdyke, e.g. Hicks, 1994). Numerical shoreline modelling is the best approach to examine the dynamics of the shoreline adjustment, but is beyond the scope of this investigation. For consistency, therefore, in this study we will assume that the river supply deficit due to dams is recovered from a span of eroding shore that extends from 2 km south of the river being considered to 2 km south of the next river up the coast (Figure 2). This pattern allows that the bulk of the effects would be found north of the river mouths, in keeping with the northward direction of the net longshore transport.

On this basis, at the Rakaia we consider a span of shore 18 km long, extending as far as the south end of Kaitoriti Spit. For this span, the river sediment supply deficit converts to an increased erosion rate from 0.63 to 1.13 m/y. The Kaitoriti Spit shoreline appears to be more-or-less stable at present, with a balance appearing to have been struck between the rate of supply of littoral drift material from the south and gravel destruction by abrasion. If a diminished Rakaia sediment supply is not recovered from shore erosion between the river mouth and the spit, then the spit would likely pass into an erosional phase. The erosion would initially be focused at the south end, possibly impacting the dynamics of the Lake Ellesmere outlet channel.

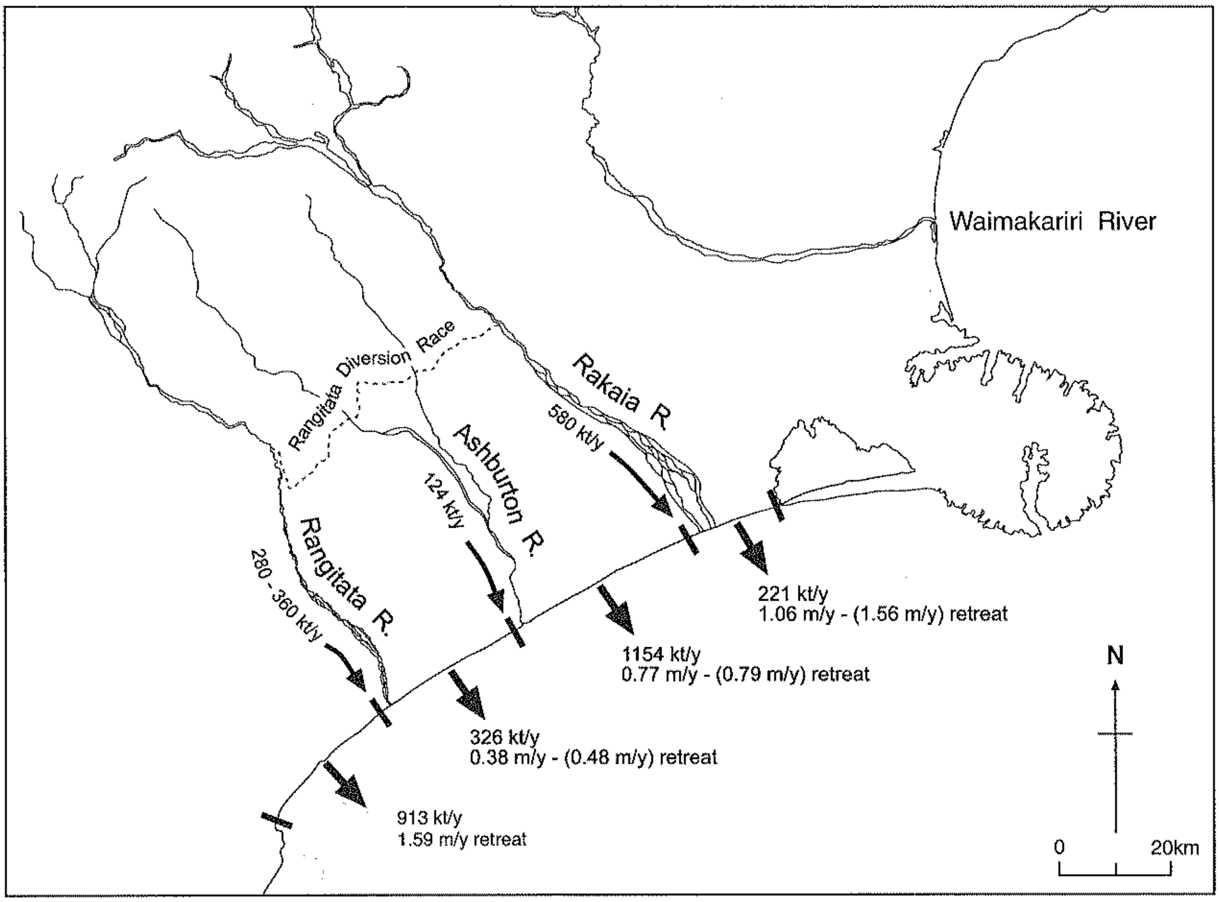

Figure 2. Schematic diagram of the Rangitata – Rakaia coasts, showing the estimated current inputs of beach sediment from cliff erosion and rivers. The left retreat rate is the current rate over the coastal segment and the rate within brackets is the enhanced rate due to damming using the assumptions in the text.

7.1.3 The effect of damming on Rakaia River mouth closure

There is no convincing evidence that the Rakaia River mouth has closed historically. Kirk (1983) considers that a flow of 45-50 m^3/s would be sufficient to maintain the opening and that most flows greater than the mean discharge (about 200 m^3/s) have the ability to initiate breaches of the barrier opposite the river. On this basis, damming the river is not expected result in mouth closure provided residual flows of at least 45-50 m^3/s were maintained. However, if a dam led to reduced flood flows, then the frequency of the mouth blowing-out opposite the river would decrease and the mouth is likely to be to be offset to the north of the river more often.

7.2 The Ashburton River

7.2.1 The effect of damming on river morphology and processes

It is assumed that any dam would be at Blowing Point on the South Branch, upstream of the Stour River confluence. This dam would capture the bed-material supplies from upstream. Also, virtually all flows would be captured and used for irrigation, except for a residual flow of sufficient quantity to allow a flow combined with those from downstream tributaries of about 6 m^3/s at Ashburton. The minimum residual flow is immaterial to this discussion insofaras low flows do not affect bedload transport. However, the "capping" of flood flows would diminish the bedload transport.

These effects would be partially off-set by the large number of tributaries downstream from Blowing Point that contribute both flood flows and bedload. Of the 1579 km^2 catchment area to Ashburton (Walter 2000), only about 403 km^2 are upstream of Blowing Point (although the North Branch, catchment area about 300 km^2, does not join the South Branch until just upstream of Ashburton).

As mentioned previously, Hudson (2000a) assessed bedload movement in the Ashburton River, based on cross-section series and records of gravel mining. In the North Branch, most of the bedload is deposited in the aggrading Blands Reach, and only ~ 10 kt/y enters the main stem Ashburton at the confluence with the South Branch. This amount is attributed to headward erosion from the confluence, which has been lowered by gravel extraction. In the South Branch, the sediment budget is dominated by gravel extraction, and the riverbed is degrading. Nonetheless, about 12 kt/y to 17 kt/y of bedload is delivered to the main stem. This is sourced from the headward erosion that extends upstream from the confluence. Damming of the South Branch will thus reduce the delivery of bedload to the main stem, and if gravel extraction continues degradation rates will increase.

7.2.2 Ashburton River beach nourishment

The current delivery of bedload to the coast is ~97-124 kt/y (Hudson 2000a) based on cross-section surveys and gravel extraction records. The source of this material is the bed and banks of the main stem Ashburton River and this degradation is attributed by Hudson (2000a) to steepening of the river because of beach retreat. The larger estimate includes 22 kt/y to 27 kt/y moving through the reach from further upstream. This stems from headward erosion of the main branches as a result of gravel-mining induced degradation in the Ashburton area. Reduction of this mining may, in time, increase sediment delivery the coast. However, at least initially, the reduced flows associated with a dam would reduce the load to the coast. On the basis of the proposed dam capturing all flood flows and that flooding is proportional to catchment area, the dam should roughly reduce flood peaks in the lower river by about 25%. If this resulted in a 25% reduction in bedload delivery to the coast, then ~73 to 93 kt/y would be delivered to the coast[6]. Hudson (2000a) believes either figure is a small proportion of the coastal sediment budget (>10.8%) so any reduction in bedload yield is unlikely to have a large effect on coastal processes.

Our view is that assuming longshore transport and abrasion remain unchanged, then the deficit in river load would be taken up by accelerated erosion of the cliffs and sub-tidal face. On this basis we calculate (Appendix 1) that for the 38 km span of shore between the Ashburton and Rakaia Rivers, for which the current supply of sediment from cliff erosion, including the sub-tidal portion is 1154 kt/y, the average current rate of coastal erosion of 0.77 m/y would increase by a maximum of 0.02 m/y to become 0.79 m/y. As discussed previously, there may not be a 1:1 replacement of river bedload with coastal erosion due to a time-lag in the response of the cliffs, thus the actual rates will be between current rates and those calculated above.

7.2.3 The effect of damming on Ashburton River mouth closure

The Ashburton River mouth is often closed for long periods. Damming of the South Branch is highly likely to increase the frequency of mouth closure and delay re-opening.

7.3 Rangitata River

7.3.1 The effect of damming on river morphology and processes

The assumption is that any dam would be at the upstream end of the Gorge. A mean abstraction rate of a further 26 m^3/s over and above that taken by the Rangitata Diversion Race (RDR) is assumed on the basis that it is the amount left from the natural mean flow after allowing 31 m^3/s for the RDR diversion and 30 m^3/s as a residual flow. This extra abstraction rate is in line with the smaller of two

[6] This assumes a simple linear relationship between flood peak flow and bedload yield, whereas in fact bedload tends to be related non-linearly to water discharge. A more detailed analysis would certainly refine this estimate, although we don't believe it would result in a gross change.

development proposals (pers. comm. John Young, RDR Management). The water is most likely to flow through the gorge and be abstracted via the current RDR diversion and by a new diversion in the vicinity of Peel Forest. It could also be assumed that the largest floods would be only slightly attenuated, but the more frequent floods and freshes would be severely reduced in magnitude and volume. Some flood releases may be required to maintain the current natural character of the river. The magnitude of the minimum residual flow is immaterial to this discussion as low flows have no significant impact on bedload transport, even though the bed may continue to move at quite low flows.

Such a dam would cut off the supply of relatively fine gravel from upstream. Downstream of the gorge there are a few right bank tributaries draining the Mt Peel area that add significant amounts of sediment to the river. The largest of these is Lynn Stream, downstream of which the morphology of the river changes from meandering to braided (Carson 1984, Healey 1997). The high gravel terraces downstream of the gorge to the Arundel Bridge are also a source of sediment. Although some gravel passes through the gorge, over-passing the coarse material that armours the bed, it is thought that these large sources of bed material downstream of the gorge currently supply most of the bed material for the lower river (Carson 1984). The channel pattern appears to indicate long-term degradation along its entire plains reach, and in the absence of a dam, this can be expected to continue (Healey 1997).

Given the current situation with an under-supply of sediment to the gorge and large sources downstream, the downstream effects of a dam at the gorge are liable to be less severe than in other rivers. In fact, a dam would reduce flood frequency and the competence/capacity of the river to transport sediment, and thus the current rate of overall degradation would likely decrease. Also, this would reduce the rate erosion by the main stem of Lynn Stream delta. This delta has already pushed the Rangitata River against the left bank cliffs, and so this tendency would increase.

With damming and abstraction it is possible that the diminished bedload moving capacity of the river will cause the meandering form to extend downstream of Lynn Stream, with more incised channels characteristic of degrading beds. Such more stable channels are likely to develop coarse armoured beds. The more stable bed in general is likely to be encroached by vegetation in a similar manner to that of the Waitaki River bed, even though there may be occasional large floods, unless there are resource consent conditions requiring regular flood releases designed to maintain the current braided and bare appearance of the river bed. Such regular releases would also help maintain bedload movement and beach nourishment.

7.3.2 The effect of dam influenced sediment delivery to the coast

Recent coastal retreat at the Rangitata River mouth (0.34 m/y) appears to be low in comparison to other parts of the Canterbury Bight (Gibb 1978). The generally slower rate of coastal retreat at the Rangitata River mouth compared to smaller nearby rivers can be attributed to its higher sea cliffs (due to its large alluvial fan) and greater sediment load (Healey 1997). Flatman (1997) has estimated the coastal retreat from the Rangitata River mouth to the Hinds River mouth to be 0.25 m/y from 1981 to 1996.

As with the other rivers, the Rangitata River steepens as it approaches the coast, with a nick point about 8 km from the coast. With the tendency of the whole plains section to be degrading and the steeper coastal section, it is likely that the bedload estimated at the gorge also reaches the coast. If that were so then 360 kt/y would be reaching the coast (Hicks 1998, Table 4). This is reasonably close to Adams' (1980) estimate of 280 kt/y; however, Reinen-Hamill (1995) had to adjust the Rangitata bedload input down to only 33 kt/y in order to calibrate his model of shoreline change. Whether this was correct or an artifact of inadequacies in the model and the other assumptions and input data is hard to pin down. Thus there remains a large uncertainty on the Rangitata's present yield to the coast.

What is more certain is that the coast each side of the mouth is eroding at just over 0.3 m/y (Gibb 1978), while Reinen-Hamill's (1975) estimate of the net longshore sediment movement past the Rangitata mouth, at 134 kt/y to the north, appears reasonable in comparison to other estimates along this coast.

Again, our view on the effect of damming the river assumes that longshore transport and abrasion will remain unchanged, thus any reductions in the river input will translate directly to accelerated retreat of the cliffs and sub-tidal shoreface. If we assume that the current river input is 360 kt/yr and that this was reduced by 30 % due to damming, then for the 28 km of shore between the Rangitata and Ashburton Rivers we calculate (Appendix 1) that the current average rate of coastal erosion of 0.38 m/y would increase by 0.1 m/y to 0.48 m/y. If Reinen-Hamill's Rangitata yield of 33 kt/y is assumed, then the erosion rate would increase by only 0.01 m/y to become 0.39 m/y. Again, there may not be a 1:1 replacement of river bedload with coastal erosion if the cliff erosion process lags sediment removal by wave action, in which case the actual rates would be between current rates and those calculated above.

7.3.3 The effect of damming on Rangitata River mouth closure

There is no evidence that the Rangitata River mouth has closed historically. If a dam led to reduced flood flows then the frequency of the mouth blowing-out opposite the river would decrease and the mouth is likely to be to the north of the river more often. Kirk (1983) maintains that a flow of 45-50 m^3/s would be sufficient to keep open the the Rakaia River and observed that the Opihi River mouth closes when average flows are less than 5 m^3/s and self-opens for discharges in the range 15-20 m^3/s. On this basis, as the residual flows after damming are unlikely to be less than 20 m^3/s, the Rangitata mouth is unlikely to close. However, as for the Rakaia River, damming is likely to reduce the frequency of freshes that cause breaches of the barrier opposite the river and so it is likely to lead to prolonged periods when the mouth is offset from the river.

8 INFORMATION GAPS

8.1 Bed–level information

We were unable to locate any bed-level surveys for either the Rangitata or Rakaia Rivers as they crossed the plains. This means there is no basis for estimates of past or future bed aggradation or degradation. This situation may be compared with the relatively large amount of information for the Waimakariri and Ashburton Rivers, where cross-section information was required for stop bank design. With new technologies such as RTK GPS, digital photogrammetry, and airborne laser survey, river bed-level information can now be acquired more quickly and cost-effectively. Thus we recommend, at the least, that a network of widely spaced cross-sections be set up on the Rangitata and Rakaia rivers as they cross the plains, and these should to resurveyed every 5-10 years to gain this basic data. Recent, detailed, RTK GPS surveys of two reaches in the Rangitata River (Duncan and Hicks 2001) could be used as part of this information gathering.

8.2 Longshore sediment movement

The wide range of estimates of longshore sediment movement make it difficult to estimate the importance of present and potential dam-affected river inputs to the coastal sediment budget. The best estimated parts of the coastal budget are the rate of coastal retreat, the rate of longshore drift as measured by the sediment trapped by Timaru Harbour works, and bedload delivery by the Ashburton River. Longshore sediment movement elsewhere, coastal abrasion rates, and sediment delivery by most of the rivers are poorly known. Wave data has been collected of the Canterbury Coast in recent years, and longer-term hindcasts of deep-water waves around New Zealand based on global wind-models have been estimated by NIWA. These data could be applied to the record of gravel accumulation at Timaru Harbour to better calibrate longshore transport models. Combining these models and wave data with a wave-refraction study would show the pattern of littoral drift and drift divergence along the whole Canterbury Bight. To date, this has only been attempted for discrete segments. NIWA (Westaway et al. accepted) is currently using detailed riverbed topography before and after floods to estimate bedload transport. This method could be used to help determine bedload delivery to the coast.

8.3 Local-scale shoreline responses

Experience and shoreline modelling show that the response of a span of shore to a reduced sediment supply is rarely uniform along the affected shore; rather, an erosion wave tends to migrate downdrift. The magnitude and migration rate of the erosion wave, and the ultimate equilibrium shoreline position, can only be predicted by numerical modelling. We recommend that such a model be set up for the northern end of the Canterbury Bight. We add the proviso that the model should adequately deal with the dispersion of river sediment from the river mouths – both the GENESIS and UNIBEST models used previously have shortcoming in this area.

8.4 Flow regimes after damming

A lack of knowledge of the likely effects of irrigation dams on the flow regime make it difficult to estimate the effect of the dams on sediment transport. It is likely that each dam will affect the flow regime differently. Dams will have different capacities to store floods. In some cases, water for irrigation may be taken directly from a dam and in other cases the river will deliver water to a diversion. The possibility of hydro-power generation from a dam also complicates the task of estimating the flow regime. Nonetheless, it would be well worth generating series of synthetic dam outflows based on assumed operating scenarios, and comparing the sediment transport potential of those regimes with that of the natural regime.

8.5 Estimation of bedload transport rates

There are a number of formulae for estimating sediment transport rates (Healey 1997) and so it should be possible to estimate the effect of damming on sediment transport rates. However, they often provide widely varying rates for the same situation and there are usually very little data to use for calibration or to assist in the choice of formulae. There is also uncertainty as to whether any choice would be as good with the altered flow regime. Much of the variation may be caused by incorrect application of the equations or using inadequate input data. However, by using several relationships an understanding of the proportional reduction in bedload transport due to damming may be gained. Improved estimates of bedload transport may be able to be gained by using two-dimensional hydrodynamic models such as *2de* (Beffa 1996) with a range of flow regimes, particularly when these can be verified or at least calibrated against field measurements (as discussed in 8.1).

9 CONCLUSIONS

1. The geomorphic setting is one of high uplift rates and high rainfalls in the mountain headwaters of the major South Canterbury Rivers, resulting in relatively high rates of sediment delivery to the rivers.

2. In addition, the relatively unconsolidated beds and banks of the plains sections of the rivers allow the rivers to source and move large quantities of bed material.

3. The Rangitata River bed downstream of the gorge appears to be degrading slowly because of the steep slope of the river bed. The Ashburton River is predominantly degrading due to gravel extraction for industrial and stop banking purposes in the mid section of the plains and to coastal retreat near the coast. One section of the North Branch is rapidly aggrading because of a reduction in bed slope. The Rakaia River profile appears to be in equilibrium, although the lower section has intense braiding features characteristic of aggradation and, in common with the other two rivers, there is probably long term degradation in the reach approaching the coast due to coastal retreat.

5. Damming the rivers will cut off the bedload supply, and immediately below the dam the bed can be expected to degrade and coarsen with a tendency to meander rather than braid. Without, or with reduced, bed-destabilising floods, dry bars will vegetate.

6. Further downstream the effects will be less noticeable as the river gains bedload from its bed and banks. In the Canterbury rivers there is a large and ready supply of bed material. The dry bars may still vegetate unless there are natural or managed floods. Tributaries may well supply flow and bed material to help restore bedload movement.

7. The general tendency for degradation with dams will be moderated by the reduced capacity for sediment transport associated with the altered flow regime, which will include a reduction in mean flows and a damping of flood flows. Where gravel extraction occurs, degradation may be enhanced because of reduced bedload transport into the extraction reach.

8. Dammed rivers will supply less bed material to the coast, mainly due to the reduced transport capacity of the altered flow regime rather than to sediment trapping in the dams themselves. The contribution of river bedload to the coastal sediment budget can be significant depending on the river size in relation to the contribution from coastal erosion. While the evidence is that the wave climate is such that large quantities of coastal gravels are moved, the contribution from the rivers is important, so any reduction in bed material supply from the rivers is likely to materially effect the coastal sediment budget and increase the rate of coastal erosion.

9. There are large uncertainties in many components of the coastal sediment budget. Recent, better wave climate data offer the opportunity to model long-shore transport and reduce some of these uncertainties.

10. Damming will inhibit fish migration and mitigation measures need to be put in place.

11. The lower and more stable flows downstream of dams may improve benthic productivity and encourage sediment to settle. Flushing flows are likely to be required to mobilise fine sediment and remove nuisance algal growths to maintain current benthic and fish communities.

12. The reduction in the number and size of floods after damming will increase the stability of the river beds and encourage invasion of vegetation and change the natural character of the river and its value as a refuge for birds. Regular, planned, channel forming, "flood" releases from the dams will be required to maintain river character.

13. Before dam filling, the area to be flooded and the bed downstream of the dam need to be surveyed to allow calculation of rates of sediment accumulation in lake deltas, and to provide base information that can be used to provide a comparison with five-yearly surveys carried out to monitor downstream riverbed changes.

14. There is no bed level information that can be used to check future bed-level changes on the Rangitata or Rakaia Rivers. A system of low level monitoring needs to be established to gather this basic data.

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APPENDIX 1: Coastal budget calculations assumptions and data sources

The basis of the coastal sediment budget and the changes due to damming are given here. The assumptions are that the main inputs to the budget are bedload from rivers, material from the both the aerial parts of the cliffs and the steep near shore sub-tidal portion of the beach, and longshore transport into the study reach. The outputs from the budget are longshore drift out of the study reach and abrasion. Long-term storage in South Canterbury lagoons is assumed to be nil. The effect of the dams is assessed assuming the longshore drift and abrasion components are constant with and without dams and that any reduction in river bedload transport into a reach is replaced by accelerated erosion of the cliff including the sub-tidal portion. We also assume that the river bedload delivered to the coast is eroded at the same rate as the more consolidated cliffs to obtain a maximum rate. It is unlikely that there will be a 1:1 replacement of river bedload with coastal erosion and the actual rates will be between current rates and the calculated maximum. These assumptions eliminate the need to estimate long shore transport which is not well quantified and when modelled the results are highly dependent on the choice of a coefficient. The rate of abrasion is also poorly quantified, but it must be high as the Birdlings Flat end of Kairortete Spit is accreting only slowly.

Rakaia River to Lake Ellesmere outlet

- Bedload is estimated from Hicks (1998) estimate of suspended sediment load of 4,464 kt/y and assuming 13% bedload (mean % from Table 4 of Hicks (1998) excluding the lower Waimakariri) gives a bedload of 580 kt/y.

- Cliff erosion: for a 18.05 km reach (2 km south of South Rakaia Huts to Lake Ellesmere outlet) a cliff retreat rate of 0.63 m/y and an average cliff height of 5.8 m = 18,050*5.8*0.63*1.8 = 119 kt/y based on Gibbs (1979) erosion rates and cliff heights from Young (ECAN pers. comm.).

- Near-shore steep gravel bed erosion. Assumes 5m between the flat sandy seabed and mean sea level, a 18.05 km coastal reach and an average rate of coastal retreat of 0.63 m/y 18,050*5*0.63*1.8 = 102 kt/y.

- This gives a total input excluding longshore drift of 801 kt/y. Thus river input is 72% of the total input

Ashburton River to Rakaia River

- Bedload is taken from Hudson's (2000a) estimate of 97 kt/y degradation plus 21.6 to 27 kt/y moving through the river from upstream. (Maximum value used in the calculations).

- Cliff erosion. For the coastal segment from 2 km south of the Ashburton River mouth to Wakanui, cliff height and erosion data are from Flatman (1997). For Wakanui to 2 km south of South Rakaia Huts cliff height data from Young (ECAN pers. comm.) and erosion rates from Gibb (1979). The segment has a length of 38.04 km, a mean cliff height of 16.9 m and an erosion rate of 0.77 m/y to give an input of 891 kt/y.

- Near-shore steep gravel bed erosion. Assumes 5m between the flat sandy seabed and mean sea level, a 38.04 km coastal reach length and an average rate of coastal retreat of 0.77 m/y: 5*38,040*0.77*1.8 = 263 kt/y,

- This gives a total sediment input excluding longshore drift of 1278 kt/y. Thus river input is 10% of the total input.

Rangitata River to Ashburton River

- Bedload: 280 kt/y Adams (1980), 360 kt/y (Hicks 1998, Table 4).

- Cliff erosion: For the coastal segment from 2 km north of the Rangitata River mouth (18.3 km from the Ophi River mouth) to 2 km south of the Ashburton River mouth cliff height and erosion rate data are from Flatman (1997). For the coastal segment from 2 km south to 2 km north of the Rangitata River mouth cliff height data are from Healey (1997) and erosion rates from Gibb (1978). The segment has a length of 27.97 km, a mean cliff height of 12.01 m and an erosion rate of 0.38 m/y to give an input of 230 kt/y.

- Near-shore steep gravel bed erosion. Assumes 5m between the flat sandy seabed and mean sea level, a 27.97 km coastal reach and an average rate of coastal retreat of 0.38 m/y : 5*27,970*0.34*1.8 = 96 kt/y.

- This gives a total sediment input excluding longshore drift of ~605 to 685 kt/y. Thus river input is 46 to 53% of the total input.

Washdyke to Rangitata River

- Coastal erosion from Washdyke Lagoon to 2 km south of Rangitata River mouth. Erosion rates from Gibb (1978). Cliff height from 1:50,000 scale maps and from Benn (1987). Segment length: 26.4 km, average cliff height 7.1 m and an average retreat rate of 1.59 m/y. Erosion including the sub-tidal portion is 913 kt/y. Bedload from Opihi and Orari Rivers not estimated.