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# A GIS Approach to Model Sediment Reduction Susceptibility of Mixed Sand and Gravel Beaches

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ABSTRACT / The morphological form of mixed sand and gravel beaches is distinct, and the process/response system and complex dynamics of these beaches are not well understood. Process response models developed for pure sand or gravel beaches cannot be directly applied to these beaches. The Canterbury Bight coastline is apparently abundantly supplied with sediments from large rivers and coastal alluvial cliffs, but a large part of this coastline is experiencing long-term erosion. Sediment budget models provide little evidence to suggest sediments are stored within this system. Current sediment budget models inadequately quantify and account for the processes responsible for the patterns of erosion and accretion of this coastline. We outline a new method to extrapolate from laboratory experiments to the field using a geographical information system approach to model sediment reduction susceptibility for the Canterbury Bight. Sediment samples from ten representative sites were tumbled in a concrete mixer for an equivalent distance of 40 km. From the textural mixture and weight loss over 40 km tumbling, we applied regression techniques to generate a predictive equation for Sediment Reduction Susceptibility (SRS). We used Inverse Distance Weighting (IDW) to extrapolate the results from fifty-five sites with data on textural sediment composition to field locations with no data along the Canterbury Bight, creating a continuous sediment reductions susceptibility surface. Isolines of regular SRS intervals were then derived from the continuous surface to create a contour map of sediment reductions susceptibility for the Canterbury Bight. Results highlighted the variability in SRS along this coastline.

Coarse sediment beaches are a feature of many coastal landscapes and provide an excellent example of natural shoreline protection, acting as a highly responsive buffer between the land and the sea (Williams and Caldwell 1988, Sherman 1991). The land adjacent to these beaches may serve a number of conflicting roles from coastal defence, wildlife habitat, and recreational area to gravel resource or construction site (Zenkovich and Schwartz 1987, Randell and Fuller 2001). The remote nature of many coarse clastic, shingle or mixed sand and gravel beaches is ideal for attracting unusual and diverse wildlife and bird life, with many species unique to these habitats; their remoteness has also provided the ideal location for military installations or major civil developments (Randell and Fuller 2001).

KEY WORDS: Canterbury Bight; New Zealand; abrasion; textural sediment mixture; Inverse Distance Weighting; coastal erosion

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Mixed sand and gravel beaches of the Canterbury Bight have been identified as a separate type from either the pure sand beaches or pure gravel or shingle beaches of the United Kingdom, United States, Canada, and Australia (Bluck 1967, Hey 1967, Carter and Orford 1984, Orford and others 1991, McKay and Terich 1992, Orford and others 1996). Kirk (1980) noted that the morphological form of mixed sand and gravel beaches is distinct, as is the process/response system, and that neither the typical morphologies nor the apparently complex dynamics of these beaches were widely known or understood. Therefore, models of process and response developed for pure sand or pure gravel beaches cannot be directly applied to mixed sand and gravel beaches (Single and Hemmingsen 2001). Jennings and Schulmeister (2002) presented a tripartite classification of gravel beaches, based on morpho-dynamic properties. The three types identified were pure gravel beaches, mixed sand and gravel beaches, and composite gravel beaches. While they developed a method for discriminating between the main types of gravel beach, they were not able to determine whether the three types were part of a continuum or not (Jennings and Shulmeister 2002).

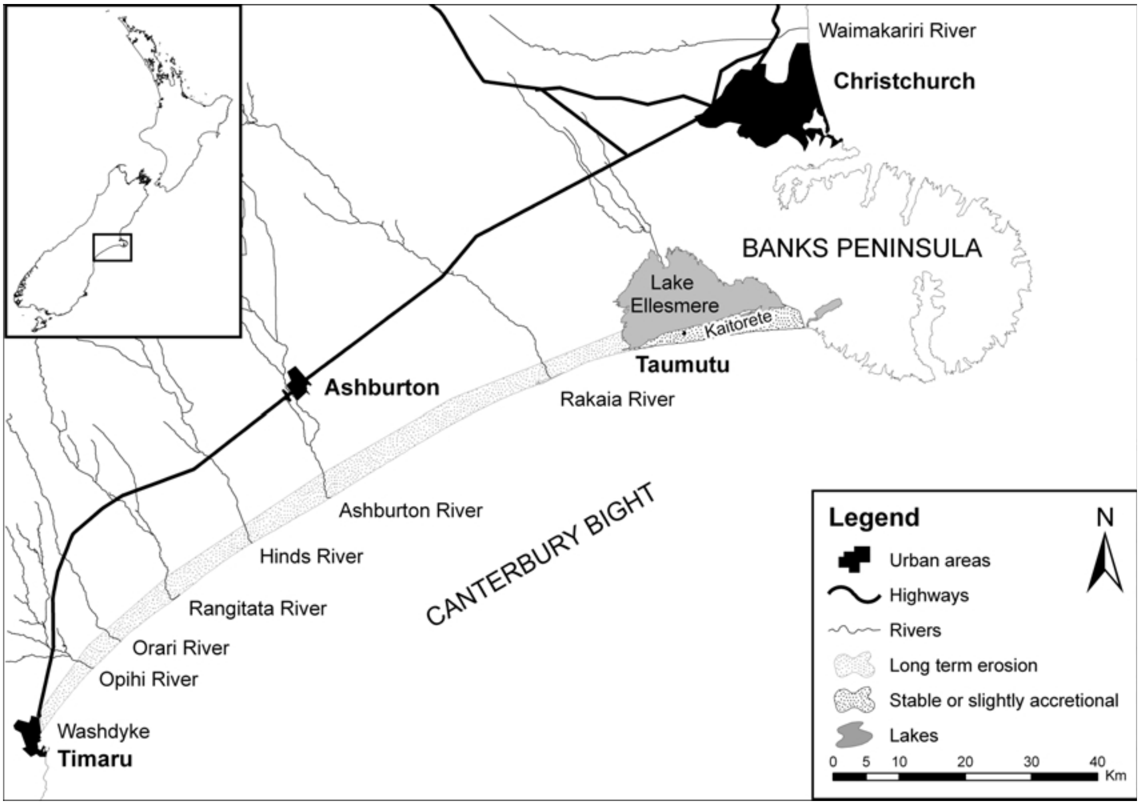


**Figure 1.** Location map showing the Canterbury Bight, South Island, New Zealand, showing the major urban areas, rivers, and lakes. The sections of the coastline that are undergoing long-term erosion or are stable are also indicated.

Nor were they able to determine what controls the development of one beach type over another. Stephenson and Brander (2003) suggested that the significance of this scheme with respect to the process regime remains to be demonstrated.

The coastline of the Canterbury Bight between Timaru and the southern end of Kaitorete Barrier at Taumutu is in a long-term erosional state over most of its length (Figure. 1). Average erosion rates reported for this coastline range between 1 to 1.5 m yr$^{-1}$ (Kirk and others 1977; Flatman 1997; Hicks 1998). The coastline is supplied with Greywacke (indurated sandstone of the Torlesse Supergroup) sediments from several large, braided rivers that drain from the rapidly eroding Southern Alps, with catchment-specific sediment yields averaging 1856 ± 261 t km$^2$yr$^{-1}$, or about ten times the world average (Griffiths 1981). However, the mean annual discharge and bedload from these Canterbury rivers varies significantly, and the large sediment loads supplied from these rivers to the coast are predominantly fine sediments transported as suspended loads (>90 %), with only a comparatively small amount of coarse bedload (<10 %) (Adams 1980, Hemmingsen 2001) (Table 1). Thus, specific sediment yields of beach nourishing material, such as coarse sand and gravels, are much lower, ranging between 10$^4$ and 10$^5$ m$^3$yr$^{-1}$ (Flatman 1997). This is particularly important for mixed sand and gravel beaches, which operate as a two-part sediment transport system, with coarse sand and gravel retained in the beaches, while fine sand is spread over the inner continental shelf (Tierney and Kirk 1978, Kirk 1992, Single and Hemmingsen 2001, Hemmingsen 2004). The mixed sand and gravel beaches of the Canterbury Bight are also supplied with sediments from unconsolidated alluvial cliffs comprised of fluvial sands and gravels of similar textural composition, comparable to contemporary sediments from the Canterbury rivers. The average erosion rate for these cliffs is 0.43 m yr$^{-1}$, and although this rate conceals the spatial and temporal variation in cliff erosion rates, cliffs contribute approximately 230,000 m$^3$yr$^{-1}$ to the Canterbury Bight coast (Flatman 1997).

The Canterbury Bight coastline is apparently abundantly supplied with beach-forming sediment, which is subsequently transported in a net northward direction to form Kaitorete Barrier (Fig. 1). However, since the 1950s, there has been little accumulation of sediment

Table 1. Mean river discharge, extreme low discharge, and estimated bedload for the main rivers of the Canterbury Bight, South Island, New Zealand

| River name | Mean flow ($m^3$/sec) | Extreme low flow ($m^3$/sec) | Bedload at outlet (kt/yr) |
|---|---|---|---|
| Rakaia | 200.0 | 68.7 | 144 |
| Ashburton | 27.6 | 2.5 | 145 |
| Hinds | 1.0 | 0.4 | - |
| Rangitata | 93.0 | 5.5 | 50 |
| Orari | 10.7 | 1.9 | 20 |
| Opihi | 19.0 | 1.6 | 71 |

Adapted from Griffiths and Glasby (1985).

at Banks Peninsula at the northern down-drift end. Currently, the 29-km-long Kaitorete Barrier is stable, or mildly accretional (Kirk 1994, Hemmingsen 2001, Hemmingsen 2004). Thus, we observe the apparent paradoxes of an abundantly supplied coastal sediment budget, a mainly eroding southern coast and a northern stable section, but no evidence of the accumulation of sediments against Banks Peninsula as might be expected with a net northward sediment transport along this coastline (Hemmingsen 2001, Hemmingsen 2004).

Coastal erosion is the result of a deficit within the sediment budget. But where does the coarse sediment go, and why are some sections of the Canterbury Bight coastline accretional, stable, or eroding? Sediment loss due to abrasion losses are the single-most unknown factor regarding mixed sand and gravel beaches (Kirk 1995, Flatman 1997, Hicks 1998, Hemmingsen 2001, Stephenson and Brander 2003). An examination of sediment budget models provided little evidence to support the hypothesis that sediments are being placed or stored anywhere within the Canterbury Bight coastal system (Kirk and others 1977, Gibb and Adams 1982, Hicks 1998). Thus, we propose that current sediment budget models inadequately quantify and account for the processes responsible for the patterns of accretion, equilibrium, and erosion of the Canterbury Bight coastline.

The reduction of sediments from mixed sand and gravel beaches is not only influenced by the size, shape, and lithology of the sediments, but also by chemical weathering effects resulting from weathering rinds and oxidation-reduction reactions (Hemmingsen 2001, Hemmingsen 2004). When attempting to account for the transport and subsequent loss of sediments from mixed sand and gravel beaches, these variables must be accounted for. By using a large number of random bulk sediment samples covering the beach profile from foreshore to backshore, containing ranges of sizes, shapes, and various degrees of weathering, Hemmingsen (2004), based on laboratory tumbler experiments, showed how one can use the textural mixture of the sediments to predict sediment size reduction due to sediment movement during transport. We use the term Sediment Reduction Susceptibility (SRS) as a term that accounts for the variation in textural composition, from both mechanical weathering and chemical decomposition of sediments, ultimately leading to an overall reduction in sediment size.

This study outlines a new method of how to apply laboratory experiments and extrapolate to field situations using a Geographical Information System (GIS), in turn providing a SRS map for the active swash-zone of the Canterbury Bight. This is achieved by relating the textural mixture of sediments to the Canterbury Bight coastline, and allows us to identify patterns in sediment particle reduction. It also differs from other sediment budget models that use average reduction rates for abrasion. This model identifies the variations in estimated loss that can be directly attributed to the textural mixture of sediments. It inherently accounts for all significant variables, such as lithology, sediment size, shape, and weathering of sediments (Hemmingsen 2004). Hence, these variables do not have to be added to the calculated loss, either individually or weighted, for the influence of each variable. Therefore, this approach is quicker and less costly than other models. Additionally, this model was developed in and for a mixed sand and gravel beach environment, whereas other models do not address this type of beach specifically (Marshall 1929; Adams 1978; Gibb and Adams 1982; Single and Hemmingsen 2001; Dornbusch and others, in press).

## Methods

### Study Area

The Canterbury Bight coastline, between Timaru and Banks Peninsula, is an area in which the coastline is geologically recent, comprised of cut and fill elements developed on vast thicknesses of alluvial gravel. The Canterbury Plains and the materials that have built them, represent unconsolidated cliffs, gullies, lowland areas and rivers, forming a physically diverse coastline along the Canterbury Bight. Alluvial gravels are capped by fine sands and extend for some distance into the Canterbury Bight. These give rise to gentle slopes on the Continental Shelf. The generally uniform offshore features influence the distribution of wave energy within the Canterbury Bight and thus are an important control on the waves and currents occurring at the beach.

### Sediment Sampling and Tumbling

Fifty-five field sites (115 samples), representative of their dominant reaches of which they were an integral part, were sampled from three positions across the profile—the swash zone just above the break-point step, the first berm at the limit of the swash zone and landward—to include material stored in the storm ridges. All samples were collected manually using a shovel (maximum depth 0.5 m, sample size from 60 to 1500 kg). Sediments were first washed in fresh water, and then dried in open trays in fan ovens at 50°C. Once dry, samples were sieved at quarter phi intervals, thereby splitting each sample into sizes ranging from −6.50 Ø (90 mm) to 4.25 Ø (0.0053 mm). Sediment sub-samples (5 kg), based on the actual cumulative size-frequency distribution of whole samples from each site, from ten of the sites (30 samples), were placed in a concrete mixer bowl (Standard Contractor's Concrete Mixer, Wylies' Brick Concrete Limited, Christchurch) fitted with two vanes equidistant within the 0.58-m-diameter bowl, and rotated at an average speed of 2.8 km $hr^{-1}$ to imitate the motion of sediments in coastal environments (Kodama 1994). The sites were selected because they represent a range of mixtures of coarse and fine materials along the beach, giving a representative sample for the Canterbury Bight. For the purpose of this experiment, the swash zone sample included only sediments from the swash zone, the mid-zone was based on cumulative frequency of both the swash sample and the lower foreshore sample, and the all inclusive sample was made up from all three positions across the beach profile. This ensured all the sediments that would be worked within each zone by wave action on the beach would be included, rather than segregated by zone (Hemmingsen 2004). With each charge of gravel, two litres of fluid were added to represent the water in the swash zone (Marshall 1928, Marshall 1929). Sediment charges were tumbled in the concrete mixer for a total distance of 40 km. Following each run (1, 5, 10, 20, and 40 km), the sediment was removed from the drum and sieved again at quarter phi intervals, and the total sample weighed once dried. This allowed us to calculate weight losses based on both sediment size and distance tumbled.

### Data Preparation and Analysis

To predict sediment reduction from textural mixture, we grouped the weights of the sieved samples into three categories: (1) pebble (−6 to −2 Ø: 4–64 mm), (2) granule (−2 to -1 Ø : 2–4 mm), and (3) sand (−1 to 4 Ø : < 2 mm) (Wentworth 1922). The contributing proportion of each category for each sample was then arcsine-square-root transformed, a transformation especially appropriate to percentages and proportions, to obtain normality (Sokal and Rohlf 1995, Zar 1999). We then applied regression techniques, using the transformed values of the pebble, granule, and sand for each sample as independent covariates, and the observed percentage loss in mass as the dependent variable. This allowed us to generate an equation to predict the SRS for all 55 sampled sites along the Canterbury Bight.

To extrapolate the results to the field, the Canterbury Bight, we established a point-grid of 5 by 57 cells in a GIS to represent the coastline from Timaru to Banks Peninsula in ArcView 3.2a (© 1992–2000 ESRI, Inc.). This grid had regular spatial intervals to allow for surface modelling and contour mapping. The core of these positions, 3 by 55 cells, were assigned the values of the calculated SRS based on the textural mixture for the three positions at each site, in the same order as the sites appear along the Canterbury Bight. The surrounding matrix of cells were assigned the values of their nearest neighbours to avoid contours created by the subsequent automated contour mapping collapsing back on themselves.

From the 5 by 57 point-grid, we created a high-resolution (25 m) smooth surface grid representing the entire sample area by Inverse Distance Weighting (IDW) using a spatial neighbourhood of four nearest neighbours. The IDW method estimates grid cell values of points with no data by averaging the values of sample data points in the vicinity of each cell, using the predictor whose form is:

$$\hat{z}\left(\chi_j\right) = \sum_{i=1}^{n} z(\chi_i) \cdot d_{ij}^{-r} / \sum_{i=1}^{n} d_{ij}^{-r} \tag{1}$$

where z is the predictor value, $x_j$ are the points where the surface to be interpolated is, $x_i$ are the data points, d is the distance from interpolation point, and r denotes the constraints placed on the interpolated neighbourhood (Burrough and McDonnell 1997). We applied isolines of regular intervals to the smooth surface grid of predicted SRS to present the sediment reduction characteristics of the Canterbury Bight. Additionally, we established a cross-sectional profile of the Canterbury Bight showing how erosion susceptibility changes with point sources of sediment supply, such as the major river outlets. From the interpolated erosion susceptibility surface, we extracted data at 25-m intervals along the length of the Canterbury Bight to calculate the mean erosion susceptibility, or calculated predicted loss rate, based on the textural mixture of sediments.

Table 2. Coefficients of determination (β) for the calculation of SRS based on the textural mixture of sediments at ten sites and three mixed sand and gravel beach-profile positions on the Canterbury Bight coastline, South Island, New Zealand ($n$ = 30)

| H/Variables | β | S.E. | $t$-value | $p$-value |
|---|---|---|---|---|
| Pebble (−6 to −2 Ø) | 2.565 | 0.501 | 5.121 | < 0.001 |
| Granule (−2 to −1 Ø) | 1.432 | 0.403 | 3.551 | 0.001 |
| Sand (−1 to 4 Ø) | 2.233 | 0.469 | 4.757 | < 0.001 |

The standard error (S.E.), $t$-value, and $p$-value also given. Model $r^2$ = 0.573. The proportions of pebbles, granules, and sand (Wentworth 1922) were arcsine-square-root transformed to obtain data normality prior to regression analysis.

## Results

Regression analysis of the textural mixture of sediment samples from ten sites, with three locations at each site, from the swash zone just above the break point step, the first berm at the limit of the swash zone, and landward to include material stored in the storm ridges, tumbled for a total distance of 40 km, explained 57.3% of the variation in the reduction of sediments (Table 2). From the coefficients of determination for the SRS, we calculated the susceptibility to sediment reduction by:

$$\sum E_{suscpt} = {}'K + (\mathrm{P}i_{pebble} \cdot \beta_{pebble}) + (\mathrm{P}i_{granule} \cdot \beta_{granule}) + (\mathrm{P}i_{sand} \cdot \beta_{sand}) \tag{2}$$

where $E_{suscpt}$ is the calculated SRS, $'k$ is a constant for the equation, $\mathrm{P}i$ $_{\text{pebble, granule, and sand}}$ are the contributing arcsine-square-root transformed constituent proportions comprising the textural sediment mixture, and β represent the coefficients of determination for the textural mixtures from the regression analysis (Table 2). The three transformed variables for explaining SRS, pebble, granule, and sand were all significant, with $p$-values of 0.001 or less (Table 2).

Figure 2 shows the SRS isolines resulting from applying Equation 2 to the point-grid of 5 by 57 cells representing the 55 sampled locations on the Canterbury Bight coastline, interpolated and extrapolated to represent the entire study area from Washdyke to Banks Peninsula. The 55 sampled sites are shown for spatial reference between the extrapolated SRS contour map and their location along the Canterbury Bight (Hemmingsen 2004). Average calculated SRS ranged from 5 to 65% by weight. The calculated susceptibility to sediment reduction increased with distance along the coast in the swash zone, from Washdyke to the Opihi River, ranging from 5 to 55%. Similarly in the backshore zone, the calculated SRS attributable to textural mixture of sediments increase with distance along the coast with the greatest losses ranging between 55 and 65%. Predicted SRS decreased in the area adjacent to the Rangitata River to a low of 5%.

Between the Rangitata and Rakaia rivers, calculated SRS attributable to textural mixture of sediments was as much as 70% (Figure. 2). An exception was the area adjacent to the Hinds River, where the calculated SRS declined to 5% by weight at the river mouth. Overall, this section of the coast retained the most homogeneous sediment mixture. From the Rakaia River to the end of the system at Banks Peninsula there were two peaks adjacent to the openings of both Waihora (Lake Ellesmere) and Wairewa (Lake Forsyth), where SRS was calculated at 65% by weight. Within this area there was a wide range in the predicted sediment losses attributable to textural mixture, particularly within the swash zone. Reduction rates decreased along the length of Kaitorete Barrier, especially in the swash zone.

Figure 3 demonstrates that the variability of SRS could be attributed to the mixture of sediment composition along the coast. A noticeable feature was the area adjacent to the coastal alluvial cliffs (central zone). In this zone, the calculated sediment reduction susceptibilities were consistently high, averaging around 65%, with the exception of the area adjacent to the Hinds River. However, this SRS was quite variable even within this zone.

The area with the greatest range was in the southern zone from Washdyke to the Rangitata River (Fig. 3). In this section some areas were particularly susceptible to reduction, whereas others were not. At the end of the southern zone, within the section of coast between the Opihi and Rangitata Rivers, were areas where SRS as low as 5% by weight were calculated. Other areas with high susceptibility to SRS occurred adjacent to the Rakaia River and proximal to the openings of both Waihora at Taumutu and Wairewa, as shown by the peaks in Figure 3.

There was an observed trend along the coastal zone, whereby SRS decreased with distance from sediment source areas (Fig. 3). This was demonstrated in the southern zone, where there was both a general trend of

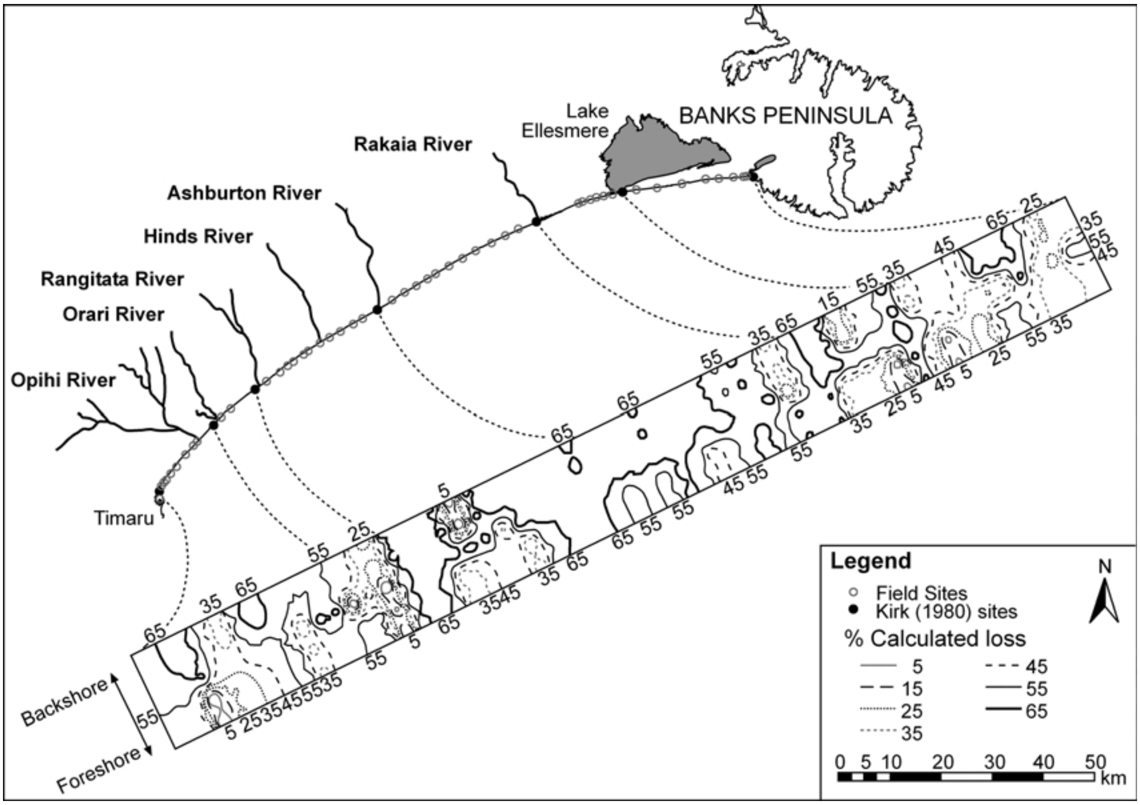


**Figure 2.** Extrapolated isolines of calculated SRS for the Canterbury Bight based on the textural mixture of sediments from 5 sites and three profile locations. The isolines were derived by applying Equation 2 to the 55 sampled sites, then using inverse distance weighting (Equation 2) to derive a 25-m resolution smooth SRS surface grid for the Canterbury Bight.

fining from Washdyke to the Rangitata River as well as the peaks and troughs adjacent to each of the other river sources. The trend was apparently disrupted along the section of coastal cliffs. However, this particular section of the Canterbury Bight provided a constant sediment supply to the coastal zone from the alluvial coastal cliffs. Additionally, the trend was repeated toward the end of the cliffed section of coast near the Rakaia River. This river is a significant source of sediment, but from here the SRS again decreased away from sediment source area. Only at Taumutu and Wairewa where sediment is sourced from the lake openings was the downward trend in SRS interrupted.

## Discussion

### The Southern Zone

In the southern zone, from Washdyke to the Rangitata River, the calculated SRS was very variable, ranging from less than 5 to over 70% by weight for a total tumbling distance of 40 km. Why is the SRS so variable in this zone of the Canterbury Bight? The area along Washdyke barrier is renourished by very fine dredge spoil from a shipping channel at Timaru Harbour (Tierney and Kirk 1978). This dredge spoil is dumped offshore and subsequently transported onshore during favourable conditions (Hemmingsen 2004). This causes the textural mixture of sediments to be dominated by fine particle sizes. The reduction of sediments is dependent on the textural mixture of the sediments. Thus, if sediments are dominated by any given size-class of sediments, or homogeneity, it will in turn reduce the susceptibility of sediment to reduction.

As the Washdyke barrier no longer receives any significant coarse sediment contributions from the south, due to an inability of the these sediments to bypass Timaru Harbour, much of the coarse material currently stored in the barrier system is highly weathered. The larger size grains were found to have well-developed weathering rinds (Hemmingsen 2004). This resulted in the material being of a poorer quality, offering little resistance to abrasive processes and thereby making these sediments more susceptible to size reduction.

The area in the middle section of the barrier showed more resistance to reduction than the sedi-

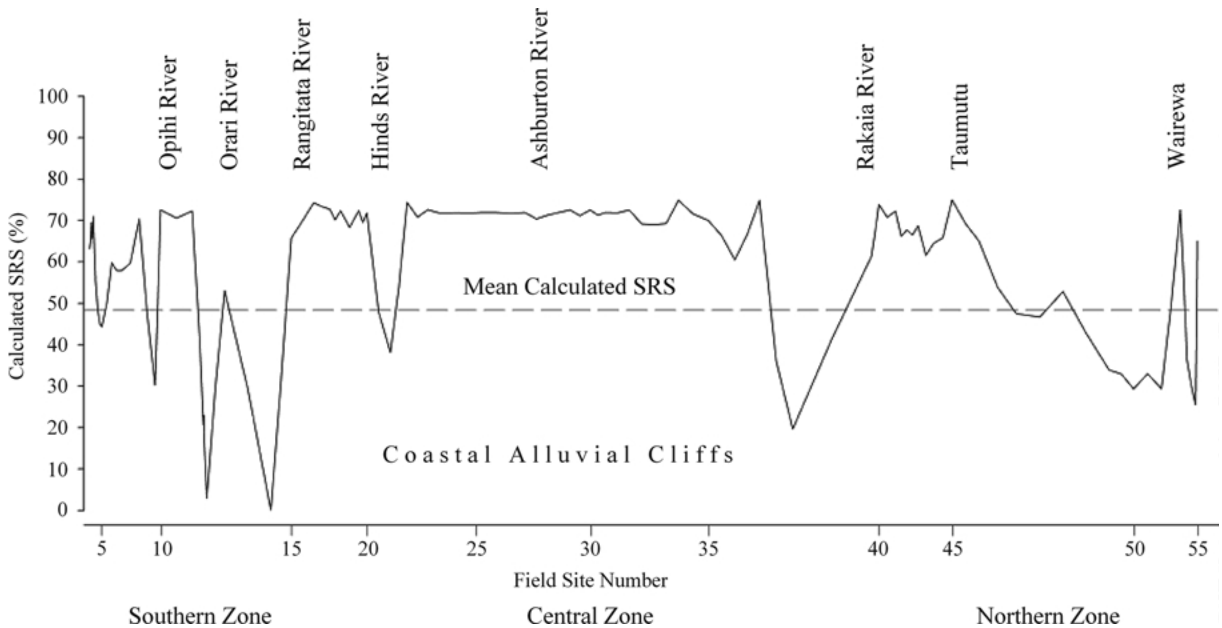


**Figure 3.** SRS profile for the Canterbury Bight, derived by extracting values from the 25-m resolution SRS surface grid. The location of the 55 sampled sites, the major Canterbury Bight rivers, and location of the coastal alluvial cliffs are illustrated.

ments in the swash zone and backshore. The sediments in this area of the profile were the remnants of the renourishment programme that ended in 1985 (Kirk and Weaver 1985, Kirk 1992).

### The Central Zone

The central zone, between the Rangitata River and Taumutu, included three large rivers and the eroding coastal alluvial gravel cliffs. This zone was the most homogeneous of the three zones of the Canterbury Bight. This was not surprising as this section of the coast is dominated by the continuous line source of the alluvial cliffs. The susceptibility of sediment to reduction in the central zone was as much as 70% by weight along the full length of these cliffs. The cliffed section is, therefore, contributing a large amount of sediment to the coastal system just to maintain the coastline against its susceptibility to reduction. Even sediment added to the system by the Ashburton River does little to alter the susceptibility to reduction in this area. An exception was the area adjacent to the Hinds River. The rapid decrease in susceptibility to reduction at the river mouth emphasised the importance of textural mixture (Hemmingsen 2004). Thus, it is not just the amount of sediment being delivered to the coast at this site, but the size composition of this material that was influencing the reduction susceptibility.

The influence of the Rakaia River lowered the susceptibility of sediments to size reduction. The importance of sediment inputs was illustrated in Figure 3 whereby a decrease in the susceptibility of sediments to reduction alongshore was observed. An increased susceptibility of sediments to reduction to the north of the river was due to the large grain sizes that were rapidly reduced to finer particle sizes. Impact forces were the dominant processes of reduction in this area of the Canterbury Bight. The textural mixture of the sediments in this zone were dominated by larger grain sizes, which resulted in the rapid destruction of the smaller grain sizes within the mixture.

The area between the Rakaia River and Taumutu showed some variation in the susceptibility of sediments to reduction. This may be due to piped outfalls that contributed small localised inputs of predominantly finer sediments from the adjacent hinterland (Hemmingsen 2004). However, in the area adjacent to the artificial lake opening susceptibility to reduction increased again due to a change in the textural mixture. This is important as the effects at this site were not only dominated by the effects of waves, but also by anthropogenic influences, by altering the structure of the barrier, and thus the textural mixture at this site.

### The Northern Zone

The influence of artificial lake openings was also apparent in the northern zone, adjacent to Wairewa. The northern zone extends from Taumutu and along Kaitorete Barrier to the end of the system adjacent to

Banks Peninsula. As shown in Figure 3, this section had only two significant peaks, one in the middle of the barrier, identified as an outlet through Kaitorete Barrier during the Holocene (Holmes 1998, Hemmingsen 2004), when the Waimakariri River avulsed from its present channel north of Banks Peninsula to the south where it discharged into Waihora. The other peak was just before the artificial opening at Wairewa where susceptibility of sediments to reduction declined to 25%. Susceptibility of sediments to reduction subsequently increased again to 55% adjacent to Banks Peninsula. This could be accounted for by the sediments reaching the end of the coastal beach system. The coarse sediments can travel no further, therefore sediments remain at this site until they are eventually destroyed by reduction processes. The fine material, which is the product of reduction, is constantly being removed from the system as fine sands and silts transported on to the continental shelf and around Banks Peninsula on to the Banner Bank by littoral drift (Stephenson and Shulmeister 1999, Hemmingsen 2004).

On average, susceptibility of sediments to reduction decreased along the length of Kaitorete Barrier, especially in the swash zone. The Rakaia River comprised the nearest significant input into the coastal system, and sediments were being reduced and decreased in size from this point-source. As the textural mixture changed, the susceptibility of sediments to reduction declined, finer sediments started to dominate the mixture, and the beaches became flatter and wider. However, the beaches became coarser and steeper again at the end of the system, where the susceptibility of sediment to reduction increased. The down-drift end of the beach is a texturally disorganised zone, not dissimilar to Washdyke at the beginning of the system, due to the range of sediment sizes being transported. Transport rates were also very different at this end of the system, where the beaches are swash aligned; therefore, the longshore component of the littoral drift no longer dominated the direction of sediment movement alongshore.

### Management Implications and Further Studies

By using a few representative sample sites along the Canterbury Bight, we used a GIS to extrapolate SRS to the entire study area. This approach offered some advantages over other methodologies, such as sediment budgets. Firstly, the method is rapid and cost-effective. By basing the model on actual sampled sites, and using IDW to extrapolate to un-sampled sites, we were able to extract patterns of SRS to the entire Canterbury Bight, showing definite patterns associated with point-sources of sediment input from rivers, as well as line-sources from coastal alluvial cliffs. Secondly, our methodology goes some way to remove the inaccuracies associated with sediment budget models where sediment inputs and outputs are not always known or accurately quantified. Previously, abrasion rates on the Canterbury Bight have been calculated as the difference between inputs and outputs, ranging from 10,000 $m^3yr^{-1}$ (Hicks 1994) to 983,000 $m^3yr^{-1}$ (Gibb and Adams 1982). Thirdly, this approach removes the need for coastal consultants to use average rates of abrasion, which are not always representative of actual sites and ignores variations in susceptibility to sediment reduction. The current literature does not identify variations in susceptibility to sediment reduction within the mixed sand and gravel coastal beach system of the Canterbury Bight.

Sediment budgets for any coastal environment can only ever be as good as the accuracy of the data being used. The limitations of sediment budget studies and modelling of mixed sand and gravel beaches have been acknowledged by Hicks (1994). He suggested that what was really required for the study of the shoreline of the Canterbury Bight was a model that dynamically incorporates the rollover and abrasion processes as well as the littoral drift (Hicks 1994). The GIS approach to model SRS could potentially be used in conjunction with studies of sediment transport to develop this contemporary dynamic model for sediment displacement on mixed sand and gravel beaches, in turn giving a solution to the apparent paradox of a lack of sediment buildup at the down-drift end of the coastline.

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