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Project: Regional Shingle Sediment Budget Report

Appendix

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01	-	Draft Report for Consultation	J. Clarke
02	01	Final Report	J. Clarke

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Appendix A – Sediment Budget Methodology

A sediment budget is essential in defining longshore sediment transport rates, sediment pathways and areas of erosion and accretion, within defined boundaries, over a given period in time (Kana, 1995). The budget provides transparent and quantitative evidence of beach losses, gains and sediment pathways, in combination with both natural and artificial movements of beach grade material. The outcomes of this report will feed into Beach Management Plans (BMP). The report predominately focuses on the shingle sediment movement, as this has the most importance to beach management operations.

The sediment budget is analysed over a range of spatial scales. Each spatial scale has been assigned a level relating to how much detail is provided, as shown below:

Level 1 – Very-fine analysis polygons
Level 2 – Fine analysis polygons
Level 3 – Coarse Sediment Budget
Level 4 – Regional Sediment Budget

The method for the production of the sediment budget is discussed in detail in this Appendix. The transparent and repeatable methods will allow future budgets to be conducted and analysed using the same techniques developed here. The limitations and solutions in the methodology have been highlighted at the relevant stages and justifications made wherever possible.

i. Volumetric Change

Beach surfaces were combined to create, where possible, continuous terrain models (gridded at 1m) across the whole frontage of the budget. Terrestrial grids were chosen preferentially to LiDAR due to the tailored nature of the surveys and the greater accuracy of collection. Coverage in certain areas, particularly around cliffs was found to be very poor. The possibility to produce DTM's based on SRCMP Beach Profiles was explored but was considered to contain too many variables in calculating volumes from cross sections. For example frontages where the spacing, orientation and position of control structures, the assumptions involved would be such that interpolating between profiles will result in an unrepresentative surface. The DTM's that are available are shown in the report in Table 3.1.

With the compiled DTM's from all available survey years, it is possible create difference models from which volumetric change between two surveys can be calculated. Negative values represent erosion that has occurred between Year A and Year B, and positive values indicate accretion. Whilst these figures show an overall change in beach volume within each discrete section, it should be recognised that the data is based on the BMP survey, which is undertaken once each year. It is therefore only a snapshot of one moment in time, and the particular dynamics of each frontage need to be taken into account. This means that the detail is often dominated by cross shore changes (E.g. Figure 1) but by integrating all changes over a certain length of beach net changes can be established. Difference models were created with each available DTM to obtain annual change over the last 9 or so years. Where gaps in the DTM's exist, difference models cannot be calculated. Instead difference models are calculated over multiple years. For example, where the 2004 data set is missing, a difference model of 2005-2003 was created. Whilst this is not ideal, it provides the most reliable method of calculating the annual change on a frontage with incomplete data sets.

Figure 1 Example of cross-shore beach change

As stated before, the report primarily deals with losses and gains in shingle rather than fine sediment. Therefore, locations where there was a predominately fine grain size were not included and not attempted to be balanced. These are taken as a case by case example and analysed in the main body of the report.

ii. Volumetric Change per 50m Length (Level 1)

Analysis of volumetric change was also undertaken at a much finer level (Level 1). The frontages were split into 50m wide polygons and analysed for volumetric change using the difference models (Figure 2). These can be combined to visually represent beach volumetric change shown in the diagrams below. Contour plots were generated through Matlab scripts. Volumetric change in each polygon over each time scale were arranged into a matrix. A contour plot was generated through utilising the matrix as a set of Cartesian coordinates.

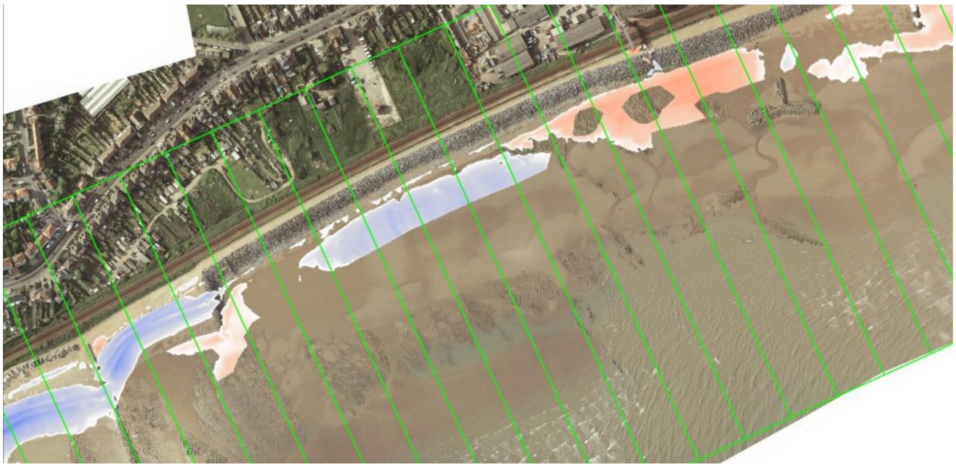


Figure 2 50m wide polygons at Bulverhythe, East Sussex

How to read spatio-temporal graphs

Spatio-temporal graphs are used to display three variables in one graph.

- The x-axis shows a distance alongshore (either as an actual distance in metres or kilometres or as an increasing number relating to the polygon used in its calculation)
- The y-axis shows time usually in years
- The z-axis shows the cumulative volumetric change. This is shown as a surface which is interpolated between the actual data points which are at the intersection of each x and y axis unit. Two contour plots are provided as follows:
  - *Year on year contour plot* – The year on year contour plot shows the volumetric change compared to the previous survey (unrelated to previous trends). This provides a valuable indication of the variability around the longer term trend.
  - *Cumulative contour plot* – The cumulative contour plot shows the cumulative change of the beach in each polygon compared to the 2003 baseline. This shows the overall trend at each location.

Examples of their use are provided below.

Example 1 – Natural Beach Change

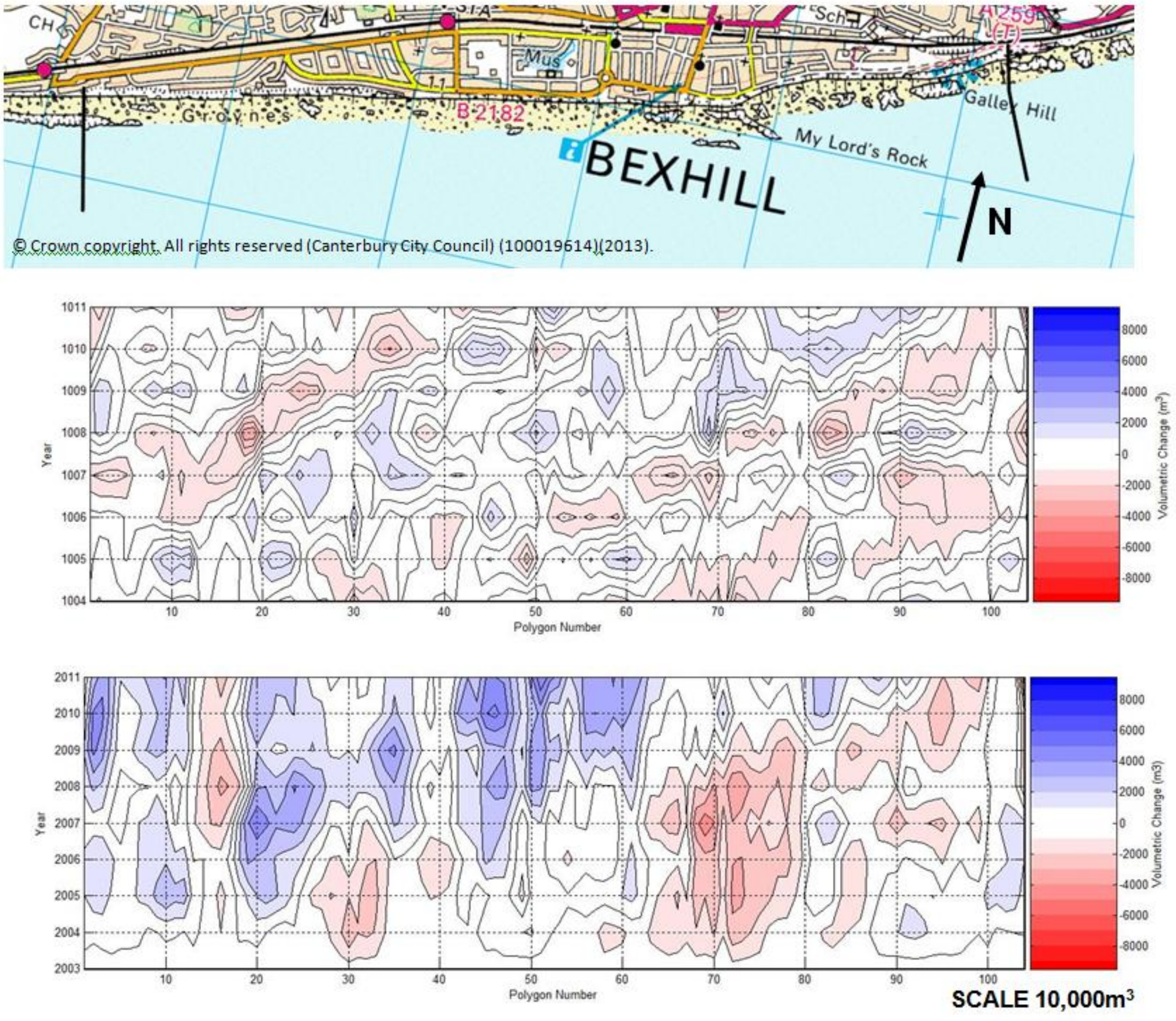


Figure 3 Volumetric change contour plot (Natural Change)

Reading temporal change: Volumetric change through time at a certain location is read off by following a vertical line. Taking polygon number 60 as an example, volumes decreased from 2003 to 2004 by ~1,000m^3 but then increase by ~2,000m^3 to 2005. This produces the cumulative total showing a volume of ~1,000m^3 above the 2003 base line. During 2006 and 2007 volumes stay slightly above the levels for 2003 but starting in 2008 it began to increase steadily (~2000m^3 in 2009, >2500m^3 in 2010 and close to 3000m^3 in 2011). The overall interpretation is one of stability between 2003 and 2007 and one of increasing volumes from 2008 to 2011. A second example is Polygon 16 which has been stable between 2003 and 2006, then dropped by ~3,500m^3 over two years and has since then been relatively stable at levels below 2003.

Reading spatial change: Change along the coast is read off by following a horizontal line. For example, in 2005, polygons 1 to 14 contained more beach than in 2003, 14 to 17 contained a bit less, 18 to 25 a bit more and the analysis can be continued for the whole unit.

Reading the spatio-temporal change: With the exception of polygons 14 to 17 all polygons up to 93 have started to gain material over the period from 2003 to 2011 and are now at or above the 2003 level. The increase started first in polygons 1 to 25 with some between 25 and 93 first loosing material below the 2003 level. Those furthest to the east have lost more for longer or stayed below the 2003 volumes for longer.

Interpretation: Sediment entering from the updrift cell has progressively filled the groyne bays from west to east. As the groyne bays have filled up they no longer increase in volume and material is passed on eastwards more quickly. At the same time in the early part of this assessment (up to 2006 around polygon 30, up to 2008 around polygon 70), longshore transport has continued to remove material from these groyne bays, first at a rate greater that the supply from the west (decreasing volumes) and later at a rate similar to the supply (maintaining lower volumes than in 2003). However the input from updrift started to exceed the removal downdrift and so these polygons filled up to now contain as much or more material than in 2003. Notable are polygons 14-17 which despite of large volumes moving across, there does not seem to be accommodation space to retain as much material as in 2003 This suggests that the volumes found there in 2003 must have resulted from some artificial placing or that the holding capacity was reduced by e.g. removing groyne planks after 2003.

Example 2 – Management Interventions

This example highlights the effect of management interventions on the spatio-temporal plots. Around polygon 5 there is a sudden increase in volumes between 2006 and 2007 following recharge on the updrift frontage. Since 2007 this area has remained stable. Polygon 82 has increased steadily from 2003 to 2008. Between the 2008 and 2009 survey, material was recycled from polygon 82 to 61/62. This results in the former turning red and the later turning blue. Over time the beach material deposited in polygons 61/62 has reduced over the following two years and spread out into polygons 66 – 72. Overall the location of below 2003 beach volumes has shifted from polygons 0 - 25 to 30-55.

Figure 4 Volumetric change contour plot (management interventions)

The data used to generate these plots is shown with the overview plot for the length of the sediment budget (Figure 5). Each dot on the graph represents one data point. Where gaps in the data exist e.g. in 2004 at Winchelsea, the trend is interpolated from the next available difference model and divided by the number of years of the calculation. This allows correlation between changes shown in the contour plots and whether this is due to actual recorded data, or interpolated data between two known points.

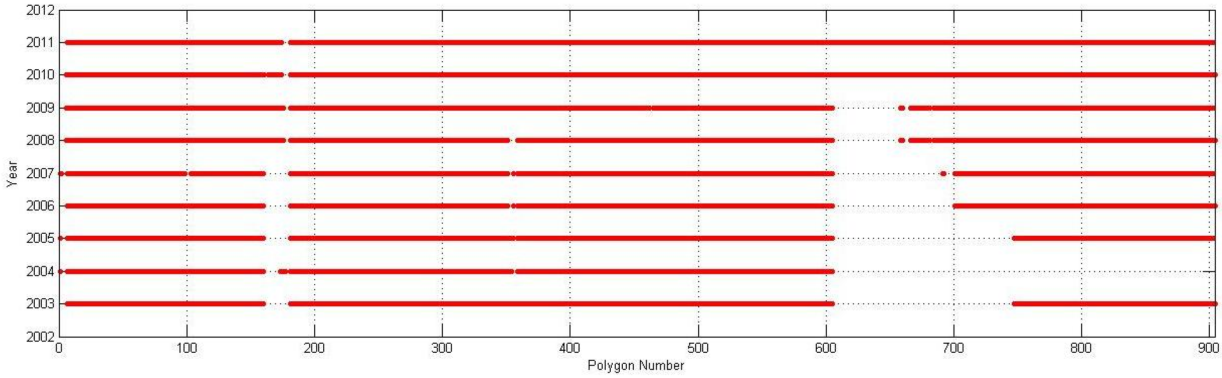


Figure 5 Sample availability plot

iii Total Volumetric Change and Average Annual Volumetric Change (Level 2)

Difference models for all available years were analysed for volumetric change through analysis polygons at Level 2. Where available, SRCMP polygons were used as they were known to be created around coastal defence, coastal processes and have boundaries at terminal structures. In locations where no polygons had been designated, a new set of polygons were created based on similar coastal behaviour, change in coastline orientation and the presence of coastal defence. These polygons were populated with the annual change from the difference models.

Initially, volumetric change was totalled and divided by the number of survey years to create the average annual volumetric change within each polygon (*Method 1*). Analysis of these results brought the reliability into question. For example Polygons that were known to significantly accrete showed minimal changes, while those known to be fairly stable showed larger than expected changes. This can be explained when looking at the coverage of each survey.

Consider a hypothetical 1x1m grid (Figure 6) losing 1m of beach over the whole extent, or $1m^3$, each year. If in 2004 the whole of this grid is surveyed then a loss of $1m^3$ is recorded, Figure 1. If in 2005, only 75% of this grid is surveyed then a loss of $0.75m^3$ is recorded. Equally if in 2006 only 50% of the grid was surveyed then a loss of $0.5m^3$ is recorded, highlighting the importance of the coverage in identifying a known volumetric change (Figure 6). If any of the survey years have a particularly poor coverage then volumetric change will be an unrepresentative figure of the actual change occurring within the polygon.

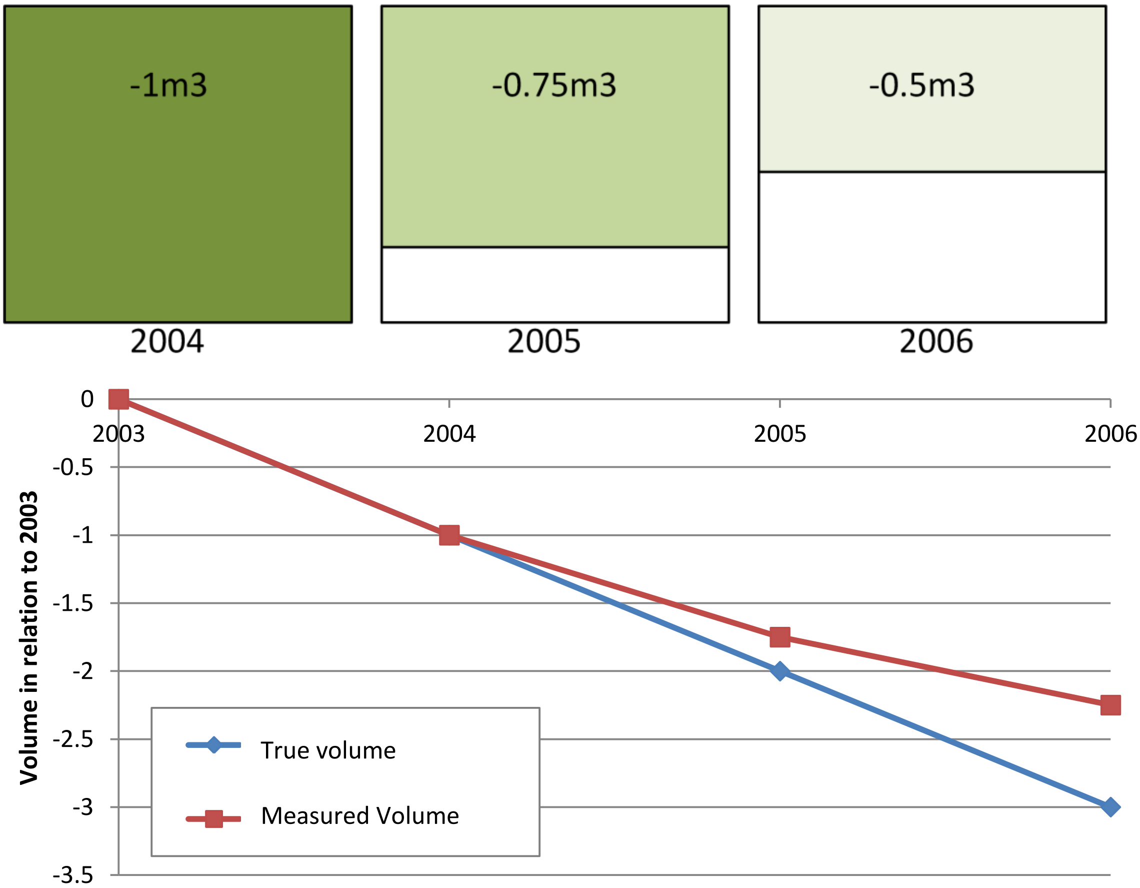


Figure 6: (Top) Schematic changes in beach volume depending on survey coverage; (bottom) Measured and true volume changes in relation to survey coverage.

By subtracting the most recent DTM from the oldest DTM, the total volumetric change over a given period can be calculated (Method 2). However, if the coverage in either year is poor then the change may be smaller than expected. In the example above if 2006 was subtracted from 2004 an annual change of -0.5m^3/yr would be calculated, lower than in reality.

One possible solution is to reduce the size of the polygons to a common extent (Figure 7) of all surveys (Method 3). However, this provides a significant problem in potentially excluding actual beach change. Smaller volumetric changes will be recorded and so this method was not seriously considered.

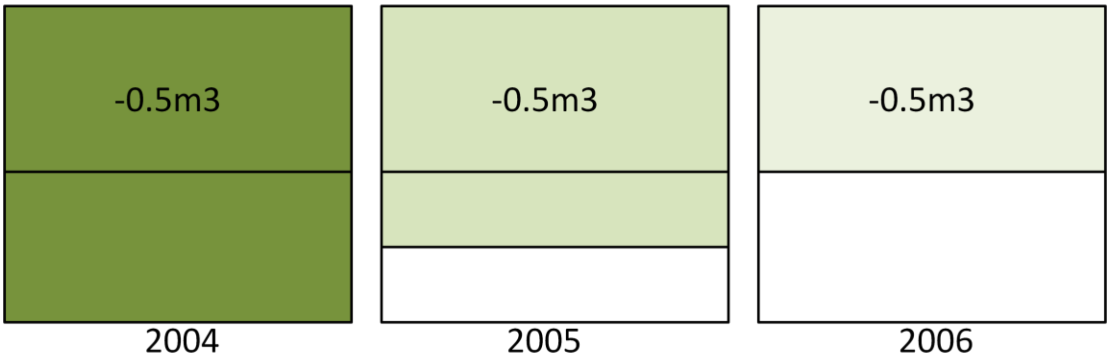


Figure 7 Examples of constrained polygons in differing survey coverage

A fourth approach is to combine survey extents from several years.

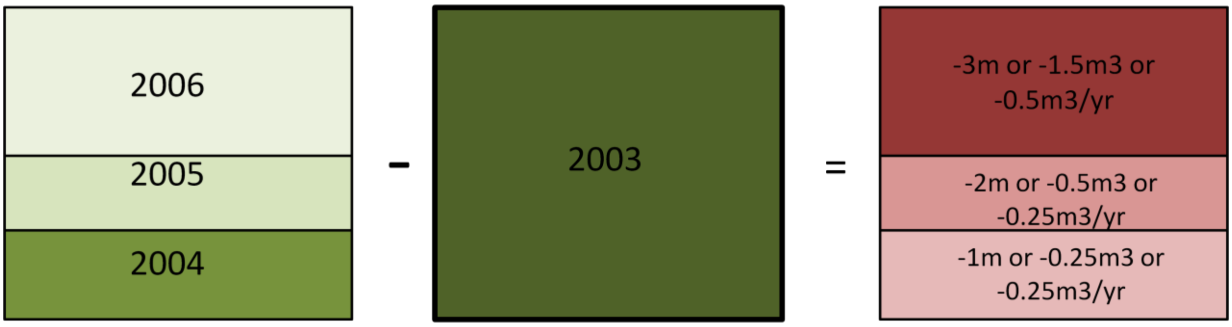


Figure 8 Examples of Spliced DTMs creating Difference Models

Data from 2003 was stamped onto 2004, onto 2005 etc. to create the baseline DTM, while data from 2011 was stamped onto 2010, onto 2009 etc. to create the most recent DTM. A difference model was run and the volumetric change polygons were populated to produce the volumetric change over the 2011-2003 period. By stamping grids on top of each other, the volumetric change over the greatest temporal range is calculated. Where this is not available, it reverts to the next available DTM calculating the volumetric change over that time scale. In the example above, the stamped DGM yields an annual volumetric change of -1m^3/yr. Although this is a highly idealised example, this is the best way to ensure that all survey extents remain the same and thus increase the reliability of the final values of annual volumetric change.

Table 1 Examples of different methods of calculation of total volumetric change

Polygon Number		TOTAL VOLUMETRIC CHANGE m^3		
Method of Calculation	**Method 1: Average all difference models**	**Method 2: 2011DTM – 2003DTM**	**Method 4: 2011DTM – 2003DTM SPLICED**	**Method 5: 2011DTM SPLICED – 2003DTM SPLICED**
1	89,241	84,724	95,071	93,944
2	-14,417	-12,626	-12,347	-12,324
3	48,136	40,309	48,398	51,110
4	-8,026	-2,838	-4,278	-4,470
5	52,035	44,902	51,778	52,300
6	-49,898	-28,091	-31,238	-43,412
7	52,874	48,416	59,318	59,563
8	-48,231	-16,127	-46,555	-46,496
9	8,422	266	-431	-881
Total	**130,136**	**158,935**	**159,716**	**149,334**

The differences between methods of calculation are shown for Winchelsea, East Sussex in Table 1. There is a significant variation in the volumetric change over all methods. However, the greatest confidence in results is obtained from Method 5, due to the limited effects of inconsistent survey coverage. The effects of this are visually displayed in Figure 4 at Rye Harbour (Polygon 9). The 2011 DTM is surveyed to 30m off the beach toe and has complete coverage of the beach. However the 2003 DTM has minimal foreshore coverage and has a portion removed due to limited access. When difference models are calculated through Method 2 and Method 5, the explanation for the different values for volumetric change is clearly evident. The Method 2 difference model excludes all foreshore losses explaining why a net gain was recorded. Using Method 5, the missing data is automatically infilled with the 2004 data set helping to fill in the annual volumetric change. This provides justification for the selection of Method 5 to produce the volumetric change. Method 5 was employed over the whole frontage to produce total volumetric change. Divided by the number of survey years yields the annual volumetric change which can be used to generate the sediment budget.

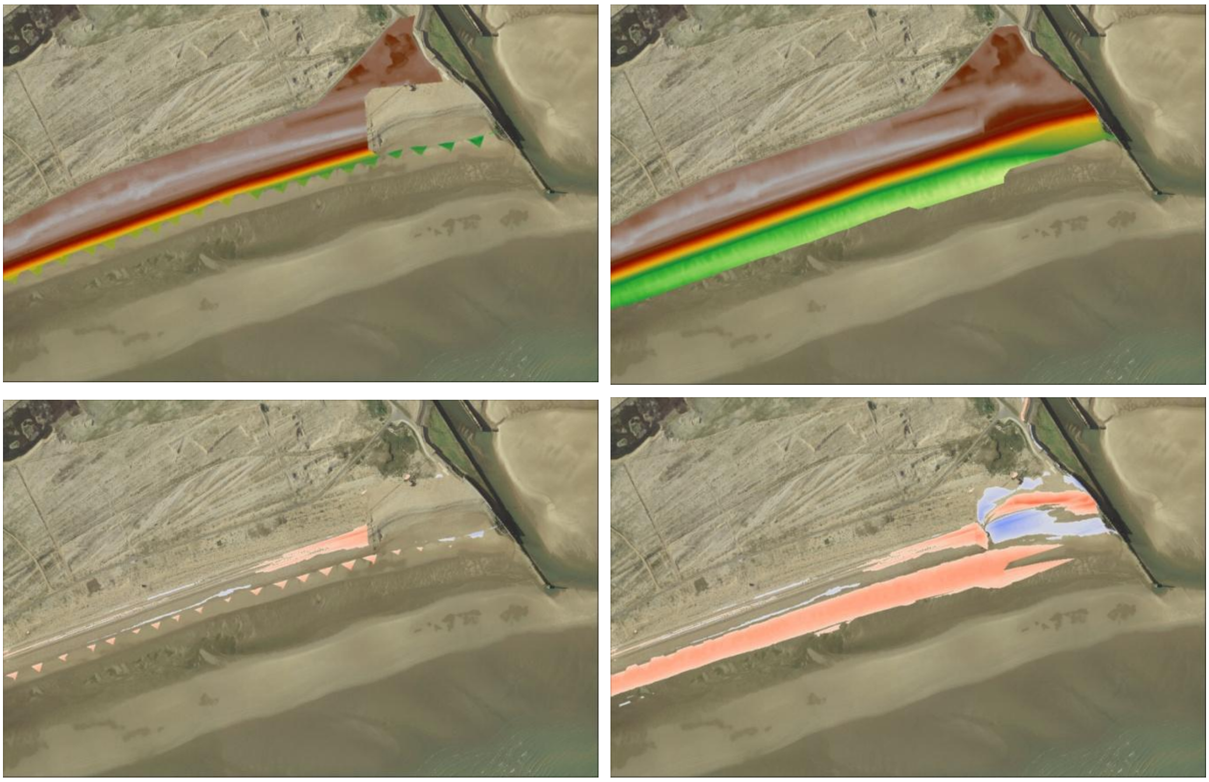


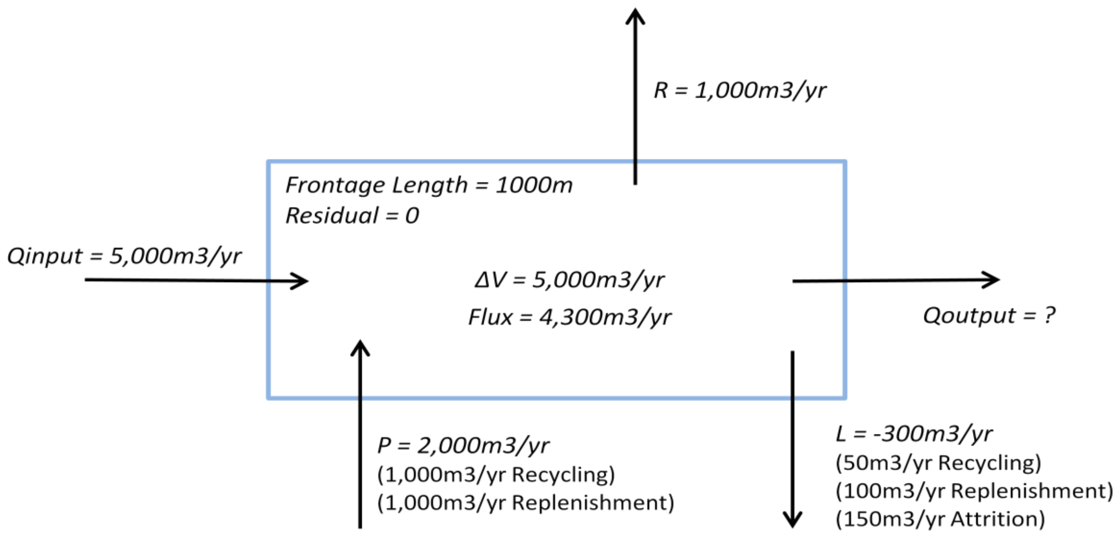
Figure 9 Examples of Poor survey Coverage from Rye Harbour, East Sussex (Top left - 2003 DTM, poor coverage; Top right - 2011 DTM, good coverage; Bottom left - 2011-2003 Difference Model; Bottom right - 2011DTM (spliced with all survey years)- 2003DTM (spliced with all survey years)

iv. Sample Balancing of a Cell

Examples of how cells have been balanced are provided below to supplement Plates 1 and 2.

Accretive Cell

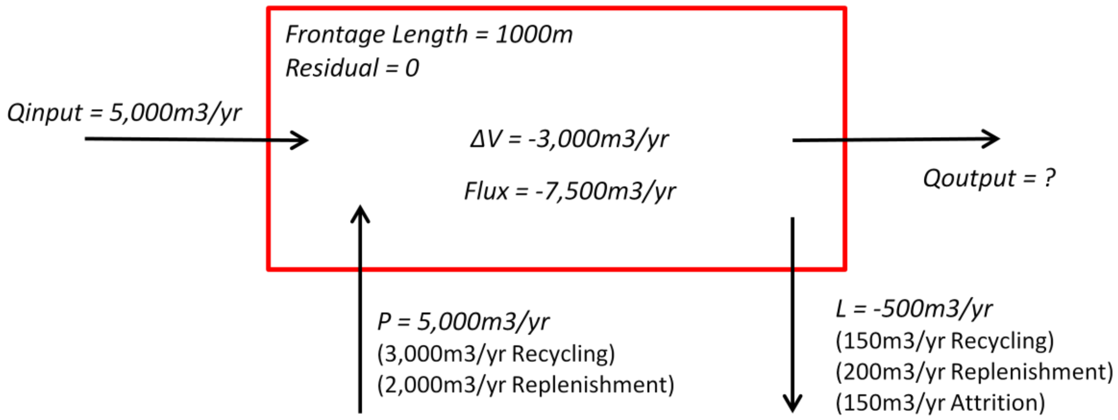
This cell is known to accrete 5,000m^3/yr based on the volume changes calculated between two surveys a year apart. 5000m^3/yr enters the cell from updrift; 2,000m^3/yr is placed into the cell through a combination of recharge and recycling; 1,000m^3/yr is removed through recycling and 200m^3/year is lost through other processes (see further below). This gives the cell a natural volumetric change or annual flux of 4,200m^3/yr ($\Delta V - P + R - L$). The annual flux can be thought of as the volume of sediment that the individual cell contributes (when negative) or takes out (when positive) of the sediment system. Comparing the 4,200m^3/yr gain with the 5,000m^3/year difference in surveyed volume means that 800m^3/yr are leaving the cell on the downdrift end. is sourced from the 5,000m^3/yr entering the cell, yielding an output volume of 800m^3/yr.



When Residual = 0:

$$Qoutput = -(\Delta V - P + R - L) + Qinput$$
$$Qoutput = -(5{,}000 - 2{,}000 + 1{,}000 - -200) + 5{,}000$$
$$Qoutput = 700m3/yr$$

Erosive Cell



When Residual = 0:

$$Qoutput = -(\Delta V - P + R - L) + Qinput$$
$$Qoutput = -(-3{,}000 - 5{,}000 - -500) + 5{,}000$$
$$Qoutput = 12{,}500m3/yr$$

Figure 10 Example balancing of cells

The cell is reducing in volume between two surveys by 3000m^3/yr. Again, 5000m^3/yr enters the cell from updrift and 5000m^3/yr is deposited on the frontage through beach management operations. With annual losses of 500m^3, this yields the flux of -9,500m^3, or 9,500m3/yr is added to the sediment system. this yields the Q_{output} of 12,500m^3/yr into the downdrift cell

v. Assumed losses

Losses expected on this frontage can be broadly split into three categories, attritional losses, replenishment losses and recycling losses. Offshore losses are not considered significant due to the predominance of coarse grained sediments on the study site and the topography and geomorphology of the beaches. The losses associated with shingle abrasion have received relatively little research over the past 60 years with no reliable relationships being drawn. Dornbusch et al. (2003) calculated losses equal to 0.225m^3/m/yr for Telscombe beach and 0.176m^3/m/yr for Saltdean Beach based on measurements over a two-year period. These frontages located in East Sussex are similar in geomorphology and sediment type to the beaches at the study site. In the absence of other data, these figures remain the best attempt at quantifying the losses expected from abrasion of shingle. The value of 0.15m^3/m/year was applied to all frontages to account for the expected losses to attrition based on published and additional unpublished data.

During placement of beach material, losses are to be expected:

- Un-sorted material placed on a beach face, contains a portion of fines. Excess fine material (when interstices are full) is washed out.
- Beach volume is also lost through compaction of the sediment following placement. This is particularly the case when material is tipped onto the beach from land based plant.
- In locations with open void defence structures (rock revetments or groynes) beach volume is lost as the material fills interstitial voids in coastal defence structures.

For example, a capital replenishment at Whitstable, North Kent of 70,000m^3 saw a loss of 14.8% over the first year and Eastbourne, East Sussex lost 22.2% of its 140,000m^3 capital replenishment in the first three months after the scheme was completed in April 2011. As a general rule, coastal engineers design replenishment schemes with expected losses in the order of 20% (Clarke and Brooks, 2008). As a proportion of this volume is expected to be transported in the direction of the dominant drift direction (and so accounted for within the sediment budget), a conservative estimate of 10% was applied to all replenishment schemes.

Due to the sorting of sediments, beach recycling typically experiences smaller losses due to the inclusion of only interstitial fines. Nevertheless, during extraction, beach material will increase in volume as sediments are mobilised and loose volume on deposition due to settlement and compaction. This loss can be seen at Hastings during the placement of 15,318m^3 of recycled material in the Spring of 2009. The preceding SRCMP survey showed a loss of 1,360m^3, or 9%, over the next few months. Therefore, a loss of 5% is applied to each beach recycling event. These assumptions have been based on the best available information in combination with best practice and engineering judgement. The losses applied to each frontage are summarised in the table below:

Table 2 Losses to a sediment cell

Source of Loss	Loss	Reference
Attrition	0.15m^3/m/year	Dornbusch et al. 2003
Losses during replenishment	10%	Clarke and Brooks 2008
Losses during recycling	5%	Clarke and Brooks 2008

Appendix B – Beach Volume Calculation

Naturally, actual beach volume cannot be calculated from the volume of the DTM alone. Beaches are typically underlain by sand, clay or rock at varying levels both along and across the beach. Therefore, calculations of the total beach volumes are dependent on the assumption of the shape and level of the basal boundary. There is very little available information on these levels across the study area.

As an example, clay levels have been explored through several studies at Whitstable showing a weak relationship between the beach toe elevation, beach width and clay level at the sea wall.

$$Clay\ height\ at\ sea\ wall = (\tan\alpha\ .\ Beach\ width) + Beach\ toe\ elevation \qquad (1)$$

Where α = 2.311° at Whitstable, used on all frontages.

When applied to frontages on the south coast, this produced substrate volumes of roughly half the DTM volume. Whilst this could be considered conceivable, a problem arises on particularly accretive or erosive frontages. As a frontage continues to erode it will rarely erode into the substrate, in part because the substrate is sufficiently protected by a layer of beach. Applying a substrate volume of half the DTM volume on an erosive frontage resulted in substrate volumes far greater than the DTM volume. Without data for trial holes on the South Coast, estimating the volume of the substrate under layer based on data from Whitstable is too large an assumption.

Therefore, it was decided to provide the volume of the DTM above the beach toe, as an indication of the beach volume, although this is likely to contain a portion of the underlying substrate. Therefore, a reference DTM was created at the beach toe elevation at each study site. A difference model was generated so that all beach above this reference DTM was considered to be a combination of small amounts of substrate and beach grade sediment to form the total volume calculated.

Appendix C – Historic Beach Volumetric Change

A historic volumetric change analysis was undertaken to infer longer term trends, as well as providing a comparison to the more detailed trends explored in the sediment budget. Mean High Water (MHW), Mean Low Water (MLW), beach toe (the change in map signature between shingle and sand/mud/rock) and back of the beach lines were digitized from historical maps from the 1890's, 1910's and 1930's. Digitizing MHW and MLW was straight forward, with lines drawn on the historical maps. However, it was often difficult to determine where the back of beach was located on a natural coast not backed by cliffs or seawalls. This provided a human interpretation error which could potentially provide erroneous results. To limit this, the back of beach line was drawn by one person and the choices kept consistent on each map. This should keep the error consistent over the three mapping years which should limit the impact on the volumetric change analysis.

For example, in the images shown here at Winchelsea, East Sussex, the decision to take the back of beach line at the border between the footpath and the main beach was taken. This was kept consistent over the three mapping years (1930 – pink; 1910 – blue and 1890 – green) so that the human interpretation error was kept consistent throughout the entire procedure.

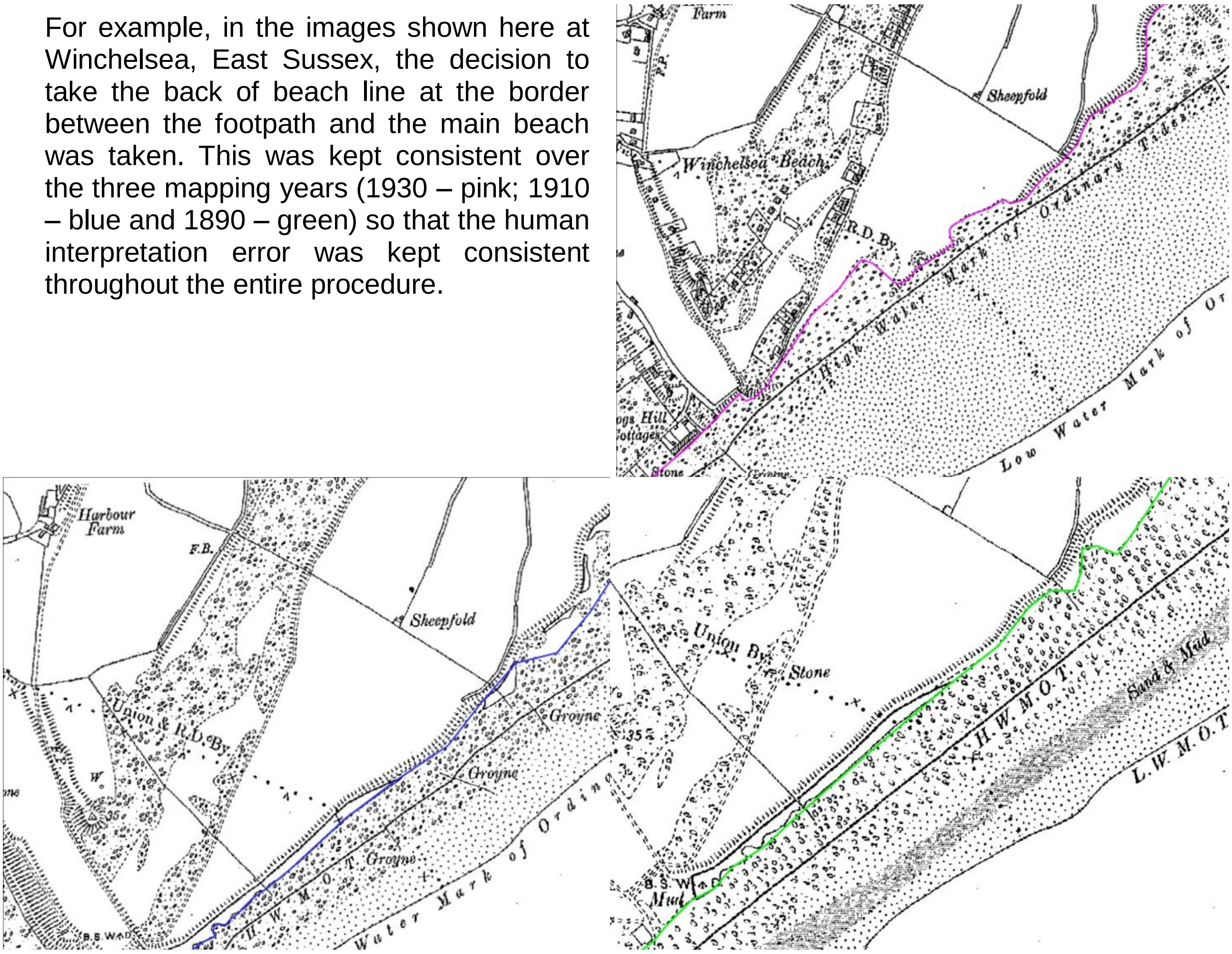


Figure 11 Examples of choice of back of beach

The location of the beach toe and beach crest were explored through known values of feature elevations. Average crest and beach toe heights, as well as the height at the sea wall were calculated from analysis of SANDS beach profiles, shown in Table 2. The crest location was calculated through Equation 2 while the beach toe location was calculated through Equation 3 (Dornbusch and Curoy, 2005).

$$L1 = \frac{Crest\ Height - MHW}{tan.\beta} \quad (2)$$

$$L2 = \frac{MHW - beach\ toe\ height}{\tan \alpha} \quad (3)$$

Where:

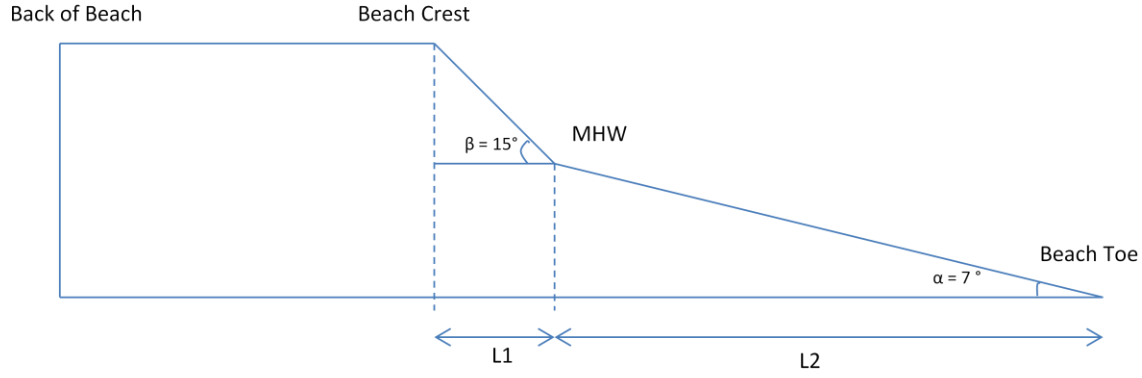


Figure 12 Calculation of Beach Crest and Beach Toe location nomenclature

With values for L1 and L2, the MHW water line could be buffered to find the location of the crest and back beach. This works on the assumption that the beach profile is dictated by the angle of repose of its constituent sediment and dominant hydrodynamic climate. The beach crest and beach toe location can be determined based on the critical angle that the sediment exists at. Although this is an idealised assumption, it is well documented that the beaches on the South Coast display these characteristics. Therefore, over the temporal and spatial scale of the historic volumetric change analysis these assumptions can be justified.

A DTM was generated through the 5 lines and their associated heights. In certain situations the buffered crest line was situated behind the back of beach line (Figure 3.6). At these locations, the back of beach line was removed so that the height at the sea wall would be based on the angle of repose of the sediment rather than the average crest height. Then, masks were created to ensure no beach was found behind coastal defence structures. In addition, in areas where the beach now is much further inland than on the historic maps, the back of beach was brought back far enough to include sufficient beach so that the loss would be reflected on each difference model. Difference models were run for all available years and the volumetric change calculated.

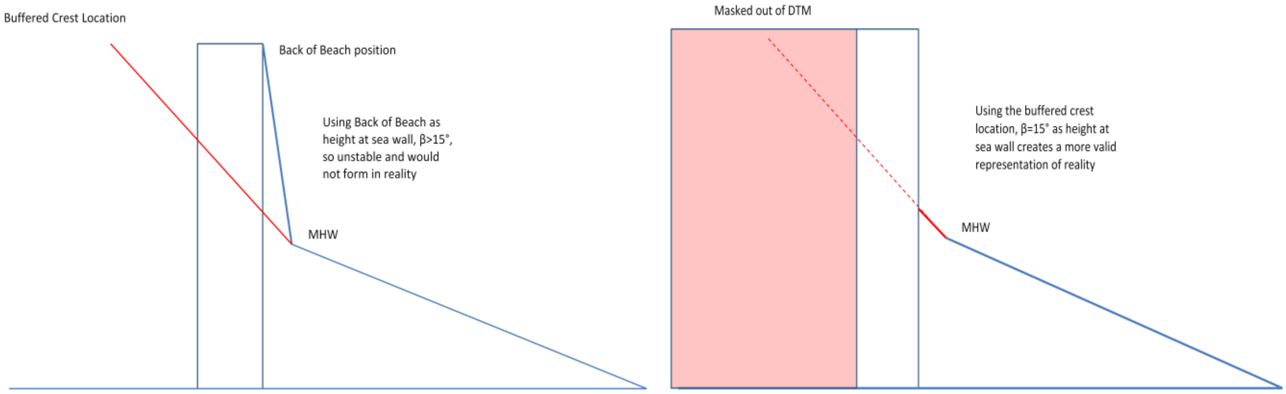


Figure 13 Method of Calculation of DTM on constrained beaches

Appendix D - Assumptions and Limitations

The assumptions made in the methodology and the limitations associated are summarised in the table below. These should be considered when using the figures from the sediment budget analysis.

Table 3 Assumptions and limitations in the methodology

Assumption	Description	Justification
	Volumetric Change	
Difference models calculated over multiple years	Where DTM's were missing either due to incomplete coverage or not covered, difference models were calculated over multiple years.	Interpolating surfaces from profiles contains too many variables and potentially erroneous beach volumetric change data. Calculating over multiple years provides most reliable method for infilling this data
Total Volumetric Change calculated through Method 5	DTM's spliced together to ensure all surfaces had the same survey coverage.	The wide range in values produced using different methods can be seen in Table 3.2. Splicing together DTM's ensures no volumetric change is 'missed' due to poor coverage.
SRCMP Survey Error	Each SRCMP survey has an accuracy of 30mm. Given any two surveys used in difference model calculations the survey error using error propagation, will be ($\sqrt{(30^2+30^2)}$) or 42mm	Beach topography remains the most accurate method of collection available over the timescales of this report.
	Historic Volumetric Change	
Feature heights averaged for each frontage	Crest height and beach toe height averaged for each frontage from SANDs profiles which are known to vary across each location.	Over the spatial and temporal scale of the analysis of these findings, small differences in these heights will not significantly alter overall changes.
Digitising beach features from historical mapping	Human interpretation error of certain beach features	Mapping undertaken by one person with decision making kept consistent throughout implementation, limiting the potential error.
Beach profile follows angle of repose	Beach crest and toe locations generated through relationships of grain size and hydrodynamic conditions, in order to produce historic DTMs.	Beaches on the South Coast known to follow this relationship well. Over the spatial and temporal scale of this analysis this assumption has a limited impact.
	Beach Volume Calculation	
Substrate volume	Substrate volume included in beach volume calculation as estimates of clay volume provided too many assumptions.	Provides an indication of beach volume, not an absolute value
	Generation of the Sediment Budget	
Losses to each cell	Attrition loss of 0.15m^3/yr, 10% of each replenishment volume and 5% of each recycling volume applied to each cell.	Assumptions made on best available data and knowledge of coastal processes.
Input from uprift frontages	Assumptions about beach sediment input have to be made at the updrift boundary.	Sediment budgets are selected so that they can be though of as self-contained coastal cells with limited sediment moving in or out. This allows reasonable assumptions about updrift input can be made.

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