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Selsey Bill to Brighton Marina

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Summary

A sediment budget for Selsey Bill to Brighton Marina was generated to gain an understanding of sediment movements through the frontage. The entire frontage is characterised by persistent longshore transport in an easterly direction.

- Selsey Bill has no hard defence to the west of the unit. Sediment transported from Selsey beach does not satisfy the gain at Pagham. Calculations suggest 12,500m^3/year is transported onshore and feeds into Selsey. It is also assumed 2,500m^3/year of material is added to Selsey from the west during strong westerly storms. The net export east from Selsey is 15,699m^3/year.

- Pagham spit is largely accretive gaining 28,272m^3/year. The transport rate from the west spit to the east spit is only 909m^3/year; highlighting the large accumulation along the west spit.

- Pagham (east) to Aldwick depicts smaller transport rates due to the lack of material carried into the unit. Calculations indicate 4,457m^3/year is added to the eastern part of Pagham Harbour through onshore movement. The west of the unit feeds the east and is consequently erosive (-10,000m^3/year). The east of the unit gains around 4,000m^3/year. 2,481m^3/year is transported into Bognor Regis.

- Bognor Regis is one of the largest units, with some of the lowest transport rates. The timber groyne field which spans the whole unit has stabilised the beach. The average annual flux rates are no larger than losses of 650m^3 and gains of 1,300m^3. 1,640m^3/year is transported into Elmer.

- Elmer beach is persistently erosive with transport rates of 7,089m^3/year into Climping.

- Climping beach receives annual beach recycling which artificially increases the transport rates to ~30,000m^3 within Climping. Material accumulates at Littlehampton Harbour where it extracted and then placed at the western extent. As a direct result of beach management this unit is stable. 3,838m^3/year leaves Climping for Littlehampton.

- Rustington has a limited sediment feed due to the presence of large trailing walls at Littlehampton Harbour. The section is mildly erosive losing, 2,000m^3/year. Transport rates are low, in the order of 1,800m^3/year due to the sheltered nature of the beaches, limited sedimentary input and high foreshore.

- Kingston Gorse is fairly stable due to the heavily groyned beaches.

- Worthing exports 6,300m^3/year as it struggles to retain the beach material placed during the large capital scheme of 2005 and 2007.

- Shoreham (west) represents a significant sediment sink as material is trapped by the terminal structure at Shoreham harbour. The frontage is accreting at a rate of 19,000m^3/year, despite 16,200m^3/year being extracted for recycling. Of this volume 12,500m^3/year is bypassed round the harbour to feed the beaches east of the harbour entrance. Transport rates in this section increase to 15-20,000m^3/year due to a switch to more permeable rock groynes as well as an open beach in the east.

- From Shoreham to Brighton, transport rates again remain high, typically around 12-16,000m^3/year due to the open nature of the beaches. The eastern end accretes the material lost from Shoreham harbour as material is trapped by Brighton Marina.

These trends are analysed over various temporal and spatial scales in the following report.

1.0 Introduction

This report details the regional shingle sediment budget for Selsey Bill to Brighton Marina. 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 data used for this report has been sourced from the Strategic Regional Coastal Monitoring Programme (SRCMP). The topographic beach data has been extensively collected since 2003 using ground based GPS measurements, LiDAR and bathymetric surveys. This data is analysed and reported over small management units, with very little regional analysis undertaken. Therefore, this report will take the local analysis to the regional scale to gain a greater insight into beach behaviour over interconnected sediment sub-cells.

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 shingle sediment budget is discussed in detail in Appendix A. 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.

2.0 Study Area

Throughout the entire sediment budget analysis, the frontage has been split into 12 sections (or cells) which broadly coincide with SRCMP survey units (Table 3.1). This also serves to maintain the boundaries between different beach management organisations which allows for easy accounting of the anthropogenic management on the individual frontages. As the dominant drift direction is from west to east, management units are always considered with the most westerly unit first.

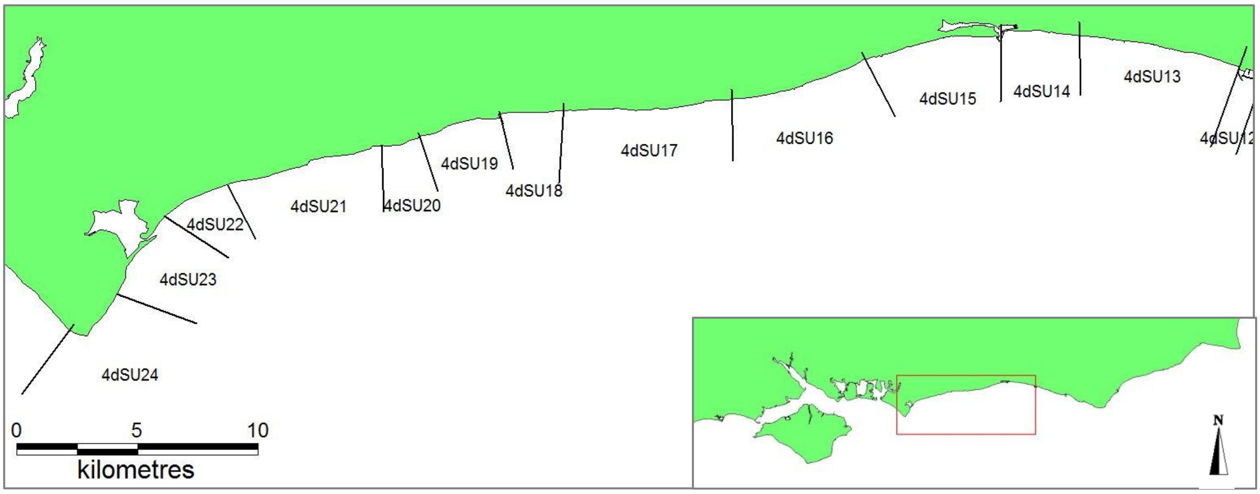

Figure 2-1 Location of study area

2.1 Selsey Bill

The shingle beaches of Selsey Bill are historically prone to erosion. The construction of hard defences, concrete seawalls and timber groynes, in the 1950s has since protected the clay headland from further erosion. Despite this, the headland is regularly exposed to approaching waves from the south east and south west. Selsey Bill has a spilt drift direction with material being transported towards West Wittering and Littlehampton. Submerged shingle deposits of the Inner Owers are located nearshore and are thought to provide a source of beach material through onshore movement.

2.2 Pagham Harbour

Pagham harbour covers the beach between East Beach and Pagham town. The double shingle sand composite spit dominates this unit. The active south side is continually accreting towards the north east; 700m since 2001. The less active north spit, connected to the mainland in front of Pagham estate is predominantly erosive. Four rock groynes were constructed in front of the estate to reduce the transport rate and increase protection for the residential housing.

2.3 Pagham to Aldwick

The 3km combined shingle sand beach between Pagham and Aldwick is largely open with no hard defences; the most eastern 300m contains six timber groynes.

2.4 Bognor Regis

The coastline between Aldwick and Middleton-on-sea is heavily defended by a combination of shingle sand beach, timber and rock groynes and a concrete seawall, along the whole frontage. Similar to rest of the coastline, material is known to travel west to east.

2.5 Elmer

The shingle sand composite beach of Elmer is historically erosive. In 1993 eight shore parallel rock breakwaters, using 100,000 tonnes of rock, were constructed to dissipate wave energy and reduce the erosion rate. This scheme saw 200,000m^3 of shingle added to the frontage as beach replenishment. A rock revetment is located between breakwaters five and six, from the west and at the most eastern boundary of the unit is a large rock groyne to trap material transported west to east.

2.6 Climping

Located at the eastern boundary of the Climping frontage is first terminal structure beach material encounters when travelling from Selsey; Littlehampton harbour walls. Historically material has accumulated here and increased the beach levels. Annual beach recycling extracts material adjacent to the harbour and it is deposited at the western boundary of Climping, allowing material to feed back through the unit. The sea defences in this unit are split into east and west; the eastern section has a timber groyne field and the western section is an open beach backed by vegetated dunes.

2.7 Rustington

The Littlehampton harbour walls extending out to the foreshore act to limit the input of shingle into the Rustington frontage. The beaches consist of a shingle sand composite material with a predominately sandy foreshore. The high foreshore limits the wave activity on the frontage and the small groyne field acts to reduce alongshore transport rates.

2.8 Ferring

The beaches from Rustington to Ferring become wider and more heavily groyned. Over the past decade there has been no regular beach management operations; however 30,000m^3 was placed onto the beach fronting Kingston Gorse in 2003.

2.9 Worthing

The groyne field continues into the Worthing frontage; however bays have become buried in certain locations. The east of the unit has undergone several beach management operations, with 64,610m^3 of replenished shingle being deposited in 2005 as part of the South Lancing to Shoreham scheme and recycling of 9,800m^3 from South Lancing in 2007. The foreshore becomes lower with distance eastwards, acting to increase exposure of the beach to wave attack during high tides.

2.10 Shoreham (west)

The west of the unit was the main site for the South Lancing to Shoreham scheme from 2003-2005. In 2003, 274,664m^3 was placed on the beach fronting South Lancing, with a further 43,073m^3 being deposited in 2005. The terminal groyne at Shoreham Harbour traps material moving in the direction of the dominant longshore drift. This has seen a large accretion over the past 100 years with the beach moving seawards by as much as 100m. Since 1993, 5-10,000m^3 has been bypassed onto the eastern beach of Shoreham Harbour to compensate for the reduced littoral drift input from the terminal structures.

2.11 Shoreham (east)

A very limited movement of sediment into the unit from Shoreham Harbour west causes this coastline to become sediment starved. The bypassed material compensates for this deficit, which would undermine the sea wall should this cease. Nevertheless, beach volumes are typically low.

2.12 Brighton

The net littoral drift in an easterly direction causes a build up of shingle at Brighton Marina. Finer material has been shown to move around the marina while it remains a sediment sink for shingle. Groynes and outfalls reduce alongshore transport rates, acting as a temporary store. Little or no beach management operations occur on the frontage.

3.0 Methodology

3.1 Source data

In order to undertake the sediment budget a review of all topographic data was conducted (Table 3.1). This review was focussed on the topographic survey data from both ground based GPS and aerial LiDAR sources, over the 2012-2003 period, the longest available timescale since regular monitoring began. Where both LiDAR and GPS measurements were available, GPS was preferentially chosen due to the tailored nature of the surveys. This data was used in the formulation of the sediment budget explained below. For more information, refer to Appendix A.

Table 3-1 Available DTM's and Difference Models for Frontages

Frontage	Management Organisation	SRCMP Survey Units (Phase III)	Available DTM's	Data Type	Difference models
Selsey Bill	Chichester District Council	4dMU24	2004 2006, 2007 2011, 2012	LiDAR	2004-2006 2006-2007 2007-2011 2011-2012
Pagham Harbour	Environment Agency	4dMU22	2004 2006, 2007 2011, 2012	LiDAR	2004-2006 2006-2007 2007-2011 2011-2012
Pagham to Aldwick	Chichester District Council	4dMU22	2001, 2007 2009, 2010 2011, 2012	LiDAR	2001-2007 2007-2009 2009-2010 2010-2011 2011-2012
Bognor Regis	Arun District Council	4dMU21	2001, 2007 2011, 2012	LiDAR	2001-2007 2007-2011 2011-2012
Elmer	Arun District Council	4dMU20	2001, 2007 2007, 2008 2009, 2011 2012	LiDAR	2001-2007 2007-2008 2008-2009 2009-2011 2011-2012
Climping	Environment Agency	4dMU19	2001, 2007 2009, 2010 2011, 2012	LiDAR	2001-2007 2007-2009 2009-2010 2010-2011 2011-2012
Rustington	Arun District Council	4dMU18	2001, 2007, 2011, 2012	LiDAR	2001-2007, 2007-2011, 2011-2012
Ferring	Arun District Council	4dMU17	2001, 2007, 2011, 2012	LiDAR	2001-2007, 2007-2011, 2011-2012
Worthing	Worthing Borough Council	4dMU16	2001, 2003, 2004, 2005, 2006, 2007, 2010, 2011, 2012	LiDAR	2001-2003, 2003-2004, 2004-2005, 2005-2006, 2006-2007, 2007-2010, 2010-2011, 2011-2012
Shoreham (West)	Environment Agency	4dMU15	2001, 2007, 2011, 2012	LiDAR	2001-2007, 2007-2011, 2011-2012
Shoreham (East)	Shoreham Port Authority	4dMU14	2001, 2007, 2011, 2012	LiDAR	2001-2007, 2007-2011, 2011-2012
Brighton	Brighton and Hove City Council	4dMU13	2001, 2007, 2011, 2012	LiDAR	2001-2007, 2007-2011, 2011-2012

3.2 Generation of the Sediment Budget (Level 3 and 4)

A sediment budget presents a quantitative model of the magnitude of volumetric change, sediment transport rates and losses and gains within a self-contained coastal cell, in a defined period of time (Rosati and Kraus, 1999). At its most basic, using the principles of conservation of mass (volume), it is an attempt to balance all inputs into a cell with all outputs leaving a cell as shown in Equation 1 below (Adapted from Rosati and Kraus, 1999):

$$\sum Qinput - \sum Qoutput - \Delta V + P - R + L = Residual \qquad (1)$$

Where:

Where:	Q_{input}	-	Volume input from the updrift cell
	Q_{output}	-	Volume output into the downdrift cell
	ΔV	-	Volumetric change within the cell
	P	-	The material placed into the cell e.g. beach replenishment
	R	-	The material removed from the cell e.g. beach recycling
	L	-	The losses to attrition and material lost during placement.

The Residual is the volume of the cell remaining or the degree to which the cell is balanced. In a balanced sub-cell the residual should near 0 or be no larger than the combined error in the data collection.

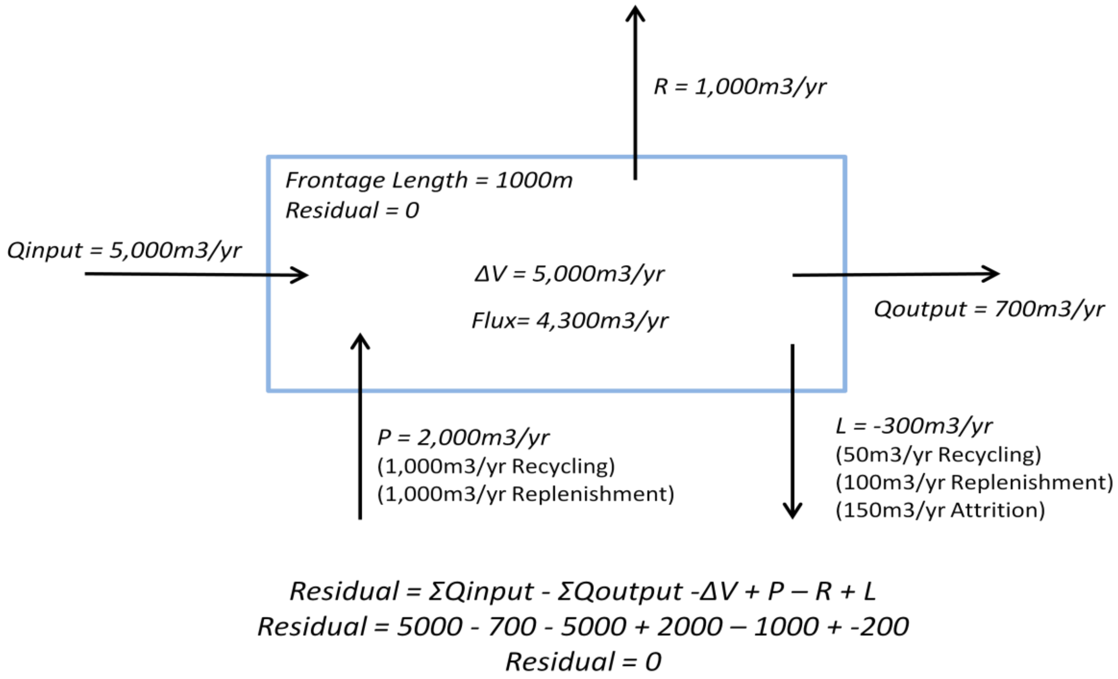

Figure 3-1 Sample balanced sediment cell

Volumetric change in each SRCMP polygon was calculated through analysis of the difference models shown in Table 3.1. Different methods for calculating *ΔV* were explored in depth provided in Appendix A. All replenishment and recycling logs were collated and *P* and *R* were calculated for each polygon.

Losses expected on this frontage can be broadly split into three categories, attrition losses, replenishment losses and recycling losses. Offshore losses are not considered significant due to the predominance of coarse grained sediments and the topography and geomorphology of the beaches. The losses applied to each cell are shown in the table below, with justification for the figures applied provided in Appendix A.

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Table 3-2 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

While the SRCMP polygons (Level 2) are useful in providing detailed losses and gains over a management unit, they are too fine when considering the regional view of the sediment budget. Polygons exhibiting similar coastal behaviour were grouped together to create a coarser system of sub-cells, or the Level 3 analysis sub-cells. This set of sub-cells now contained values for $\Delta V, P, R \text{ and } L$. Using these figures, the average annual flux can be calculated through:

$$Flux = \Delta V - P + R - L \qquad (2)$$

The flux can be thought of as the volume of sediment added (when flux is negative) or removed (when flux is positive) of the sediment system. This is an important parameter for working out what volume of sediment is actually being exported out of the cell after all losses, extractions and placements have been excluded.

With the residual nearing 0 in a closed sub-cell, Equation 1 can be solved for Q_{input} *and* Q_{output}. Starting at the most western extent of Eastbourne where the sediment input from Beachy Head into the frontage is known to be minimal or $Q_{input} = 0$:

$$Qoutput = -(\Delta V - P + R - L) + Qinput \qquad (3)$$

The Q_{output} of the updrift cell then feeds the downdrift cell as the Q_{input} and the next cell can be balanced. Examples of this can be found in Appendix A.iii. An overview budget was also developed helping to place the changes within the context of management frontages (Level 4). This can provide feedback on those frontages that are significantly gaining or losing material. Equation 1 can be applied over the whole sediment budget with the residual determining whether or not the cell can be thought of as a self contained sediment unit.

Finally, when using the Q_{output} figures to assess sediment transport rates it needs to be recognised that an *a priori* assumption of net transport direction has been made. In most areas along the study a distinct net transport direction prevails each year but is obviously composed of transport in either direction. For a large scale sediment budget covering several years, annual net transport is the crucial factor though locally and on operation time scales, actual rates are invariably different in both magnitude and direction.

3.3 Historic beach calculation

Historic beach DGMs were generated through an assumed relationship between the MHW, beach crest and beach toe elevation. MHW marks were mapped from historical images from the 1890's, 1910's and 1930's. For a more in depth methodology on the creation of historic DGMs from historical maps refer to Appendix C. The elevations used to generate the DGMs are shown below.

Table 3-3 Data used to generate Historic DTMs

Cell	Height (mAOD)					Distance from MHW (m)	
	Back of Beach**	Crest **	MHW*	Beach Toe **	MLW*	Beach Crest (L1)	Beach Toe (L2)
Selsey Bill	5.25	5.25	1.95	-1.2	-1.55	12.32	25.65
Pagham Harbour	5.5	5.5	1.9	-1.5	-1.9	13.44	27.69
Pagham to Aldwick	6	6	1.9	-2	-1.9	15.30	31.76
Bognor Regis	5.5	5.5	1.95	-1.5	-1.95	13.25	28.09
Elmer (West)	5.5	5.5	2.08	-1.5	-1.43	12.77	29.15
Elmer (Central)	5.5	5.5	2.08	0	-1.43	12.77	16.94
Elmer (East)	5.5	5.5	2.08	1	-1.43	12.77	8.79
Climping (West)	5.5	5.5	2.08	1	-1.43	12.77	8.79
Climping (East)	5.5	5.5	2.08	0.5	-1.43	12.77	12.87
Rustington	5.3	5.3	2.08	0.00	-1.43	12.01	16.94
Ferring	5.5	5.5	2.10	-0.10	-1.60	12.69	17.91
Worthing	5.8	5.8	2.20	-0.60	-1.95	13.44	22.80
Shoreham (West)	6.0	6.0	2.28	-1.00	-2.05	13.88	26.71
Shoreham (East)	6.0	6.0	2.35	-2.00	-2.20	13.62	35.43
Brighton	6.3	6.3	2.35	-2.00	-2.20	14.74	35.43

* Note: found from Admiralty tide curves; ** Found through analysis of SANDS profiles

4.0 Results

The results have been split into their various temporal and spatial scales. Note: Level 2 (SRCMP polygons) are not analysed, as this level was a processing level used to gain volumetric change values to feed into the Level 3 analysis. Level 2 was considered to be too fine to conduct a sediment budget analysis over a regional scale. As this is a feeder report for the individual Beach Management Plans, full analysis of trends will be discussed at length in that report.

4.1 Level 1 - Volumetric Change per 50m Length

The year on year volumetric change has been analysed in the following pages to gain an insight on the variability around the mean volumetric change (ΔV) used in the sediment budget analysis in Section 4.2 and 4.3. The methodology for the production of the contour plots is explained in depth in Appendix A.

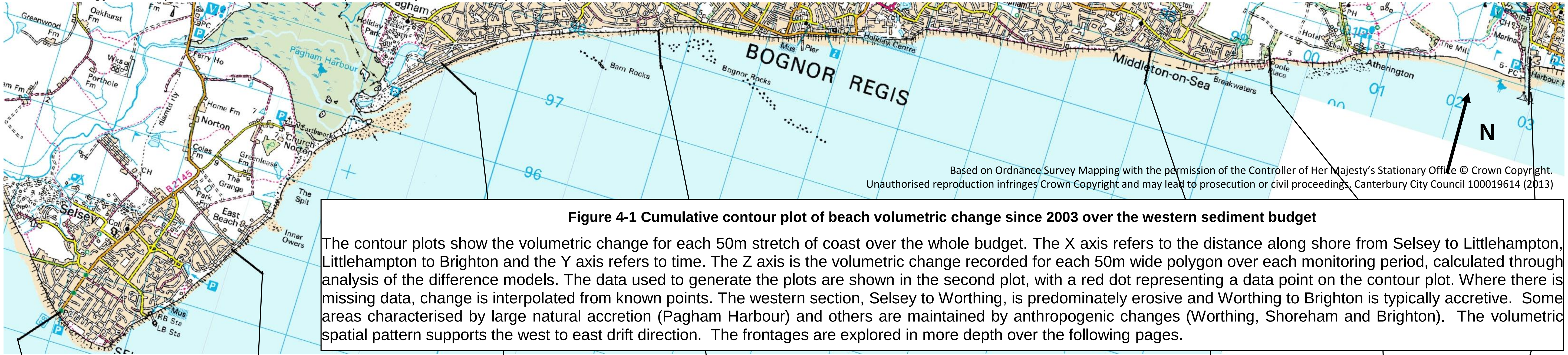
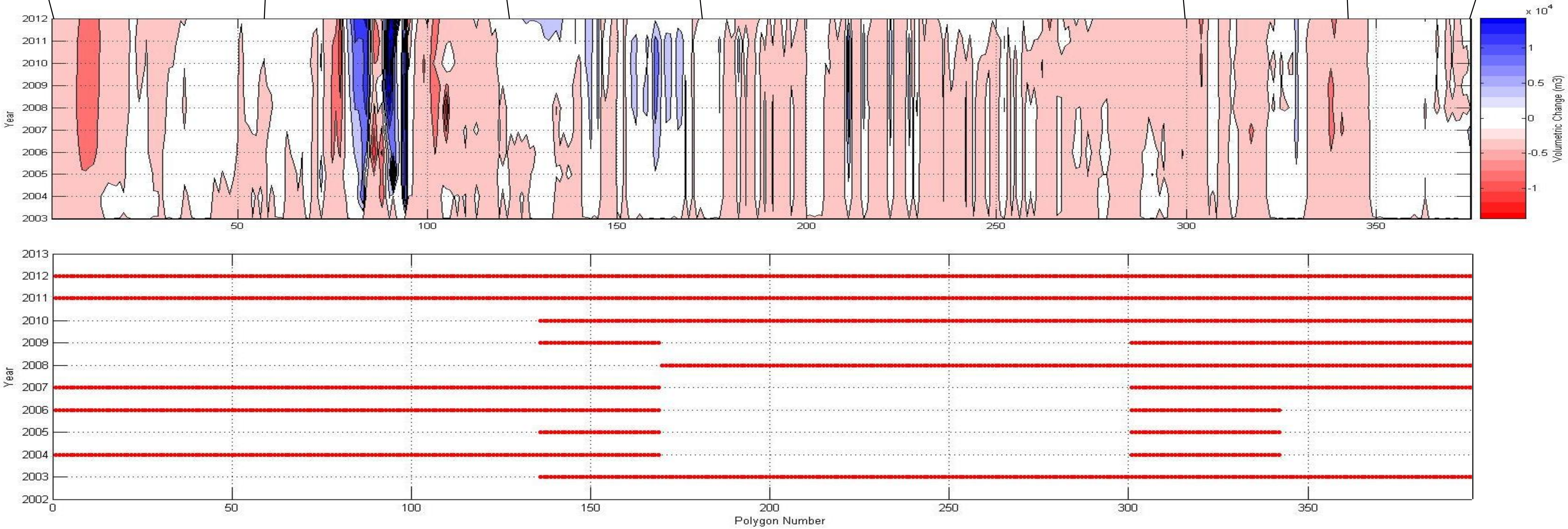


Figure 4-1 Cumulative contour plot of beach volumetric change since 2003 over the western sediment budget

The contour plots show the volumetric change for each 50m stretch of coast over the whole budget. The X axis refers to the distance along shore from Selsey to Littlehampton, Littlehampton to Brighton and the Y axis refers to time. The Z axis is the volumetric change recorded for each 50m wide polygon over each monitoring period, calculated through analysis of the difference models. The data used to generate the plots are shown in the second plot, with a red dot representing a data point on the contour plot. Where there is missing data, change is interpolated from known points. The western section, Selsey to Worthing, is predominately erosive and Worthing to Brighton is typically accretive. Some areas characterised by large natural accretion (Pagham Harbour) and others are maintained by anthropogenic changes (Worthing, Shoreham and Brighton). The volumetric spatial pattern supports the west to east drift direction. The frontages are explored in more depth over the following pages.



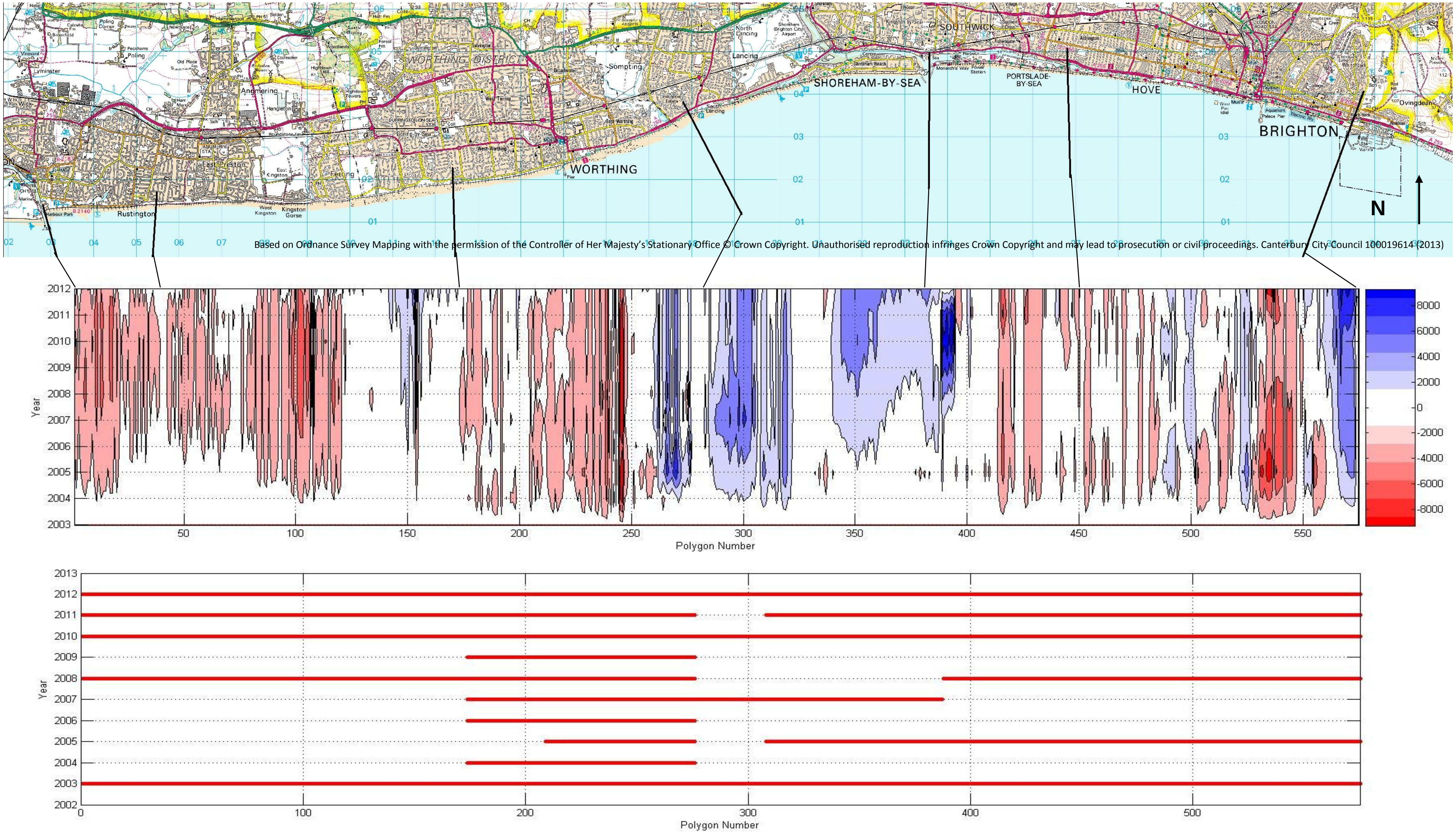
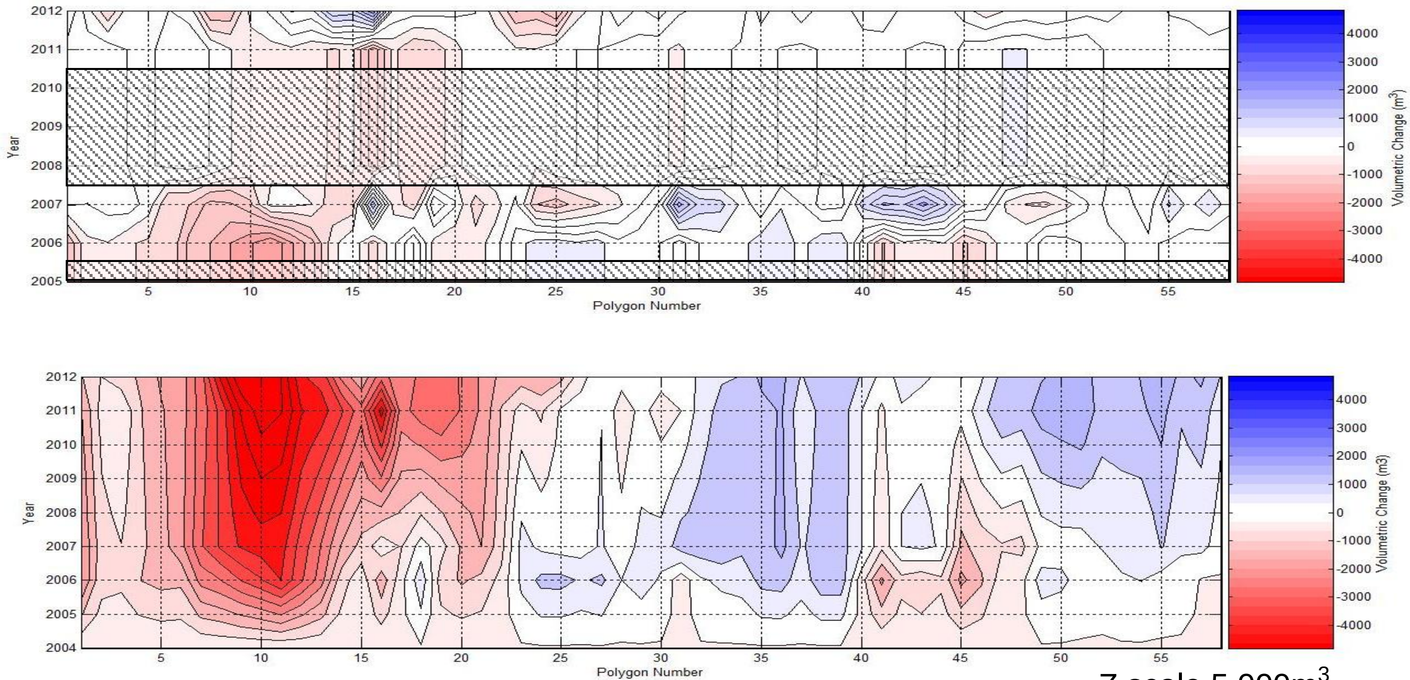


Figure 4-2 Cumulative contour plot of beach volumetric change since 2003 over the eastern sediment budget

4.1.1 Selsey Bill

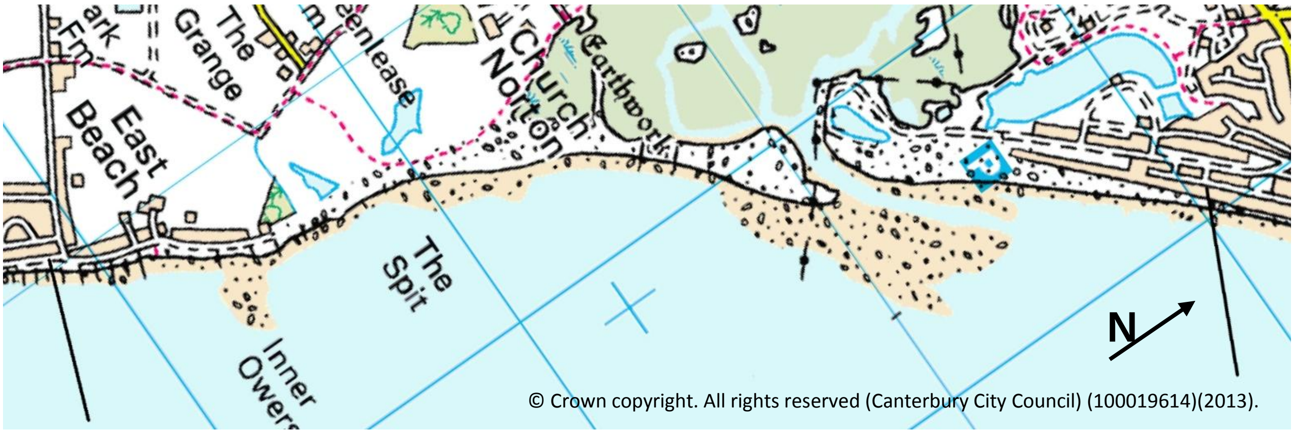


Z scale 5,000m^3

Figure 4-3 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Selsey Bill since 2003

The southern peninsula of Selsey Bill has a split in drift direction of west to east from Selsey to Brighton and east to west from Selsey towards West Wittering. Since 2003 material has been lost at the drift divide; Polygons 8 to 12. The rest of the unit is relatively stable.

4.1.2 Pagham Harbour



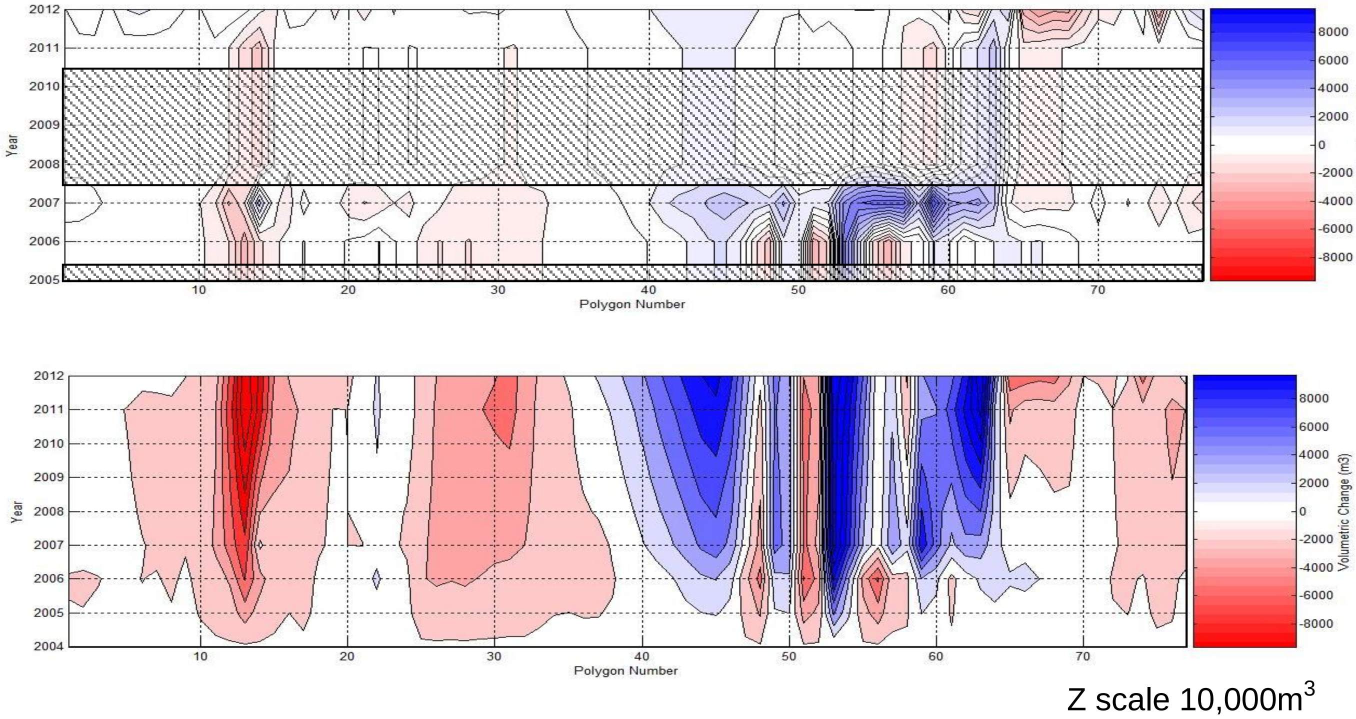
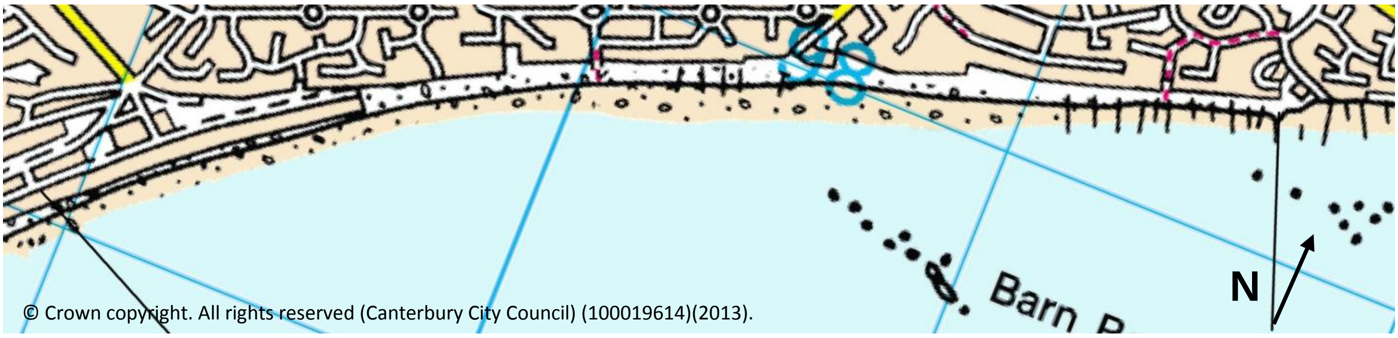


Figure 4-4 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Pagham Harbour since 2003

Pagham Harbour is the most dynamic stretch of coastline within the sediment budget. Since 2003, the spit has continued to accrete annually, which can be seen in Polygons 50 to 65. It must be noted that the volume lost from Selsey is not sufficient to match the gain at Pagham and it is known that no material moves onto the spit from the east which suggests an offshore source is feeding Pagham spit. The eastern side of the double spit is dominated by erosion due to material being held at the spit; more recently in 2009 to 2012.

4.1.3 Pagham Harbour to Aldwick



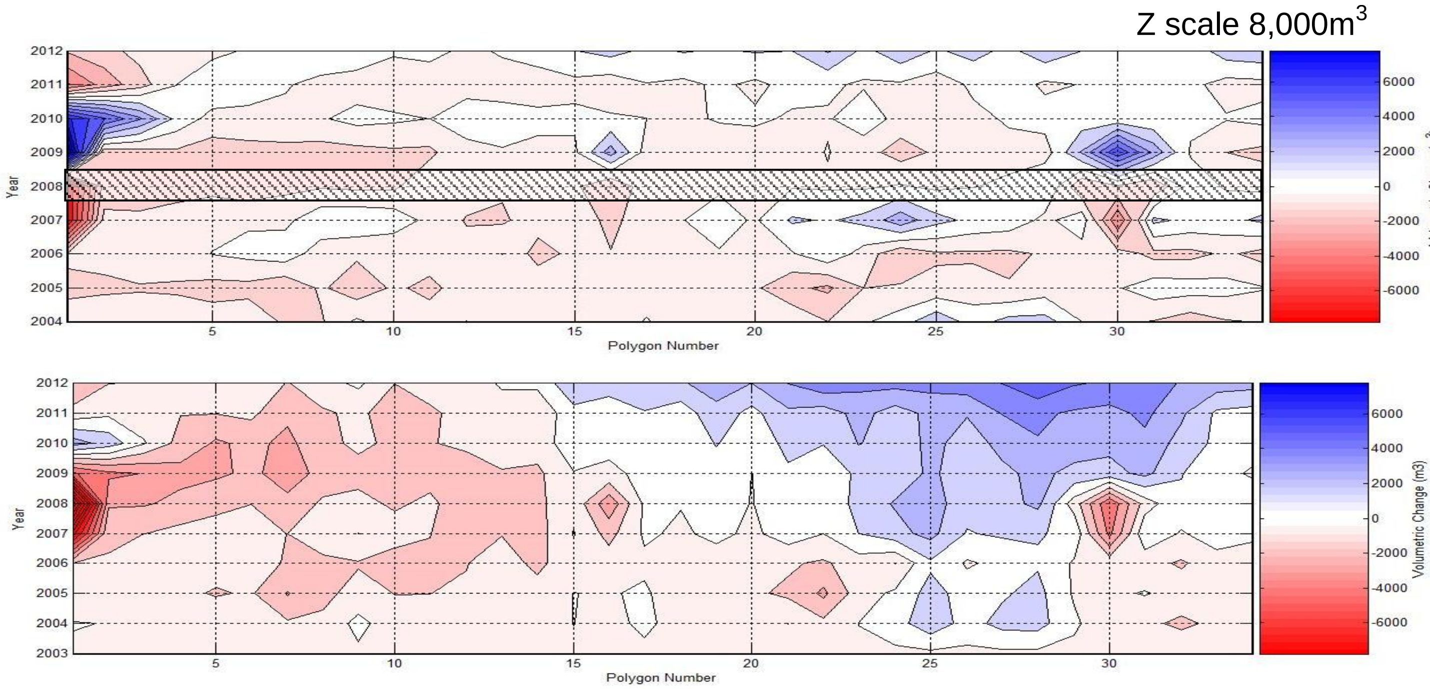
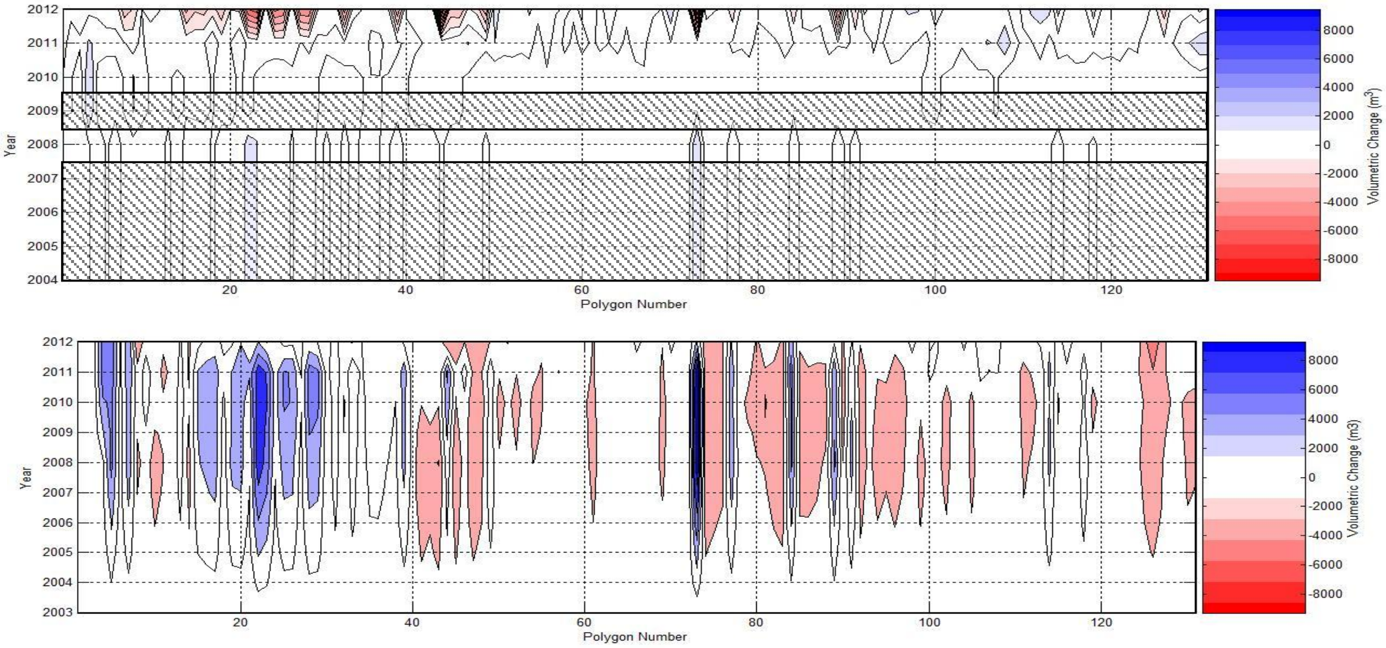


Figure 4-5 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change between Pagham and Aldwick since 2003

Pagham to Aldwick is predominantly an open beach. This contour plot mirrors the cumulative plots and highlights the movement of shingle from Polygons 1 to 15. The cumulative plot shows movement of material from the west of the unit to Polygons 16 to 35 over time.

4.1.4 Bognor Regis

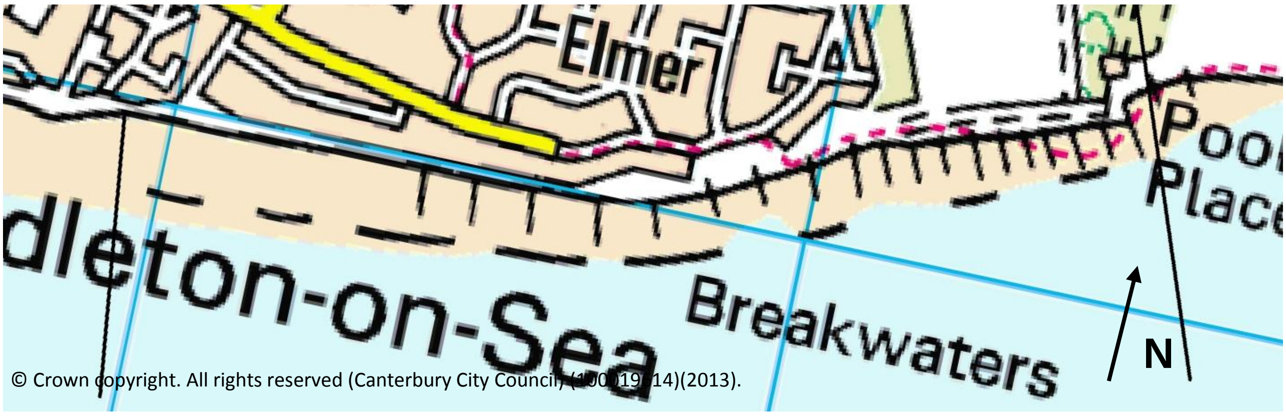


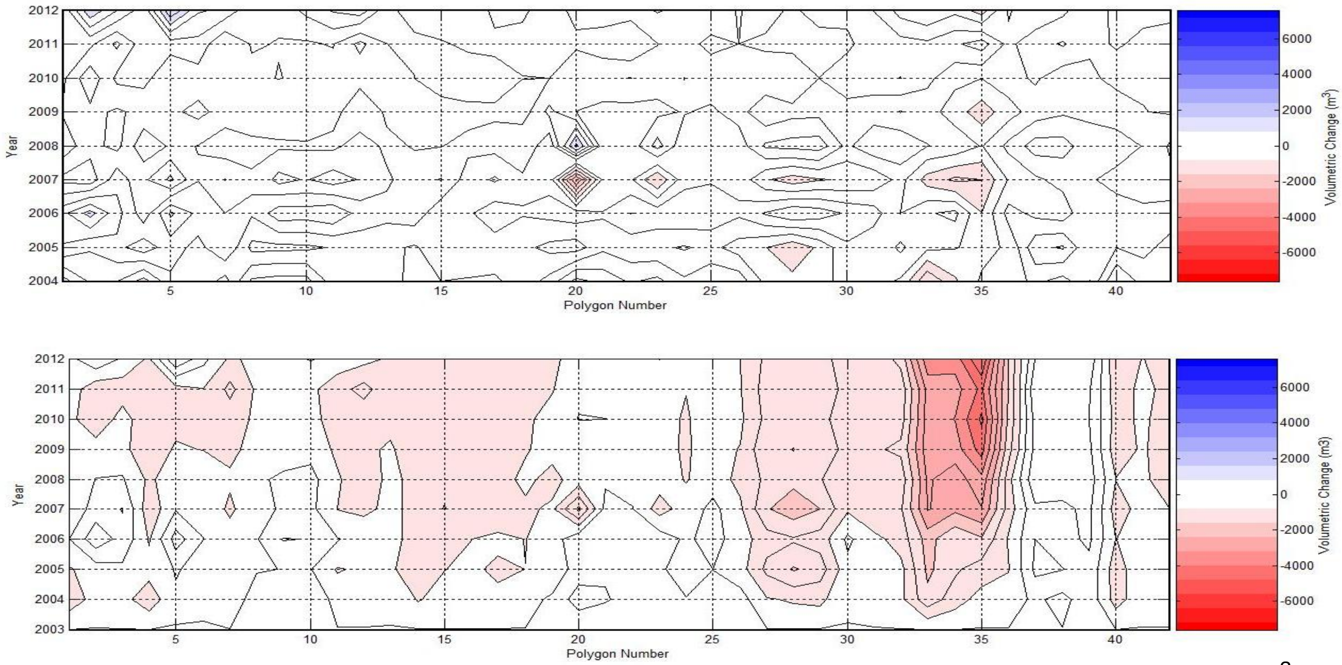
Z scale 10,000m^3

Figure 4-6 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Bognor Regis since 2003

The contour plot suggests this beach is relatively stable, with most of the beach change occurring during 2011 and 2012. The cumulative contour plot highlights the trend of the beach and shows pockets of gain and loss within a groyne bay or across several bays. The western side of the unit has gained material (to the Pier) year on year. East of the Pier is stable yet skewed to erosion with the change in orientation causing a localised progressive accretion.

4.1.5 Elmer



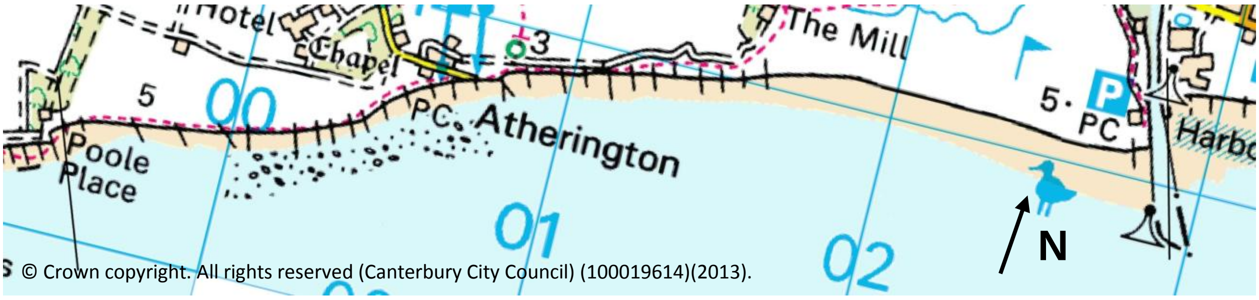


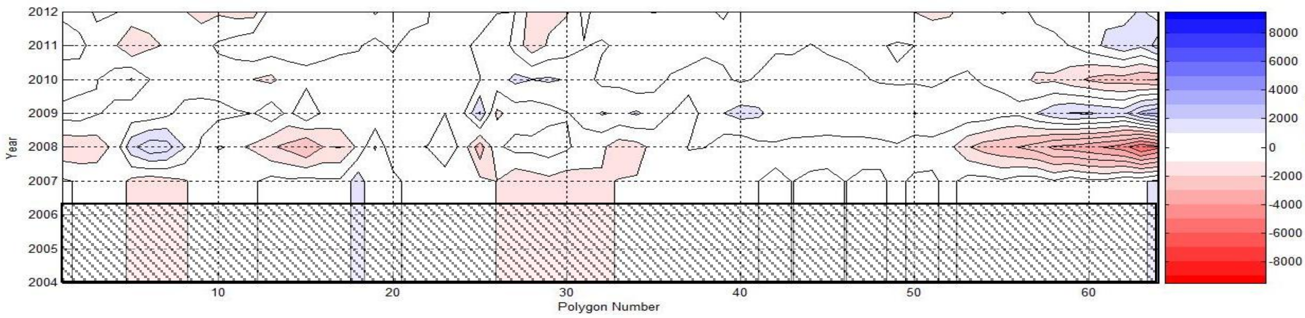
Z scale 8,000m^3

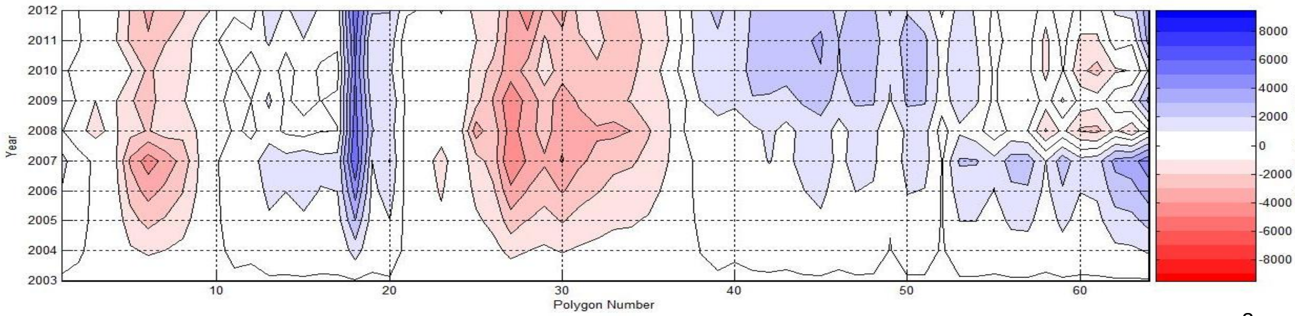
Figure 4-7 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Elmer since 2003

The beach at Elmer is relatively stable, with much of the frontage losing no more than a few thousand cubic metres. Close to the change in orientation the beach behaviour differs from the rest of the unit, as small persistent losses have occurred since 2004; the year on year trend shows these losses to be less than 1,500m^3.

4.1.6 Climping





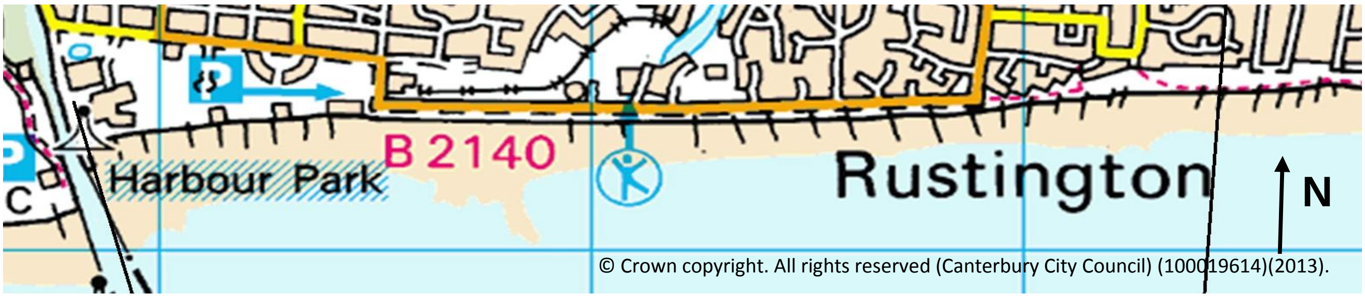


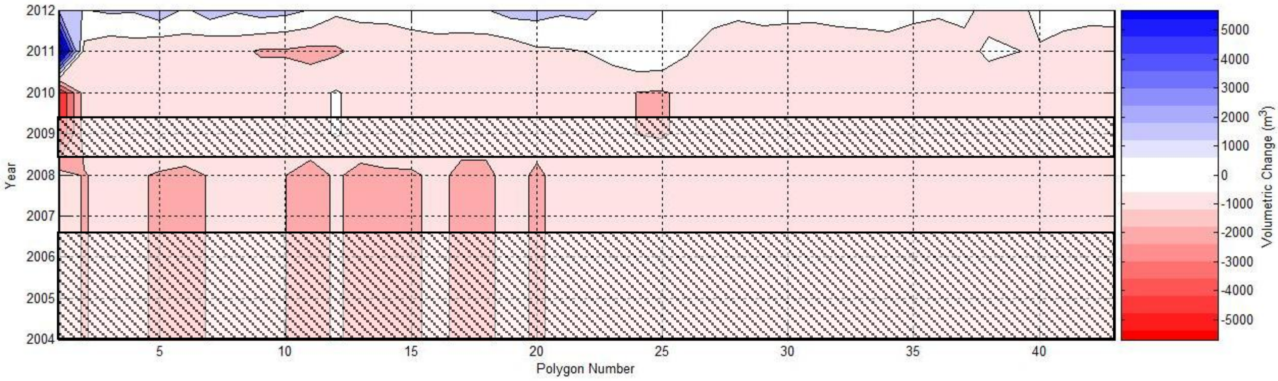
Z scale 10,000m^3

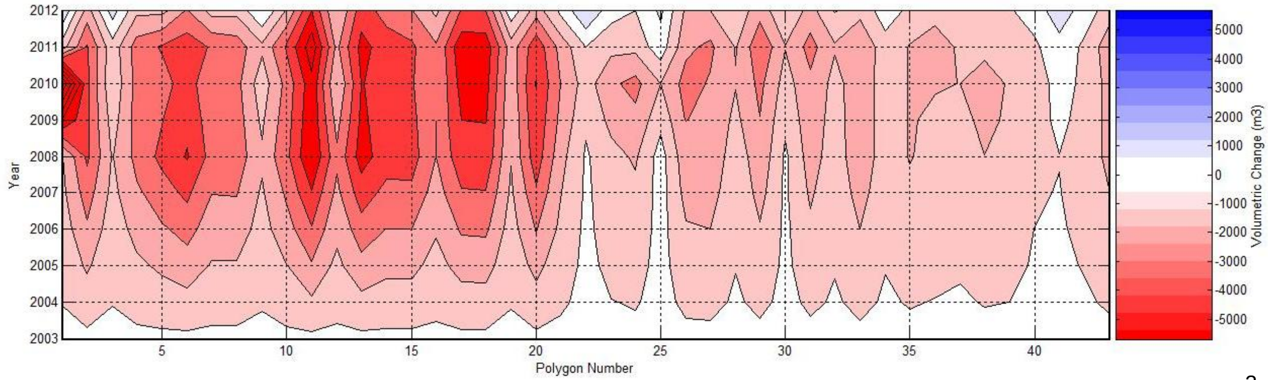
Figure 4-8 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Climping since 2003

The cumulative contour plot indicates material is moving in pockets eastwards. The loss near Poole Place (Polygons 1 to 10) is reflected as gain in polygons 17-19. Again, a loss at Atherington is reflected a gain in Polygons 40-50. Polygons 55 to 64 show a mix of trends as a result of the terminal structure, which traps material west to east. Polygons 60 to 65 show a natural accretion to 2007 followed by erosion as material is extracted and deposited at polygons 10 to 20.

4.1.7 Rustington





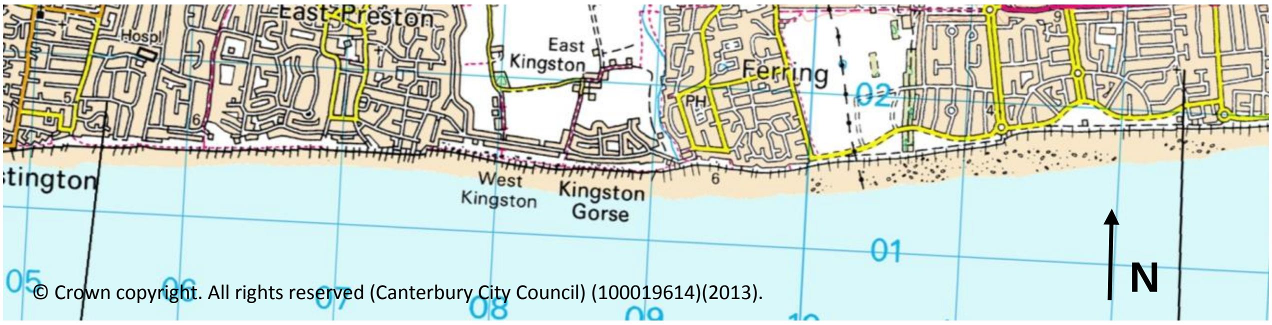


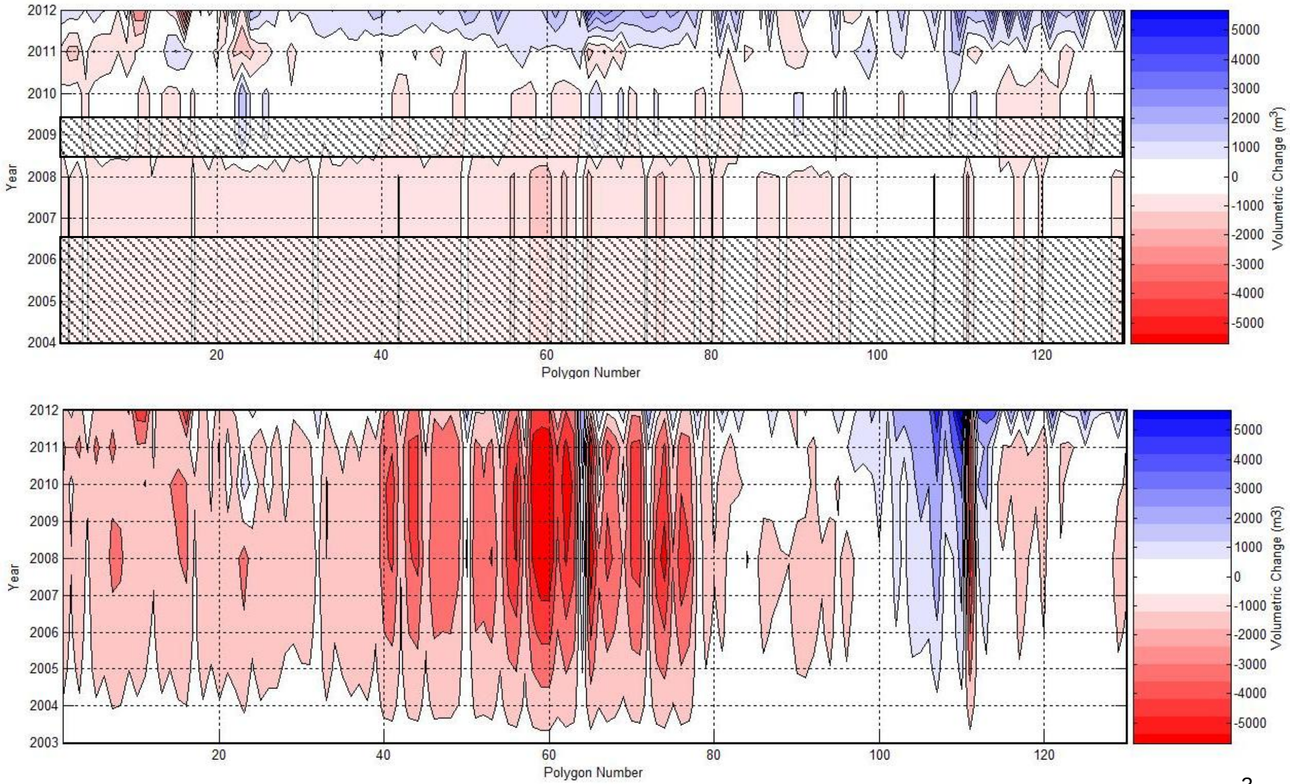
Z scale 6,000m^3

Figure 4-9 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Rustington since 2003

Rustington has shown gradual but consistent losses of volume over the past 9 years. The losses are intensified around the harbour arm where the beach has become starved of sediment due to the terminal structure of Littlehampton Pier. Losses are typically less with distance eastwards due to a small amount of sediment feed from the erosion of the beach just east of the Pier.

4.1.8 Ferring



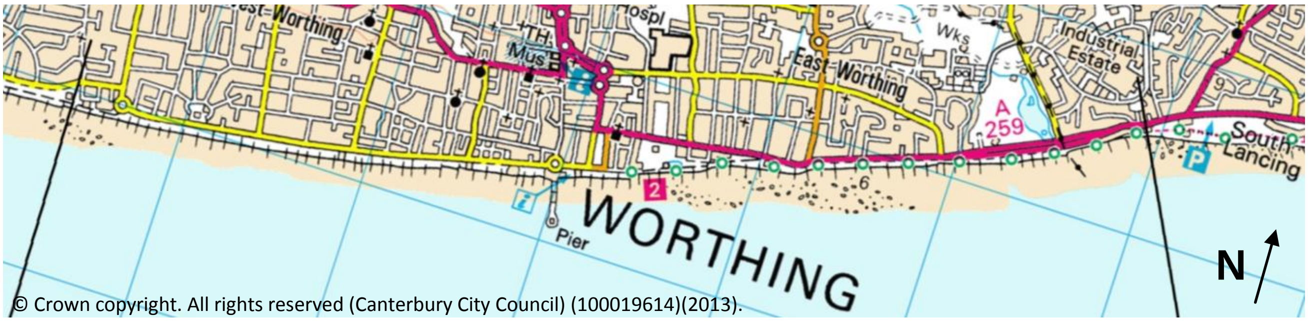


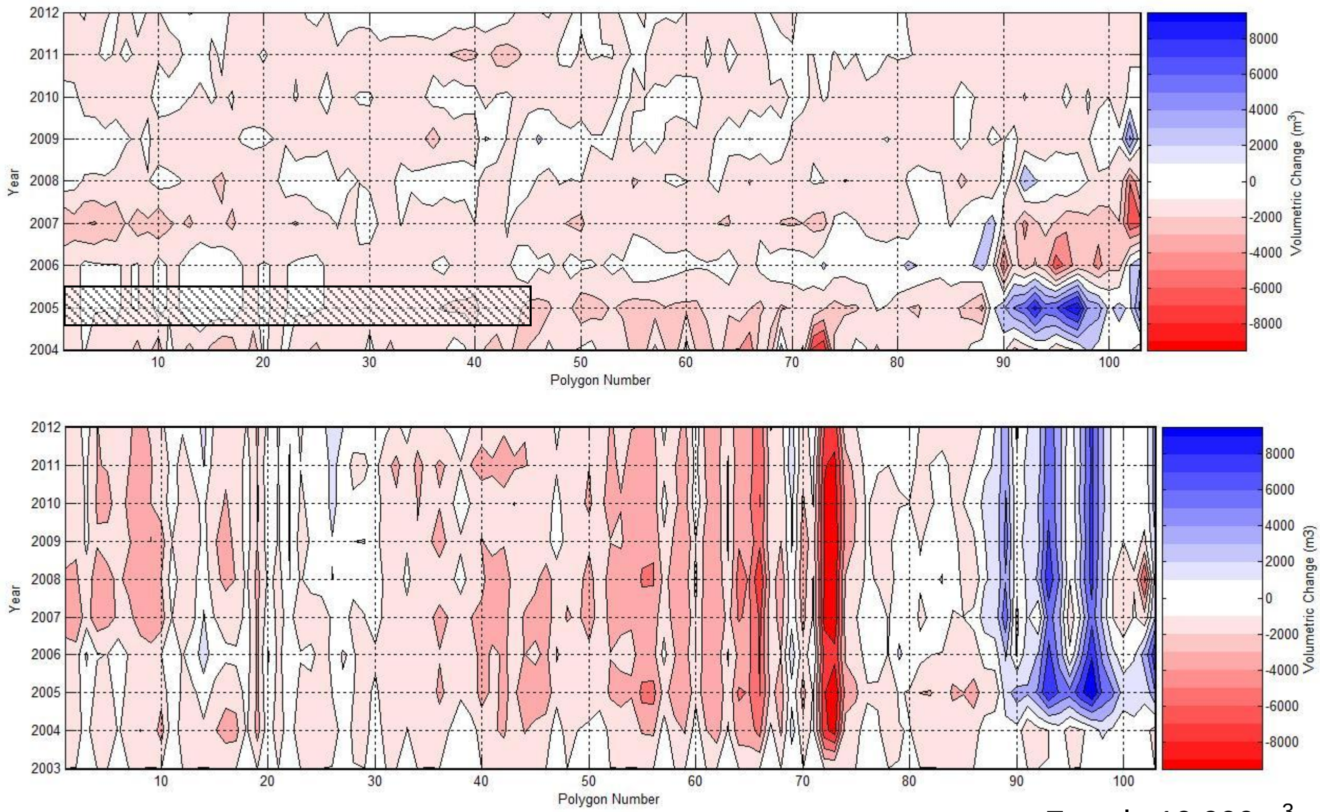
Z scale 8,000m^3

Figure 4-10 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change for Rustington to Ferring since 2003

From Rustington to West Kingston (Polygon 40) we see a similar consistent but marginal erosive trend as in Figure 4.10. Polygons 40 to 80 show significant losses at the beach fronting Kingston Gorse. However, in the spring of 2003, 30,000m^3 of recharged shingle was placed at the frontage at this location. The large-scale erosion seen here is a response of the beach to the placed material as it struggles to retain the shingle. Further east at Polygon 100 to 110 an accretion of material is noted which could be the material lost from the replenishment scheme.

4.1.9 Worthing



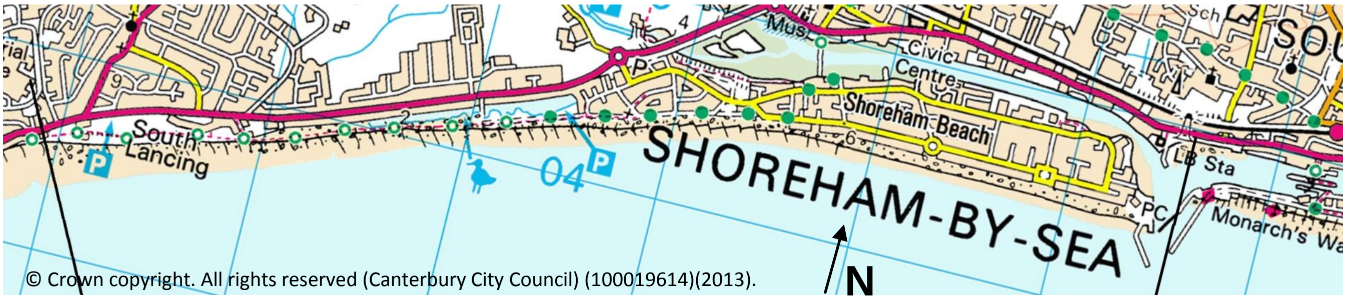


Z scale 10,000m^3

Figure 4-11 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change for Ferring to East Worthing since 2003

The western end of Worthing is dominated by minor losses, with a concentrated loss around polygon 72-73. While this appears significant, the loss from 2003-2005 does not increase with time but remains constant. This loss could be explained by losses in response to increased beach volumes prior to 2003 or an extracted volume in 2004 causing beach volumes to be lower than the baseline year in 2003. The gain in 2005 at Polygon 90 to 100 can be explained by the capital recharge scheme depositing 100,000m^3 into the east of the unit. The beach has managed to retain these levels showing very little loss with time.

4.1.10 Shoreham (west)



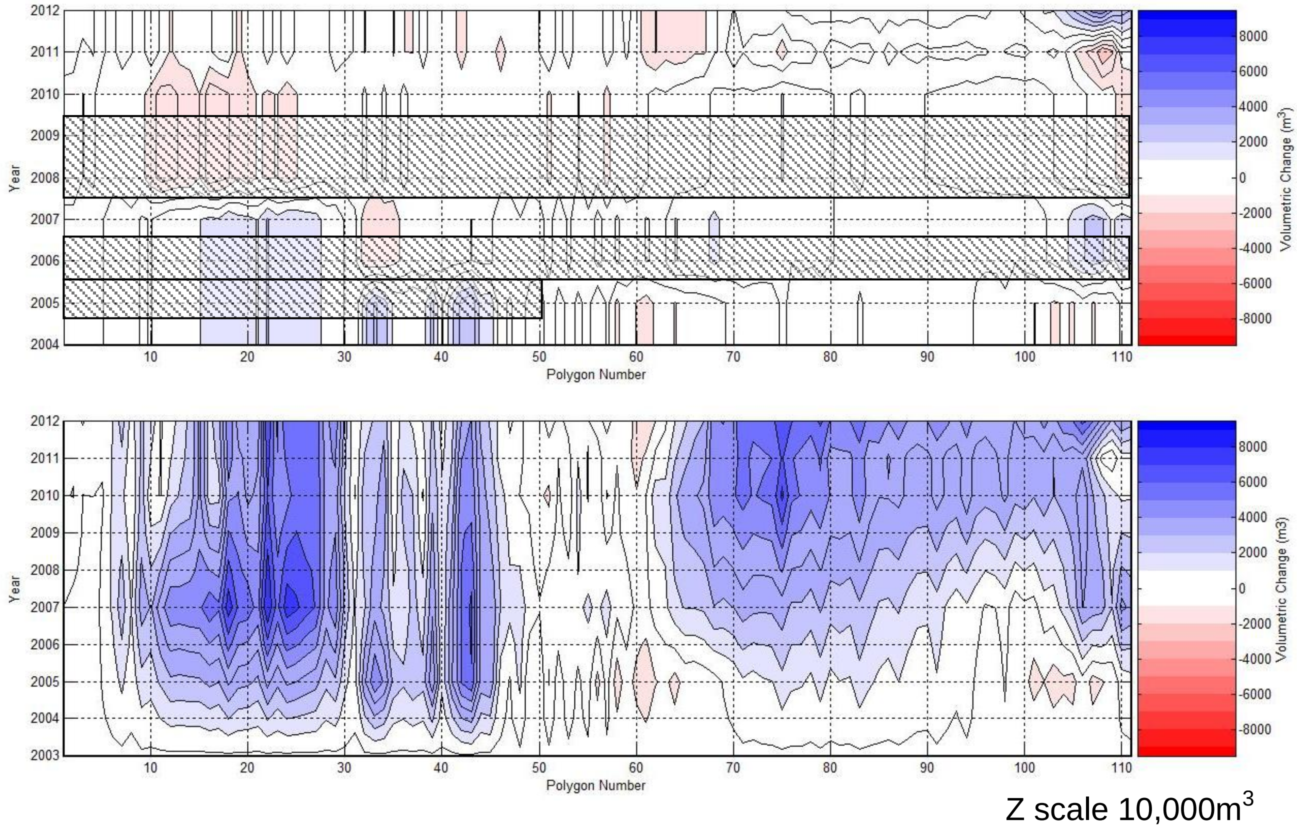
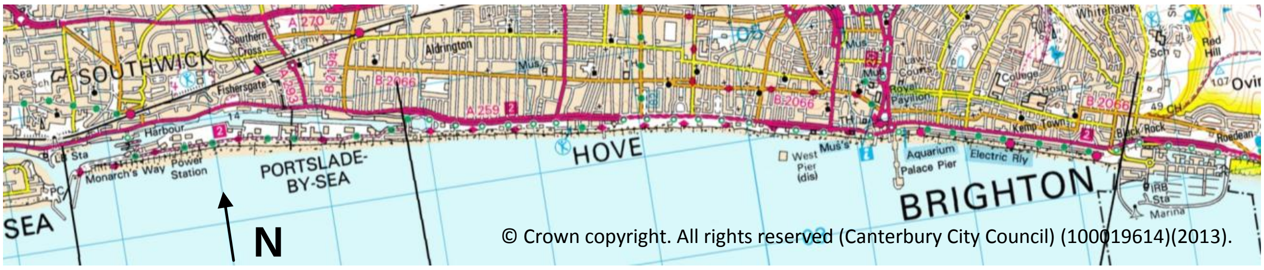
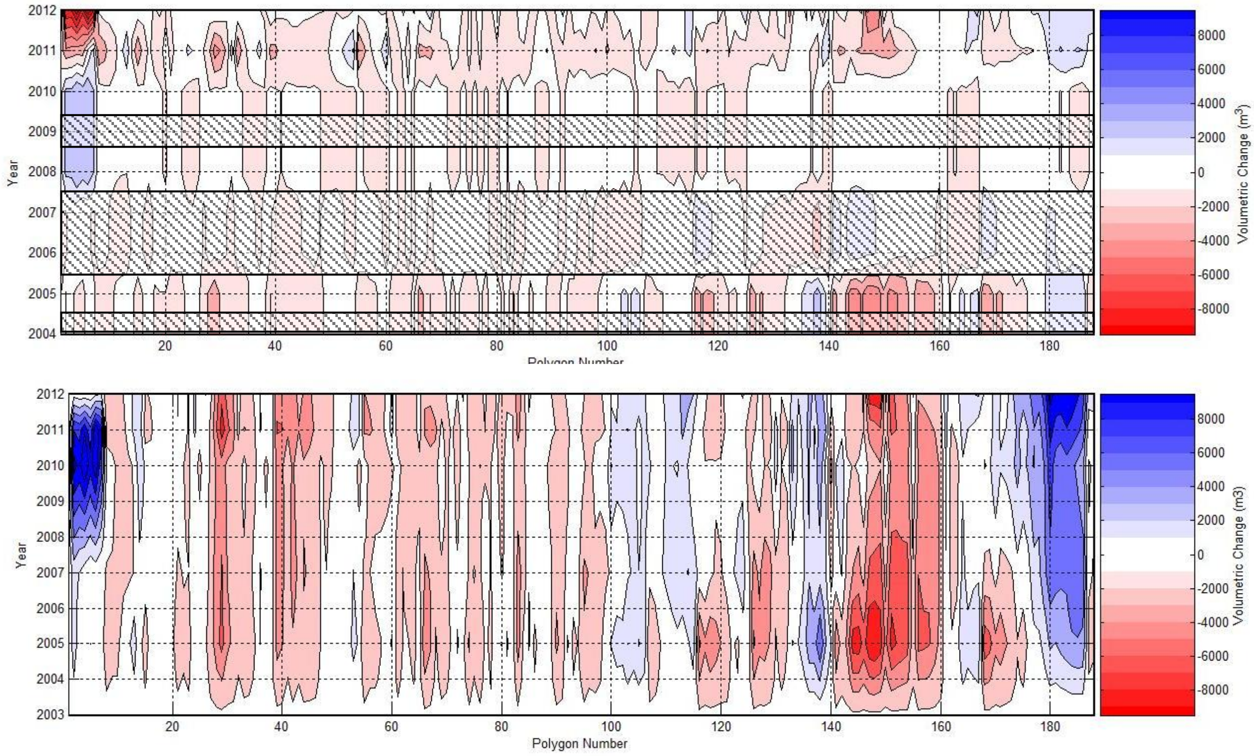


Figure 4-12 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Shoreham since 2003

The sink for the losses from the previous three contour plots can be seen here. There is a significant accretion of material across the whole unit. The gains from Polygon 61 onwards can be considered as natural gains due to the terminal structure at Shoreham Harbour trapping material moving in the dominant drift direction from west to east. The gains in 2007 are due to the Shoreham to Lancing Scheme which deposited over 200,000m^3 of recharged material, with losses associated with the scheme shown to 2012. In 2011 a large extraction at the harbour arm can be seen at Polygon 108, returning beach levels to a 2003 volume. However by 2012, this area has already begun to show large gains.

4.1.11 Shoreham Harbour to Brighton Marina





Z scale 10,000m^3

Figure 4-13 Year on year (top) and cumulative (bottom) contour plot for beach volumetric change at Brighton since 2003

Polygons 1 to 5 show a large volumetric increase since 2007. This is due to regular bypassing of shingle round the harbour mouth. The majority of the unit is dominated by erosion, with pockets of accretion noted at Polygon 132 to 140 at the large controlling structures adjacent to the pier. The beach immediately east of the pier becomes more open, showing greater magnitude of losses to the rest of the unit. The terminal structure at Brighton Marina has caused a consistent build up of material, preventing sediment from being transported further east.

Figure 4.14 summarises the findings from the Spatio-temporal plots by providing a cumulative annual loss or gain from each frontage over the reporting period. This can provide a direct comparison between each frontage, to identify their behaviour in relation to the adjacent frontages. Elmer and Selsey Bill indicate year on year losses shown in Figure 4.3 and 4.7. In contrast, Pagham Harbour is naturally accreting along an open beach, allowing the spit to extend freely. Further east, Shoreham (west) is accreting adjacent to a terminal structure; however the capital scheme in 2005 explains the significantly larger beach volumes. Note: As Pagham Harbour unit contains both the accreting spit and the eroding eastern section of Pagham Harbour, total volume changes are less than those quoted for the spit growth alone.

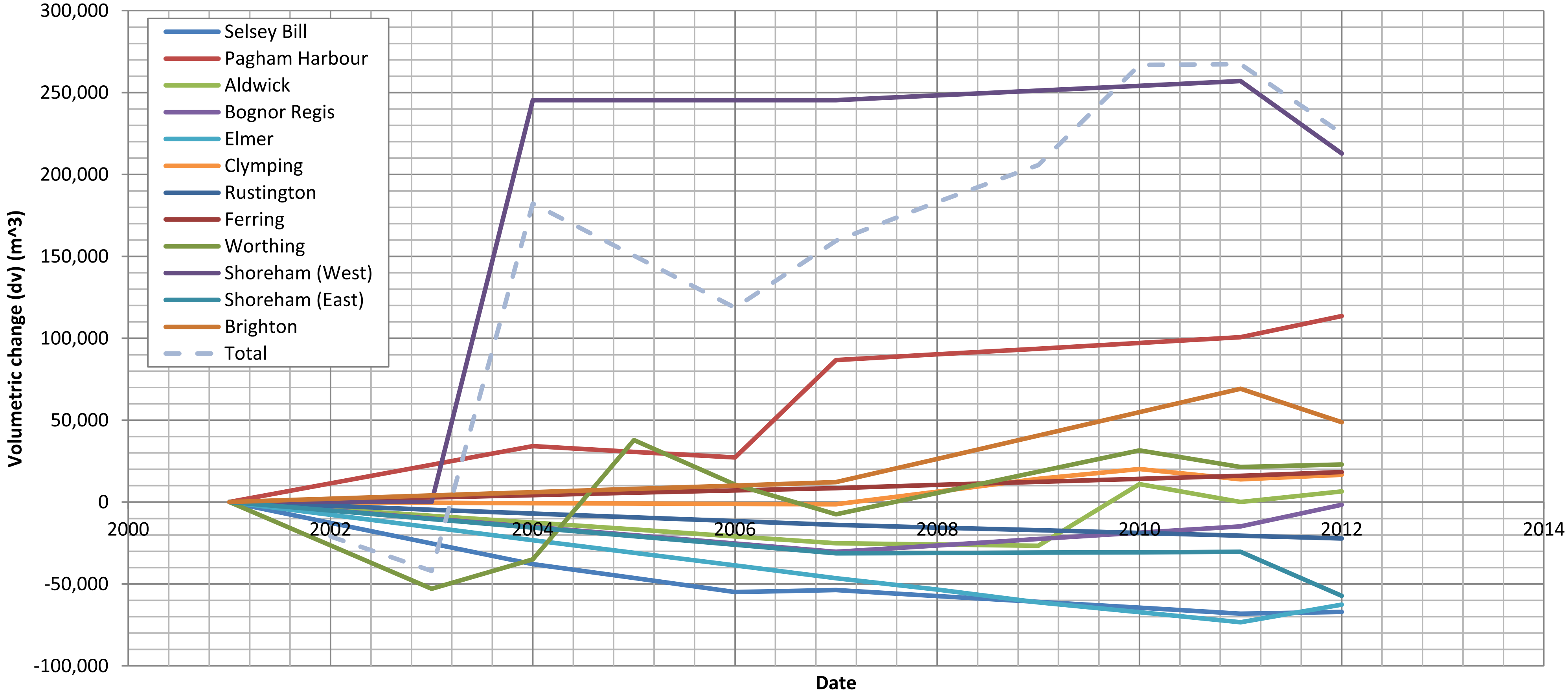


Figure 4-14 Cumulative volumetric change (dv) on all frontages since 2001

4.2 Level 3 - Coarse Sediment Budget

The level 3 sediment budget breaks down the management units into sub-cells according to similar coastal processes. The data is provided in visual and tabular format in the proceeding pages. The sediment budgets have been split into 3 interrelated sediment budgets due to the presence of large terminal structures. They are still, however, linked through management activities as well as small shingle movements so are to be considered in the same Beach Management Plan.

Explanation of the behaviour of Selsey Bill to Littlehampton

The contour plots highlighted that the gain at Pagham spit was greater than the loss at Selsey Bill. Pagham harbour spit has grown 700m since 2001, and when quantified through difference models equates to a gain of 280,000m^3 or 28,000m^3/year (Polygons 4 and 5). Applying the principles of conservation of mass (volume) for the cells of the spit and those leading up to the spit shows a transport rate in the order of 7,700m^3/year entering polygon 4; producing a residual volume of 20,319m^3/year of unaccounted accretion on the spit. Since the dominant wave direction is from the south west, very little (if any) sediment is thought to cross over the river mouth from the east to west.

May et al. (2003) highlights a strong offshore feed of sediment at two locations, adjacent to the spit and at the tip of Selsey Bill. On analysis of photographs for the area, large offshore shingle banks are clearly evident which could be interacting with the coastline. The large shingle banks of Malt Owers and The Streets, at between -1m and -3mAOD extend 1000m offshore. Without regular multi-beam bathymetric surveys, calculations of the volumetric change on these banks are not possible. However, in order to balance the cells at Spit, a volume in the order of 12,500m^3/year needs to be sourced offshore from these locations.

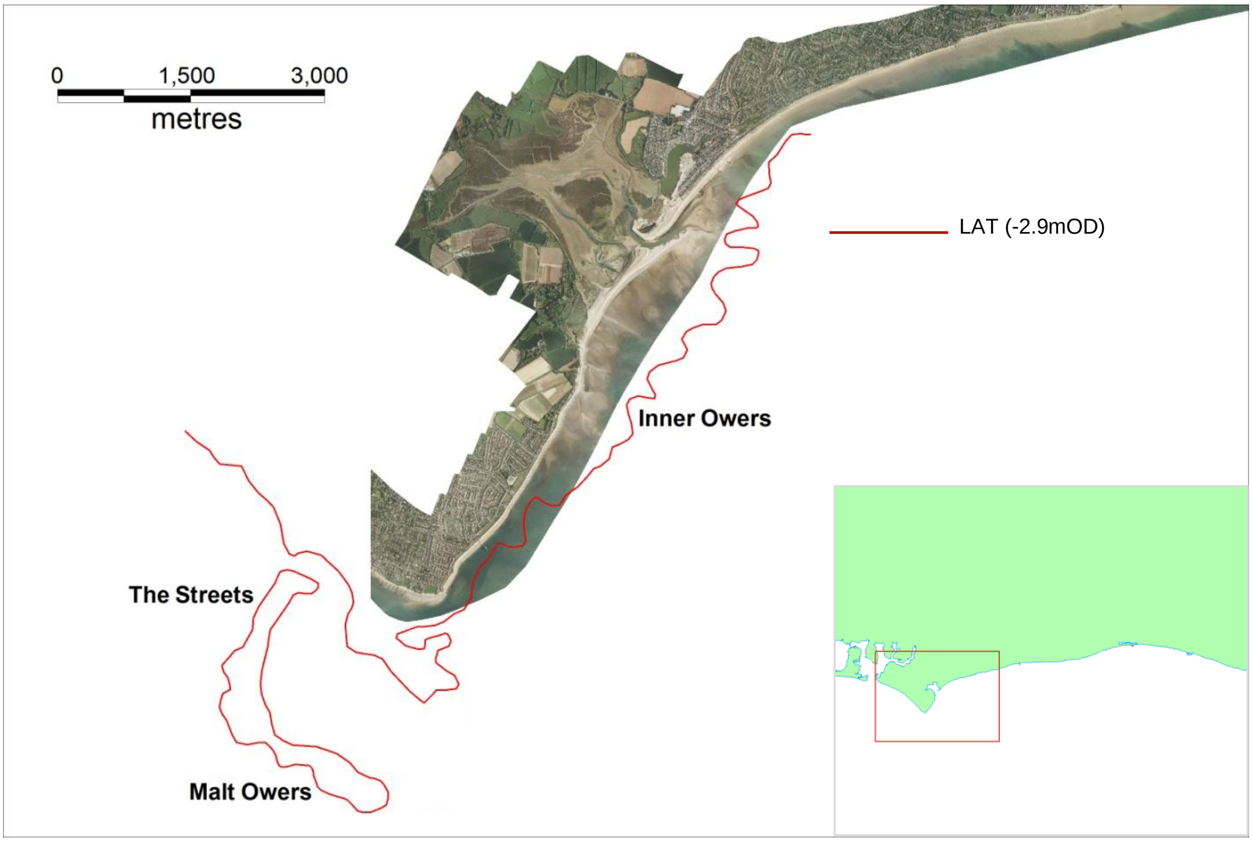


Figure 4-15 Locations of offshore shingle banks

Two single beam surveys were undertaken for the banks fronting Pagham Spit. Difference models were calculated for the foreshore of the beach fronting the west of the Harbour, and analysis polygons calculated a net loss from the foreshore. An example of a difference model calculation for Pagham spit is provided below, highlighting the losses experienced on the foreshore.

Figure 4-16 Example difference model from 2011-2007 at Pagham Harbour

Source: www.westsussex.info

These banks are known to feed shingle onto the spit and so the calculated losses were fed into the cells, as a means of quantifying the onshore transport at this location. In reality, this transport rate is probably higher as there is a seaward feed of material, which still registers a net loss in the polygons created here, so there is the additional volume entering the cell that is moved on.

With the additional feed of material from the two offshore locations, the cells at Pagham spit could be balanced, with 909m^3/year passing over the mouth of the Harbour. The foreshore fronting the eastern part of Pagham Harbour showed a net gain in sediment. Difference models for the beach showed continual erosion within the sheltered portion of the harbour. It is thought that there is a transport mechanism of shingle from the beach onto the foreshore through fluvial erosion of the beach. Hence 4,500m^3/year of the 7,000m^3/year loss from this section is shown to be transported onto the foreshore.

The transport rates vary across the frontage as a result of defence structures and anthropogenic influences. A combination of losses at Selsey and material transported onshore means 15,699m^3 is transported through Selsey Bill to Pagham Harbour. Within Pagham this volume is intensified to a maximum transport rate of 22,391m^3. Material accumulates along Pagham Harbour beach, reducing the transport rate further down the coast. The eastern side of Pagham Harbour transports 3,506m^3 into Aldwick. Transport rates are in the region of 2,000m^3 and 6,000m^3 throughout Aldwick, which reduce further throughout Bognor Regis to 140m^3 to 1,600m^3 due to the timber groyne field slowing longshore transport. Elmer exports

7,000m^3 into Climping which exceeds transports rates of 30,000m^3 due to annual recycling. A total of 3,838m^3 is believed to leave Climping through cross shore movement and accumulate on the high foreshore of Littlestone.

Explanation of the behaviour of Littlehampton to Shoreham

The 3,838m^3/year residual volume remaining at Climping was deemed to be able to be transported around Littlehampton harbour onto the high foreshore. There is well documented evidence of shingle movements into the Littlehampton channel as well as around the trailing walls.

In general, sediment transport rates from Littlehampton to Shoreham Harbour are low at 1,000-2,000m^3/year due to the presence of dense groyne fields and minimal sedimentary input from Rustington. However, this rate increases into Shoreham Harbour as the groynes become wider and more permeable. The largest transport rates are found on the open beach stretch at Shoreham. A residual of -3,190m^3/year is left at Shoreham Harbour, showing that this sediment budget is relatively well balanced, with only a small deficit of material.

Explanation of the behaviour of Shoreham to Brighton Marina

The section from Shoreham Harbour to Brighton Marina has uniform beaches in both sediment type and morphology. Therefore, the decision was taken by the authors to average the residual for this budget across the whole stretch. This works on the assumption that this is a closed sediment cell where limited sediment moves in or out of the unit, this can be justified when looking at the large terminal structures that enclose the unit. Therefore, the residual produced is a combined error of the general rules for attrition, recharge and recycling as well as the survey error in the data collection. This assumes that the loss is uniform across the coast allowing computation of more plausible transport rates. This was achieved through calculating the total residual for the frontage, -11,177m^3 and dividing it by the length of the beach. When multiplied by the individual sub-cell length, this produces the correction factor or unaccounted losses for each sub-cell, reducing the flux.

$$Distance\ Weighted\ Residual\ (DWR) = \ Length\ of\ cell.\left(\frac{residual\ for\ section}{length\ of\ section}\right)$$

As the flux produces the transport rate, it stops a compounding of errors through the unit producing more reasonable transport rates. The final residual for the budget is 0 due to the corrected losses. However, no attempt at hiding the residual has been made, with it still appearing in the total for unaccounted losses.

In general transport rates are larger than on any other frontage in this report and remain fairly consistent at between 8 and 16,000m^3/year. This is due to the open nature of the beaches with limited controlling structures to reduce littoral drift rates.

Table 4-1 Level 3 – Coarse Sediment Budget from Selsey Bill to Littlehampton (m^3/yr)

Cell	Sub-cell	Average annual change (ΔV)	Recharge (P1)	Recycling		Losses			Average annual flux (ΔV-P+R-L)	Qinput/Qoutput from/to foreshore*	Qoutput
				Deposition (P2)	Extraction (R1)	Attrition (L1)	Recharge (L2)	Recycling (L3)			
Selsey Bill	SB1	-6,017	0	0	0	-142	0	0	-5,875	12,500	18,375
	SB2	-1,315	0	0	0	-85	0	0	-1,230	0	19,604
	SB3	1,949	0	0	0	-137	0	0	2,086	0	17,518
	SB4	1,745	0	0	0	-75	0	0	1,820	0	15,699
Pagham Harbour	PH1	489	0	0	0	-81	0	0	571	156	15,284
	PH2	-2,606	0	0	0	-42	0	0	-2,564	1,300	19,148
	PH3	-2,514	0	0	0	-81	0	0	-2,434	810	22,391
	PH4	9,674	0	0	0	-108	0	0	9,783	-55	12,553
	PH5	18,391	0	0	0	-98	0	0	18,489	6,845	909
	PH6	-7,180	0	0	0	-127	0	0	-7,053	-4,457	3,506
Pagham/ Aldwick	AW1	-2,952	0	0	0	-141	0	0	-2,811	0	6,317
	AW2	1,816	0	0	0	-140	0	0	1,956	0	4,361
	AW3	1,724	0	0	0	-155	0	0	1,880	0	2,481
Bognor Regis	BR1	1,187	0	0	0	-139	0	0	1,326	0	1,155
	BR2	862	0	0	0	-146	0	0	1,008	0	147
	BR3	-341	0	0	0	-107	0	0	-234	0	380
	BR4	131	0	0	0	-110	0	0	240	0	140
	BR5	-216	0	0	0	-59	0	0	-157	0	297
	BR6	-883	0	0	0	-246	0	0	-637	0	934
	BR7	-639	0	0	0	-116	0	0	-523	0	1,457
	BR8	-249	0	0	0	-67	0	0	-183	0	1,640
Elmer	E1	-2,022	0	0	0	-116	0	0	-1,906	0	3,546
	E2	-3,669	0	0	0	-126	0	0	-3,543	0	7,089
Climping	CL1	-377	0	24,200	0	-146	0	-1,210	-23,221	0	30,310
	CL2	-723	0	0	0	-70	0	0	-654	0	30,964
	CL3	-439	0	0	0	-161	0	0	-278	0	31,242
	CL4	3,056	0	0	-24,200	-148	0	0	27,404	0	3,838
Selsey Bill to Climping		8,883	0	24,200	-24,200	-3,168	0	-1,210	13,262	17,099	

* Qinput/Qoutput - Negative values represent a loss from the beach to the foreshore. Positive values are the onshore gain from the foreshore to the beach.
Note: For sub-cell location diagrams please refer to Section 6.0

Table 4-2 Level 3 – Coarse Sediment Budget from Littlehampton to Shoreham Harbour (m^3/yr)

Cell	Sub-cell	Average annual change (ΔV)	Recharge (P1)	Recycling		Losses			Average annual flux (ΔV-P+R-L)	Qoutput
				Deposition (P2)	Extraction (R1)	Attrition (L1)	Recharge (L2)	Recycling (L3)		
Rustington	R1	-668	0	0	0	-89	0	0	-579	579
	R2	-780	0	0	0	-114	0	0	-666	1,245
	R3	-861	0	0	0	-103	0	0	-758	2,003
	R4	285	0	188	0	-89	0	-9	195	1,808
Kingston Gorse	KG1	329	0	0	0	-138	0	0	467	1,341
	KG2	350	0	0	0	-168	0	0	518	823
	KG3	-838	0	0	0	-113	0	0	-724	1,548
	KG4	481	0	0	0	-114	0	0	595	952
	KG5	1,857	2,727	0	0	-56	-273	0	-542	1,494
	KG6	151	0	0	0	-94	0	0	244	1,250
	KG7	-25	0	59	0	-47	0	-3	-35	1,285
	KG8	-225	0	0	0	-139	0	0	-87	1,372
	KG9	74	0	131	0	-31	0	-7	-19	1,391
	KG10	-480	0	0	-190	-200	0	0	-90	1,480
Worthing	W1	-511	0	0	0	-81	0	0	-430	1,910
	W2	-280	0	0	0	-93	0	0	-187	2,098
	W3	-20	0	0	0	-96	0	0	76	2,022
	W4	292	0	0	0	-60	0	0	352	1,670
	W5	-274	0	0	-158	-52	0	0	-64	1,735
	W6	-144	0	0	0	-52	0	0	-92	1,827
	W7	1,511	0	0	0	-142	0	0	1,653	173
	W8	1,130	1,468	158	0	-155	-147	-8	-186	359
	W9	382	4,405	4,177	0	-119	-441	-209	-7,432	7,791
Shoreham (West)	SW1	2,469	8,879	0	-891	-171	-888	0	-4,460	12,251
	SW2	3,703	11,650	0	-2,777	-118	-1,165	0	-3,886	16,138
	SW3	2,368	7,318	0	0	-119	-732	0	-4,199	20,337
	SW4	-2,903	0	0	0	-151	0	0	-2,751	23,088
	SW5	13,440	0	0	-12,555	-283	0	0	26,278	-3,190
Littlehampton to Shoreham		20,714	36,448	4,713	-16,570	-3,186	-3,645	-236	3,190	

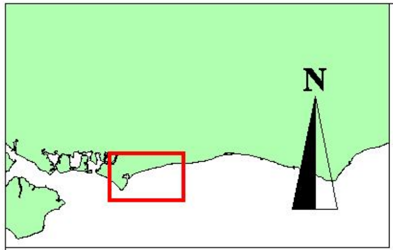
Note: For sub-cell location diagrams please refer to Section 6.0

Table 4-3 Coarse Sediment Budget from Shoreham Harbour to Brighton Marina (m^3/yr)

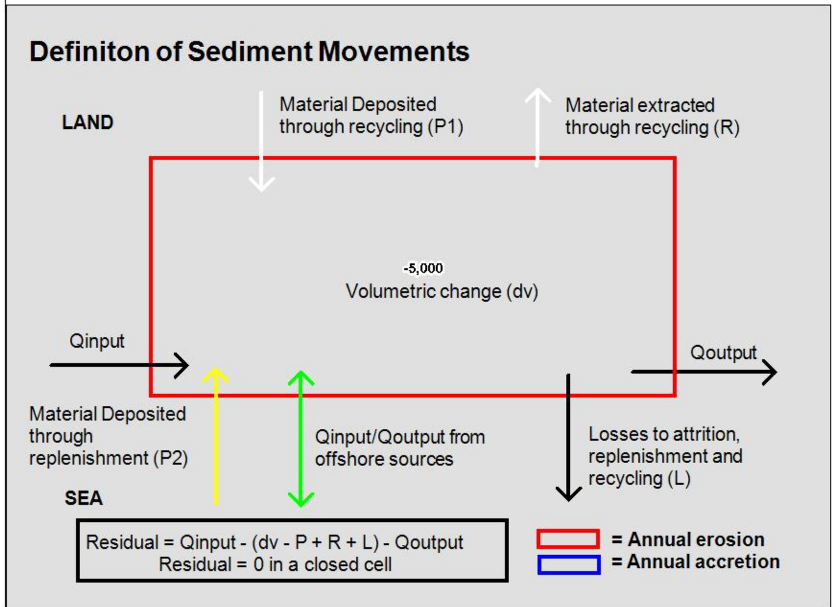
Cell	Sub-cell	Average annual change (ΔV)	Recharge (P1)	Recycling		Losses			Unaccounted losses (DWR)**	Average annual flux (ΔV-P+R-L)	Qoutput
				Deposition (P2)	Extraction (R1)	Attrition (L1)	Recharge (L2)	Recycling (L3)			
Shoreham (East)	SE1	-121	0	13,245	0	-72	0	-662	-549	-12,631	12,083
	SE2	-351	0	0	0	-104	0	0	-789	-247	11,541
	SE3	-3,748	0	0	0	-205	0	0	-1,556	-3,543	13,528
	SE4	-975	0	0	0	-83	0	0	-628	-892	13,792
Brighton	B1	-2,551	0	0	0	-125	0	0	-949	-2,426	15,268
	B2	-2,572	0	0	0	-155	0	0	-1,174	-2,418	16,512
	B3	-606	0	0	0	-124	0	0	-938	-482	16,056
	B4	-2,185	0	0	0	-169	0	0	-1,280	-2,016	16,792
	B5	7,685	0	0	0	-93	0	0	-702	7,778	8,312
	B6	857	0	0	0	-21	0	0	-161	878	7,273
	B7	-315	0	0	0	-21	0	0	-161	-294	7,407
	B8	-2,967	0	0	0	-159	0	0	-1,208	-2,808	9,007
	B9	7,092	0	0	-690	-143	0	0	-1,083	7,924	0
Shoreham Harbour to Brighton Marina		-757	0	13,245	-690	-1,473	0	-662	-11,177	-11,177	

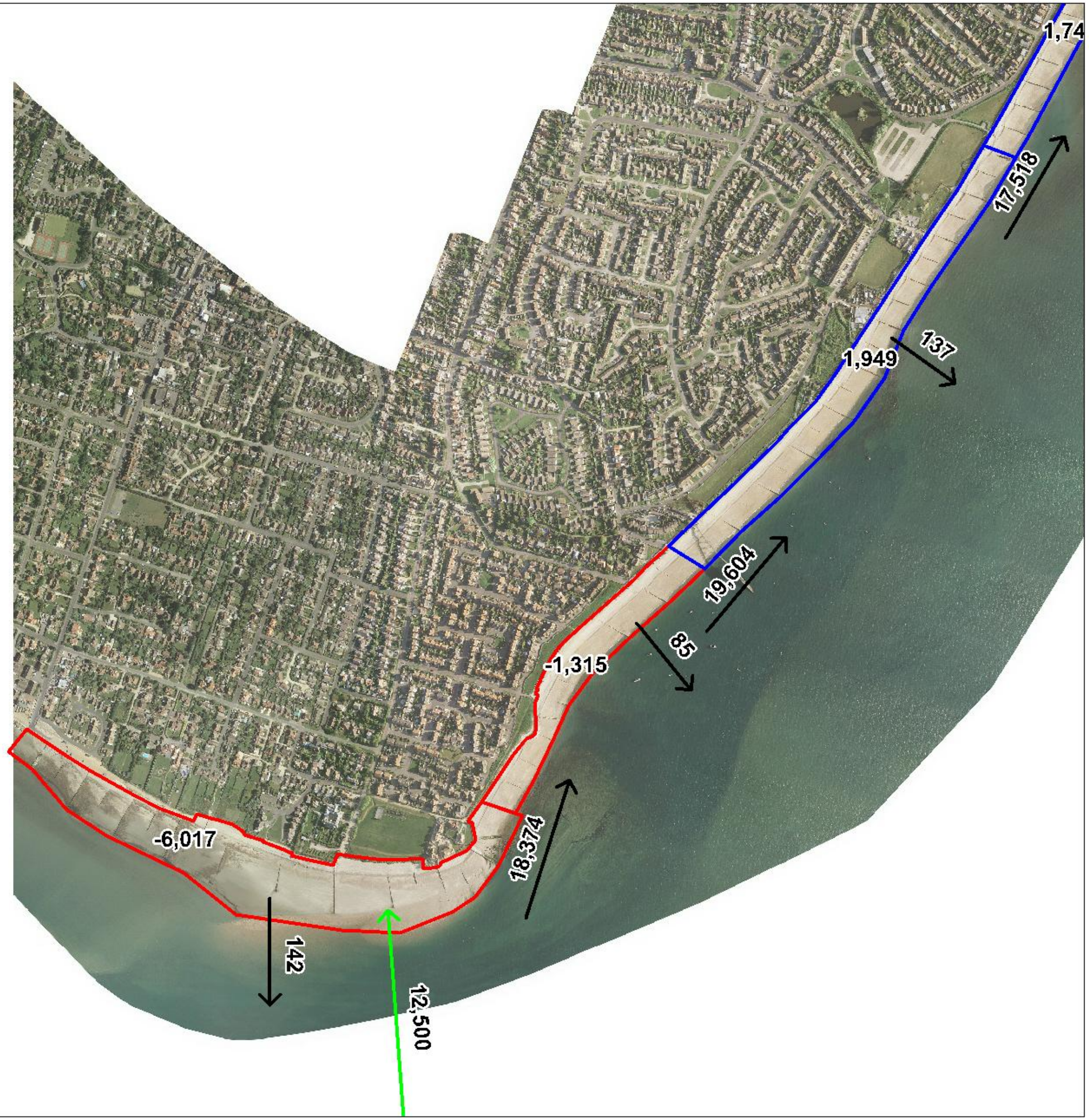
** Distance Weighted Residual represents a further unaccounted loss, created through dividing the residual across the frontage to bring transport rates and behaviour in line with expected trends. See above for more details

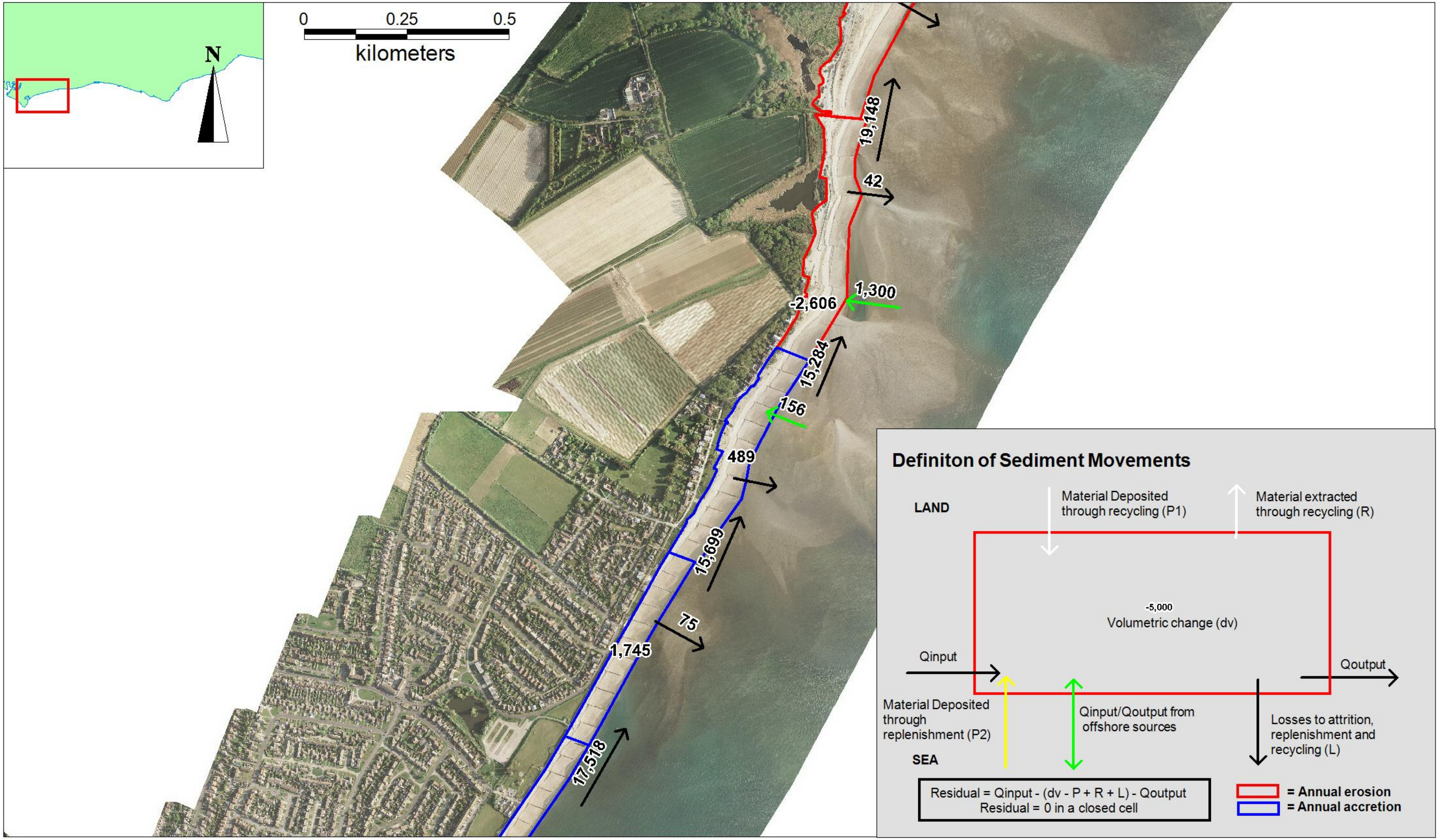
Note: For sub-cell location diagrams please refer to Section 6.0



0 0.25 0.5
kilometers






N
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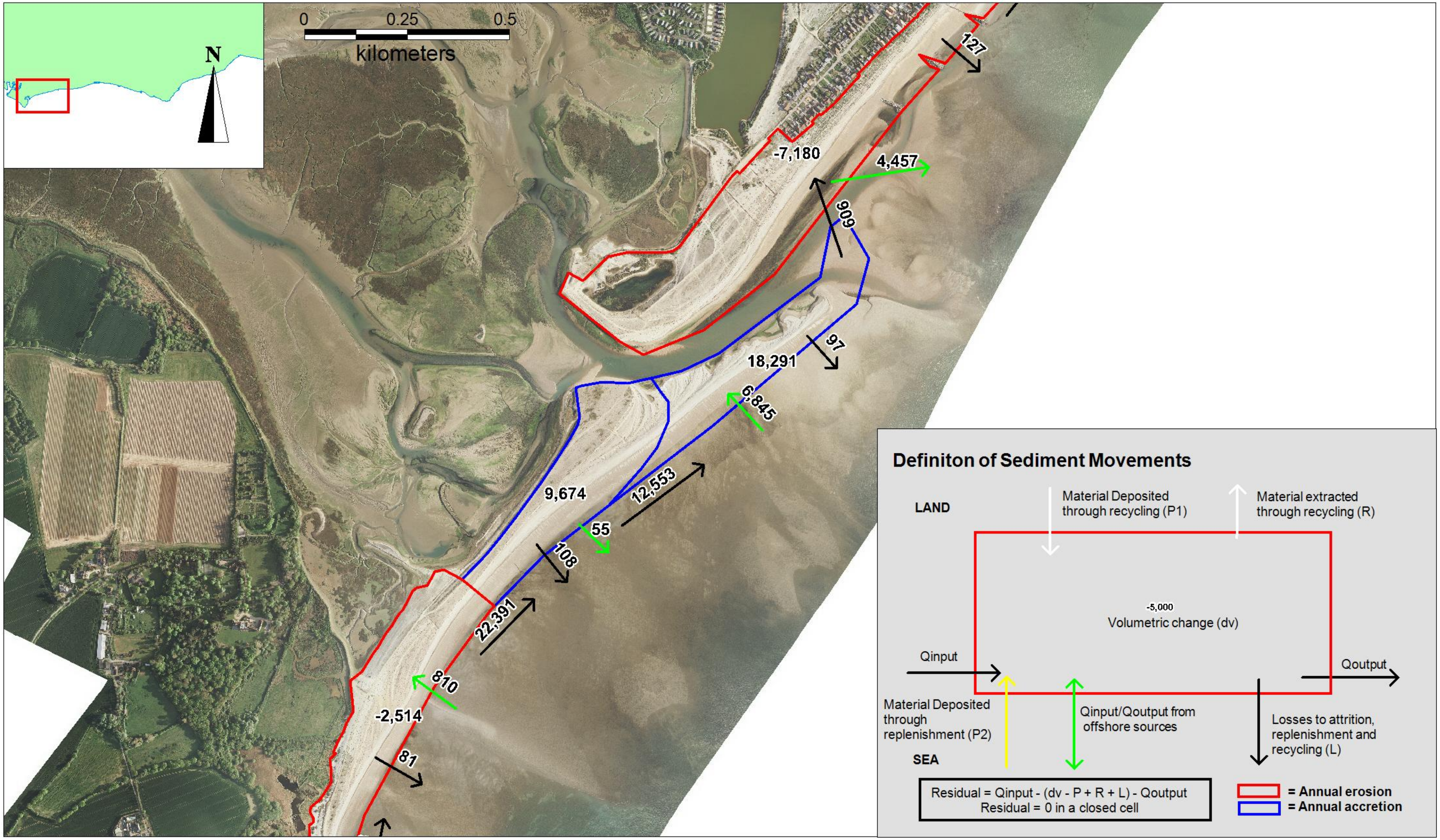
kilometers
19,148
42
1,300
-2,606
15,284
156
489
15,699
75
1,745
17,518
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion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909
97
18,291
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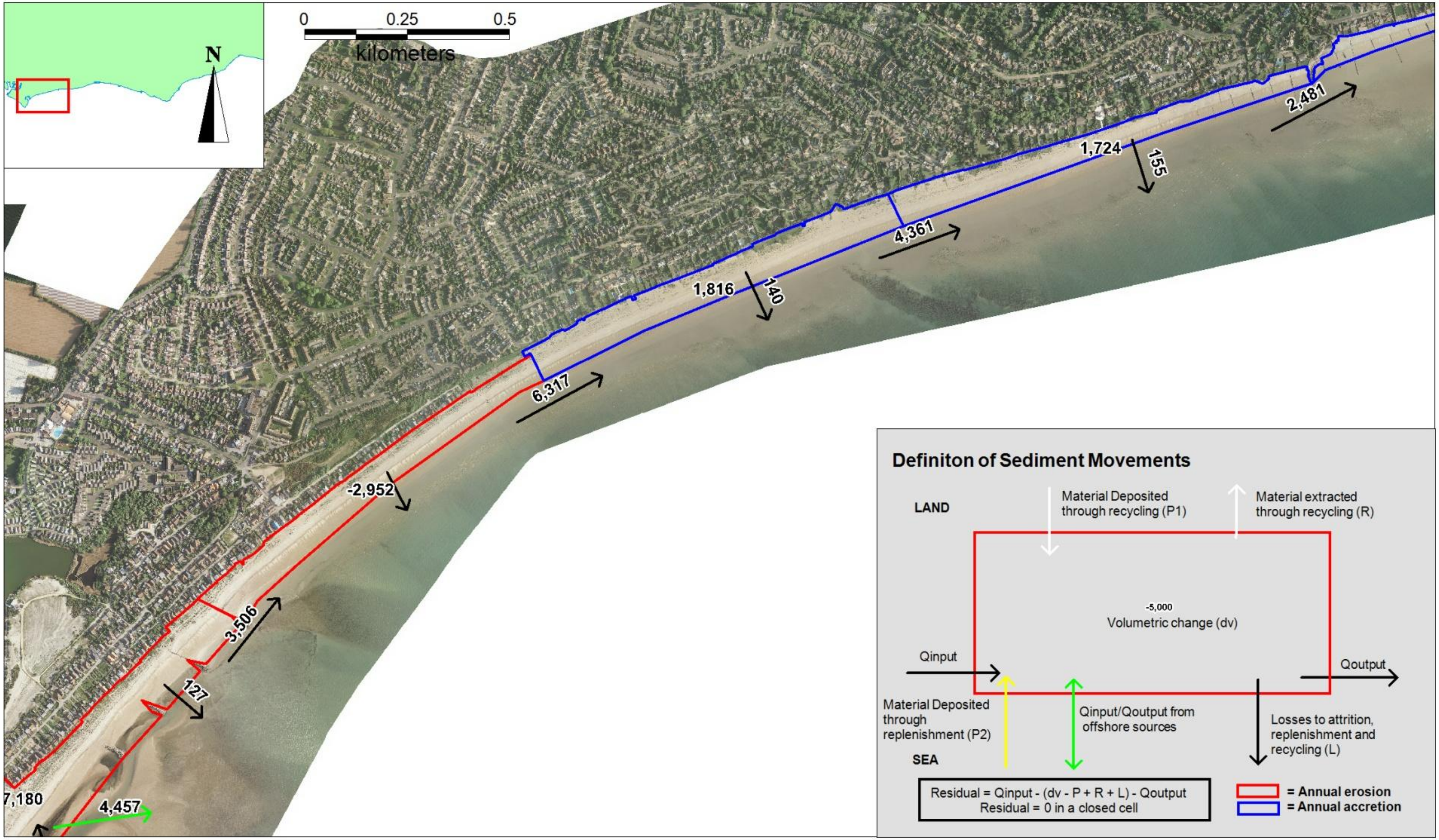
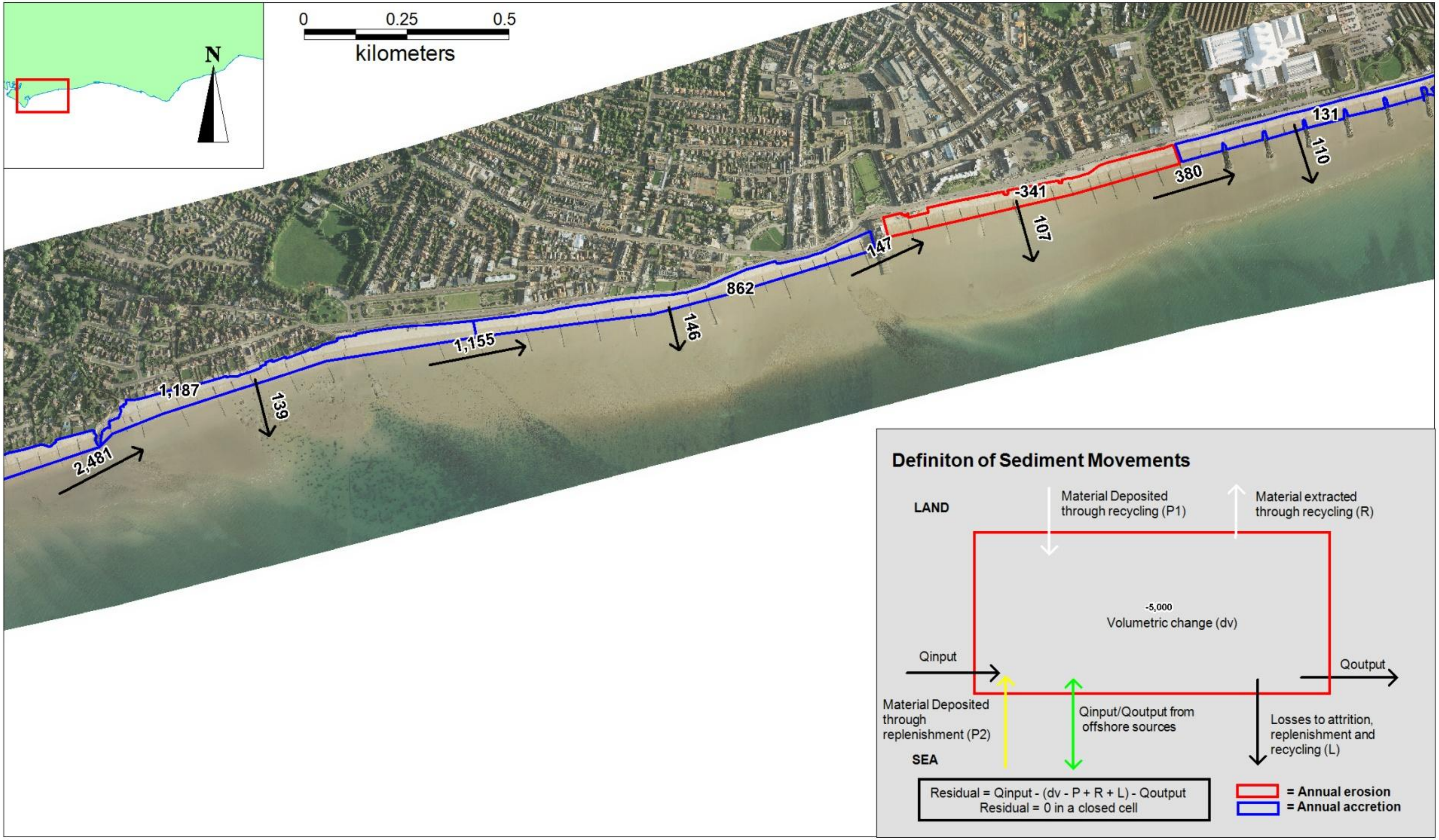
9,674
12,553
55
108
22,391
810
-2,514
81
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion



Selsey Bill to Brighton Marina Sediment Budget

Pagham

Plate 2a (4 of 8)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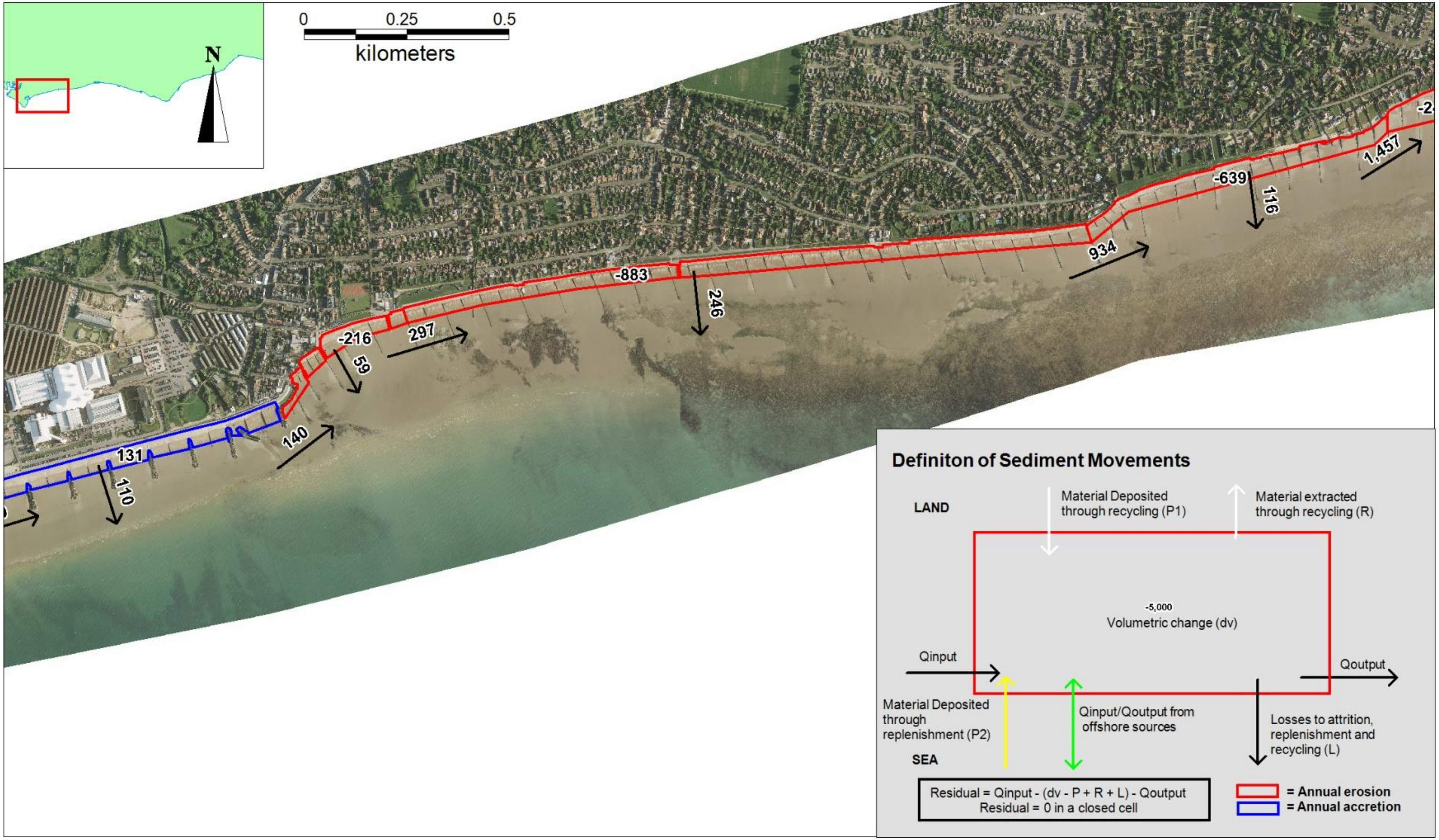
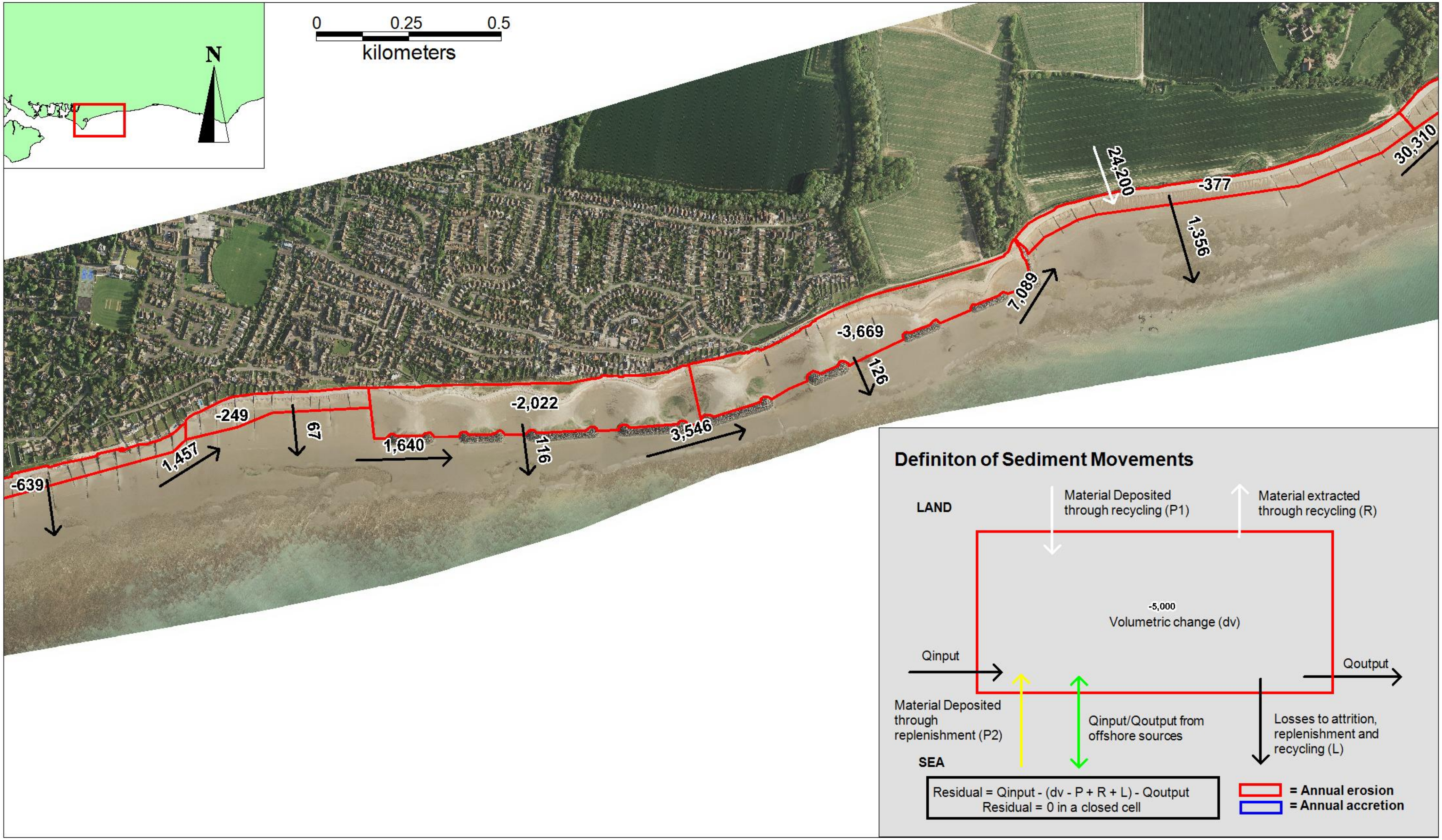
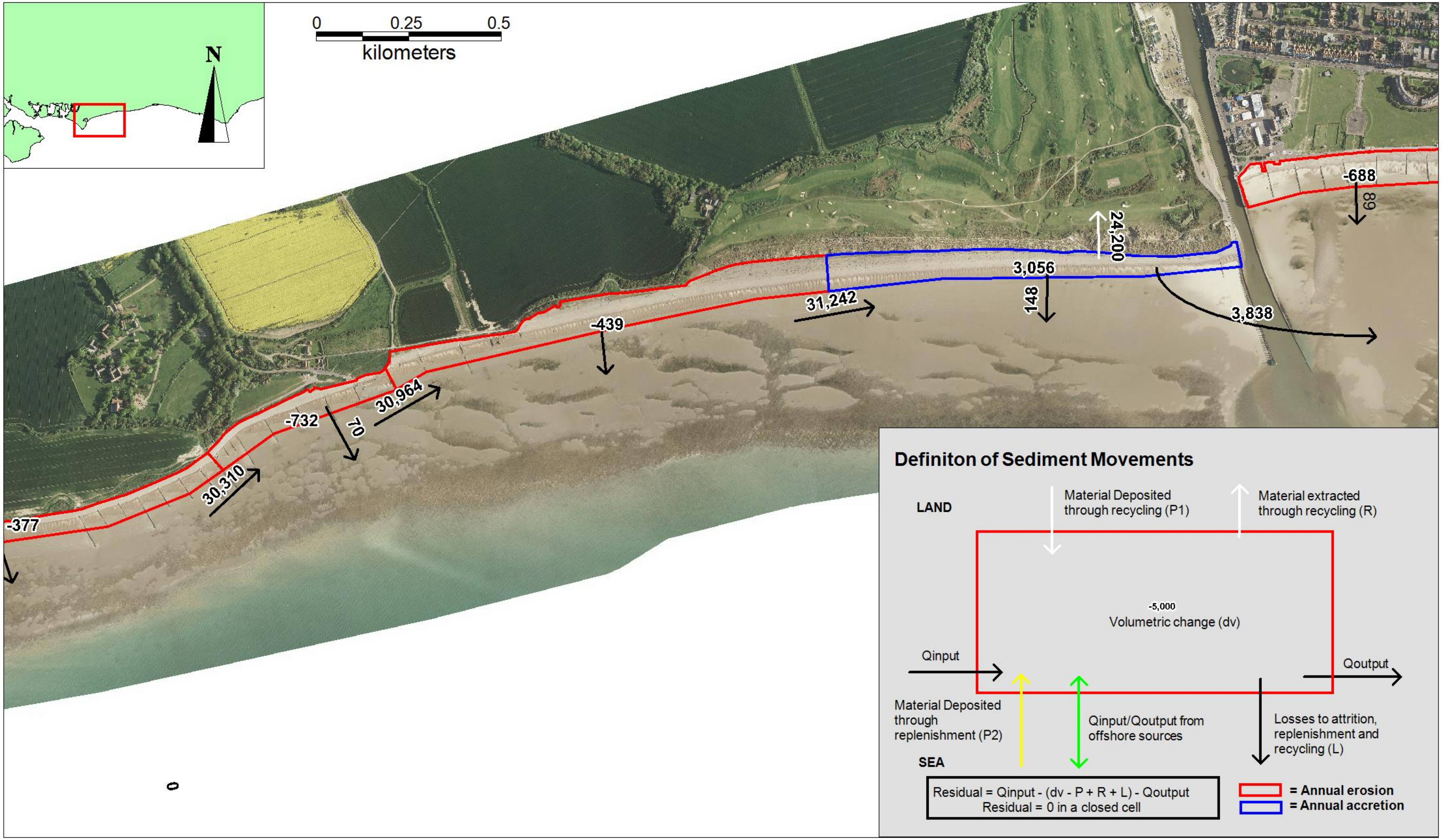
1,155
146
862
147
-341
107
380
131
110
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion


0
0.25
0.5
kilometers
N
-2
1,457
-639
116
934
-883
246
-216
297
59
140
131
110
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion


N
0
0.25
0.5
kilometers
-639
1,457
-249
67
1,640
-2,022
116
3,546
-3,669
126
7,089
24,200
-377
1,356
30,310
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion


0
0.25
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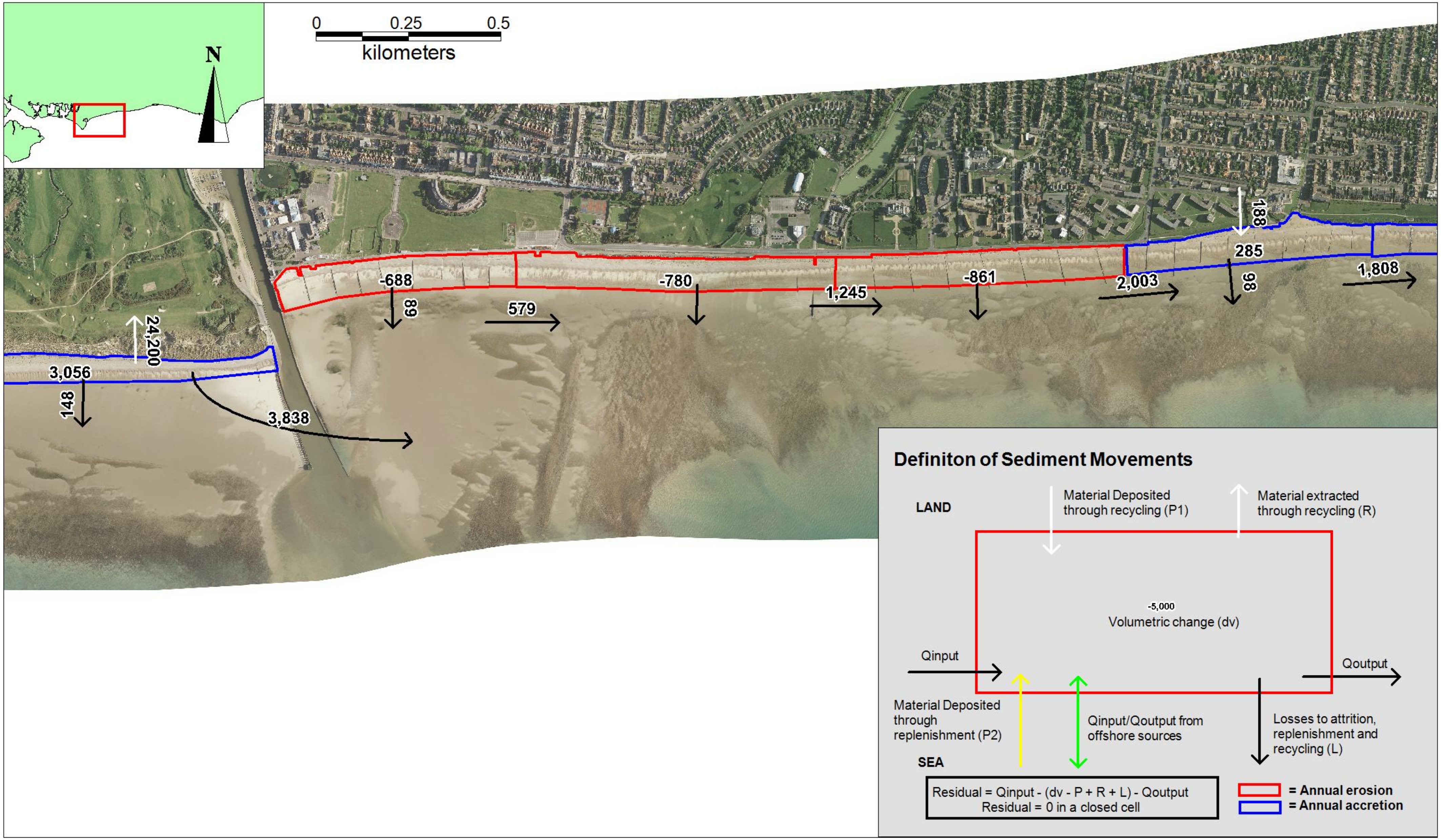
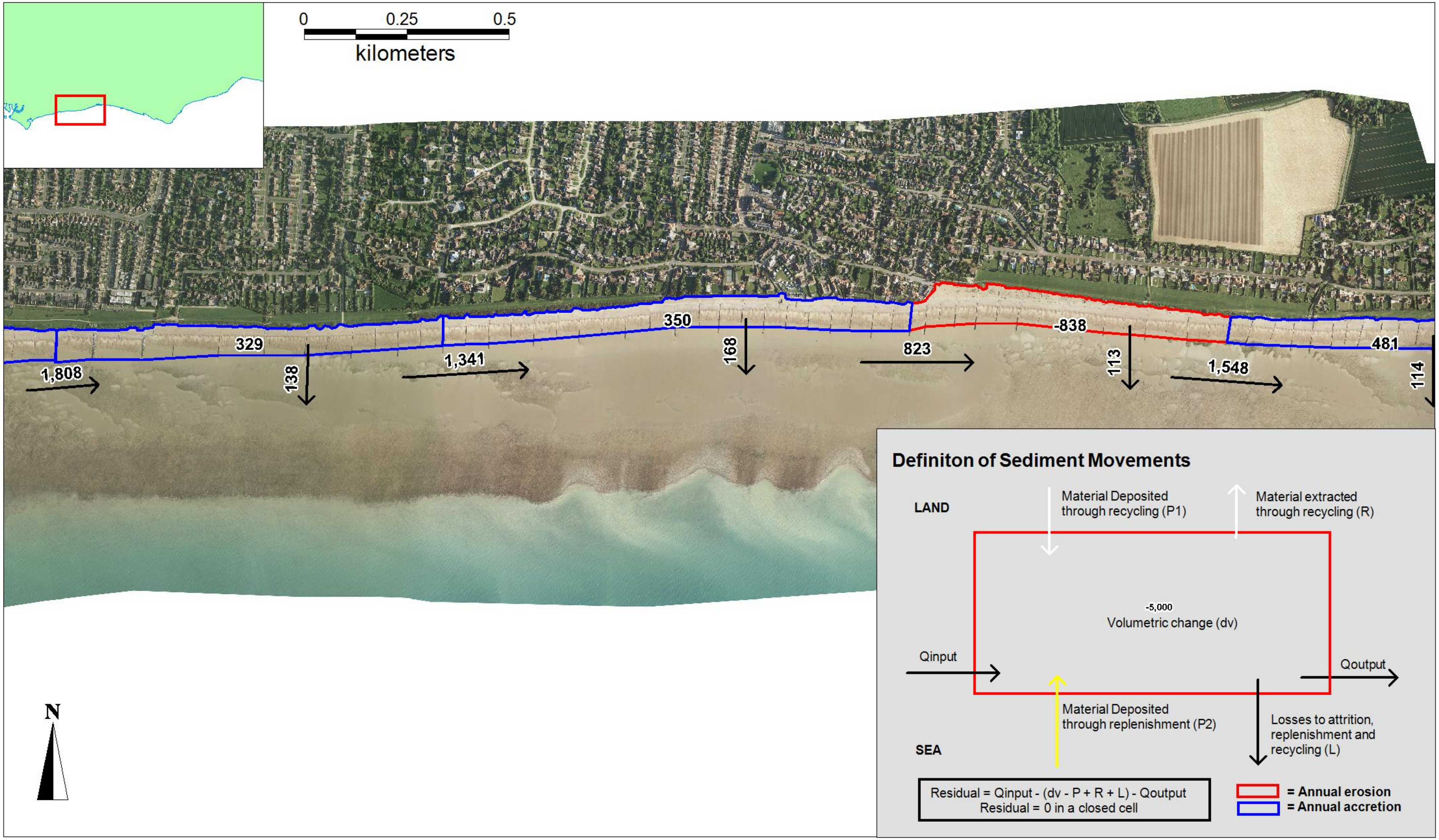
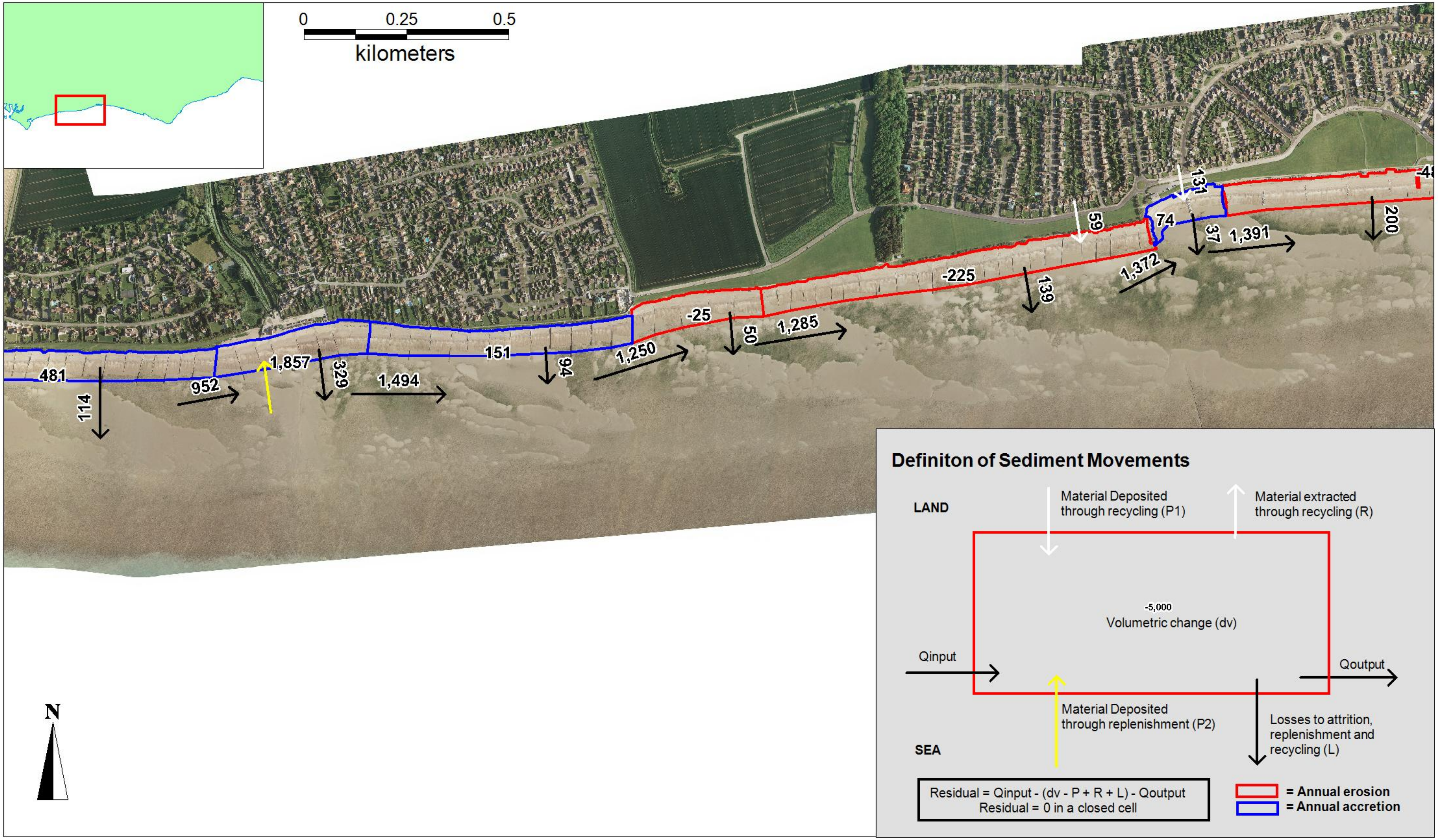
kilometers
N
-688
89
24,200
3,056
31,242
148
3,838
-439
30,964
-732
70
30,310
-377
0
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion

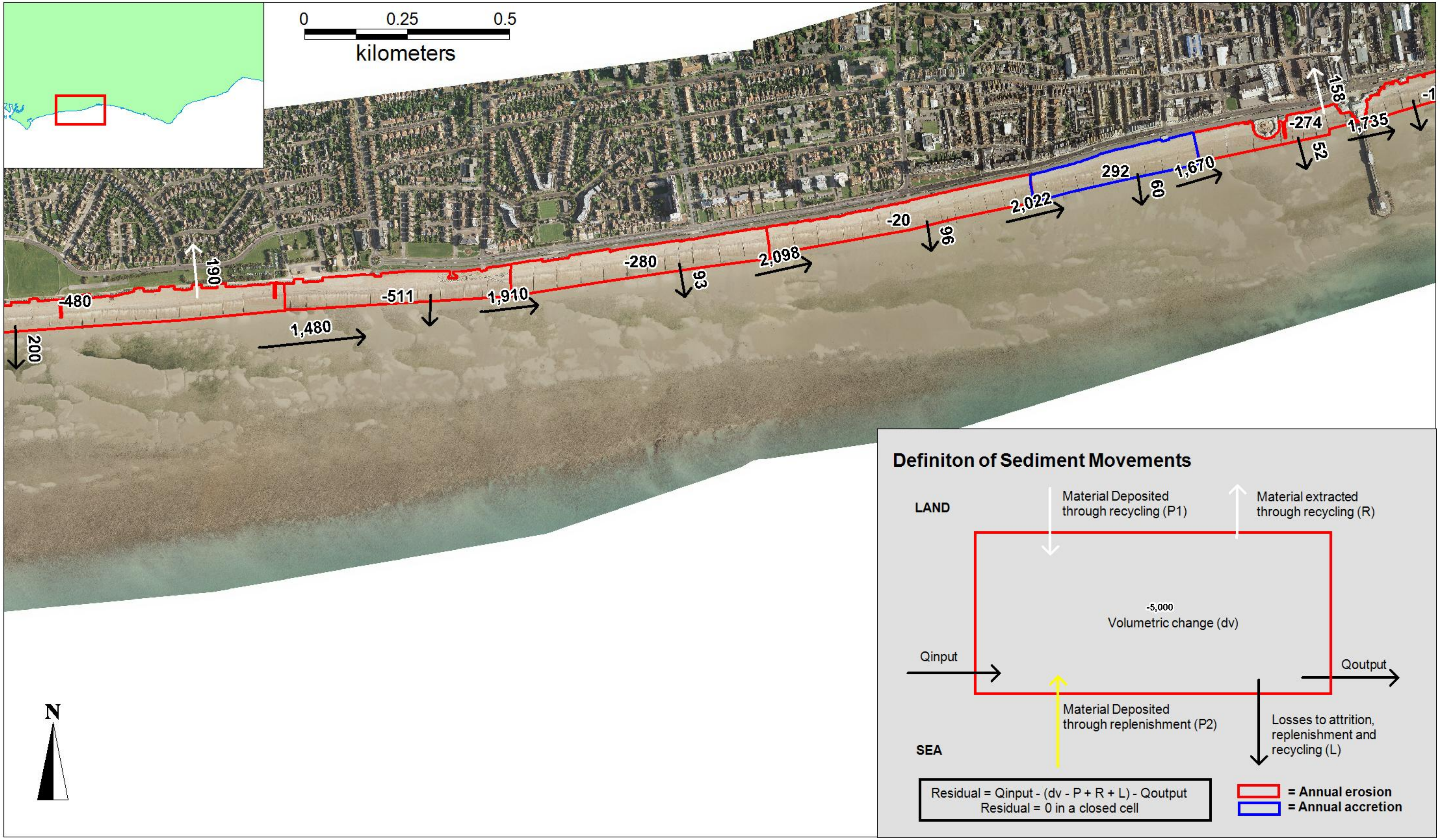

0
0.25
0.5
kilometers
N
-688
89
579
-780
1,245
-861
2,003
285
98
188
1,808
24,200
3,056
148
3,838
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion

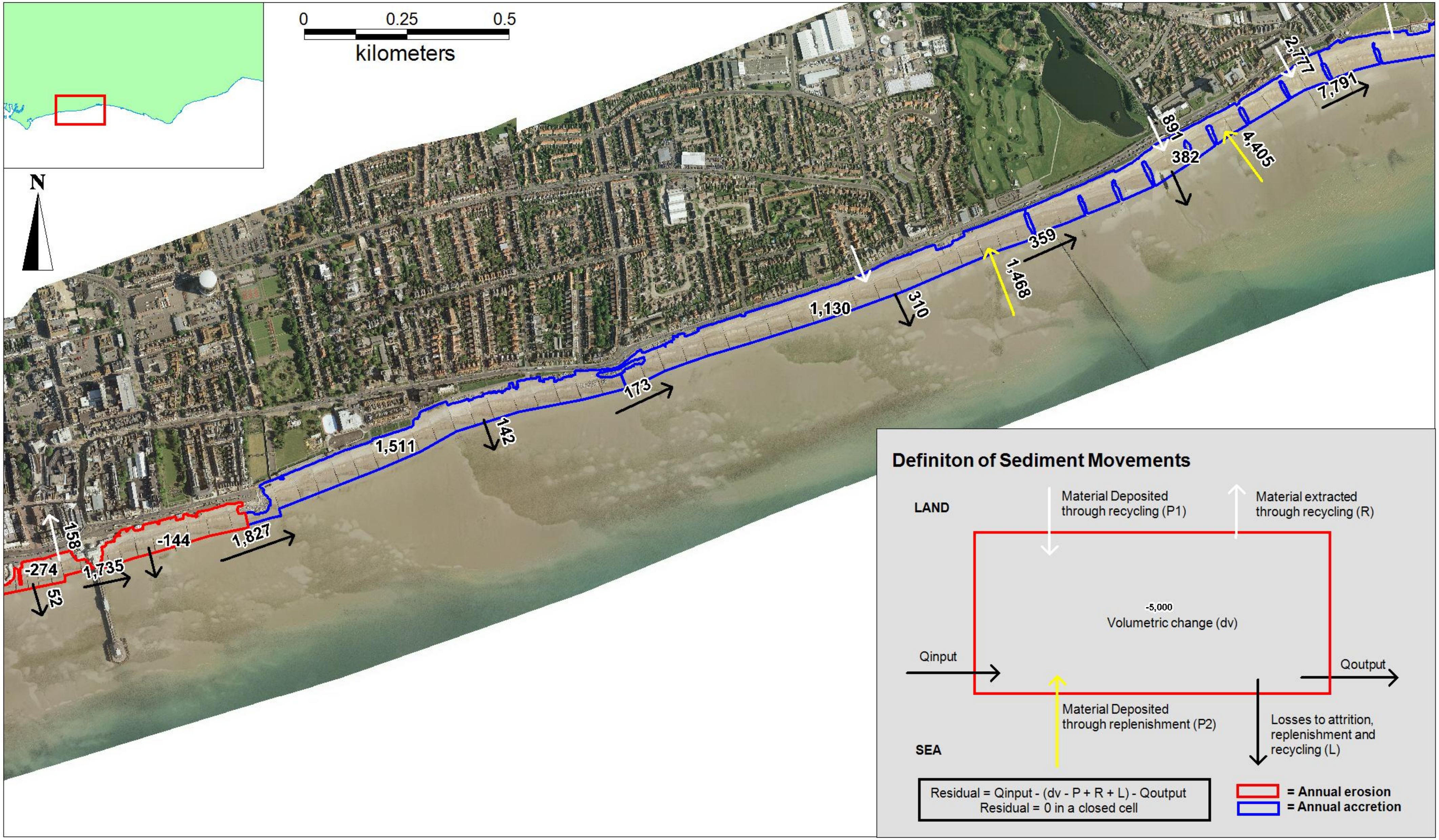

0
0.25
0.5
kilometers
1,808
329
138
1,341
350
168
823
-838
113
1,548
481
114
N
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion

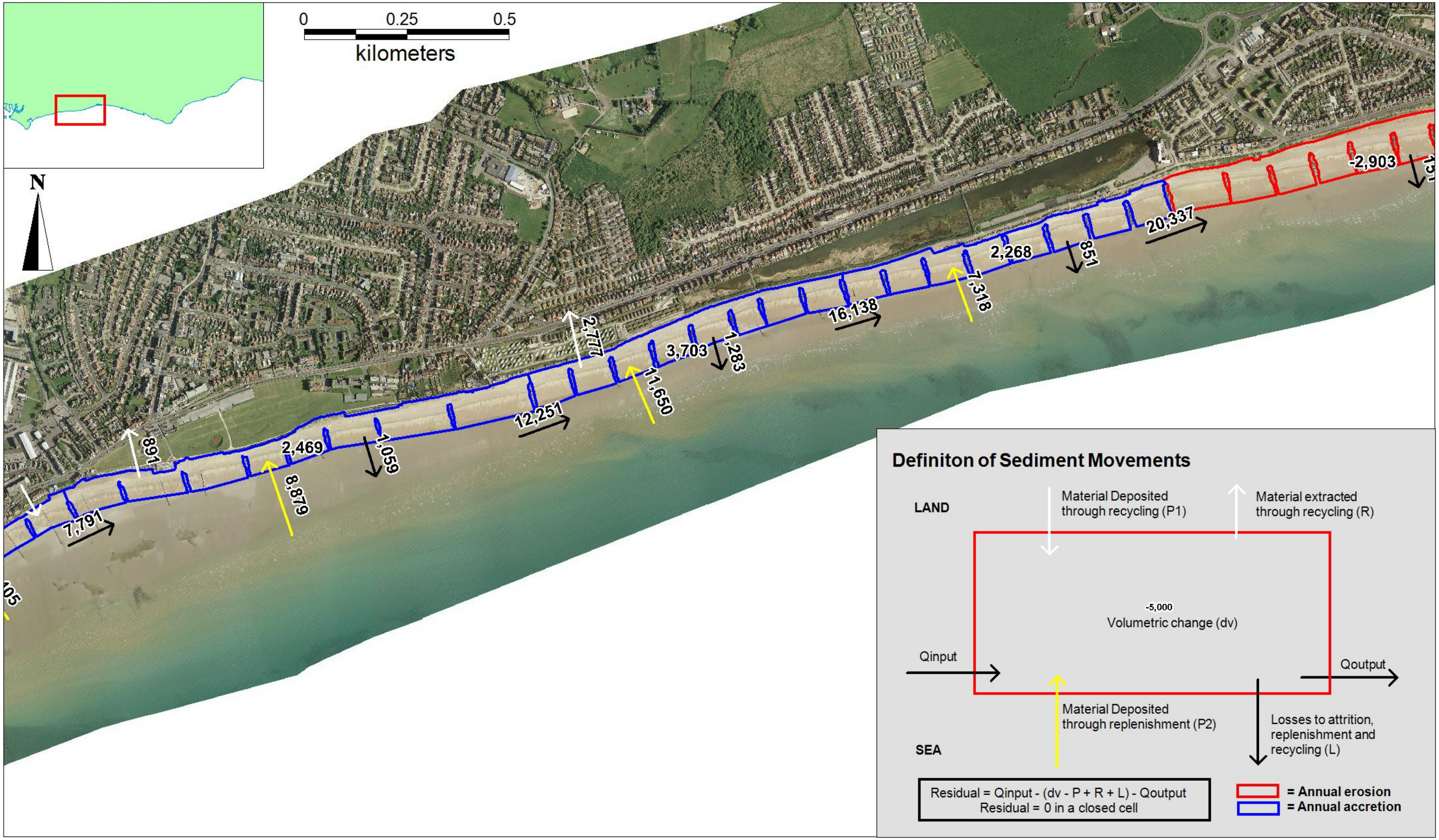
South East Regional Coastal Monitoring Programme **Level 3 - Sediment Budget**

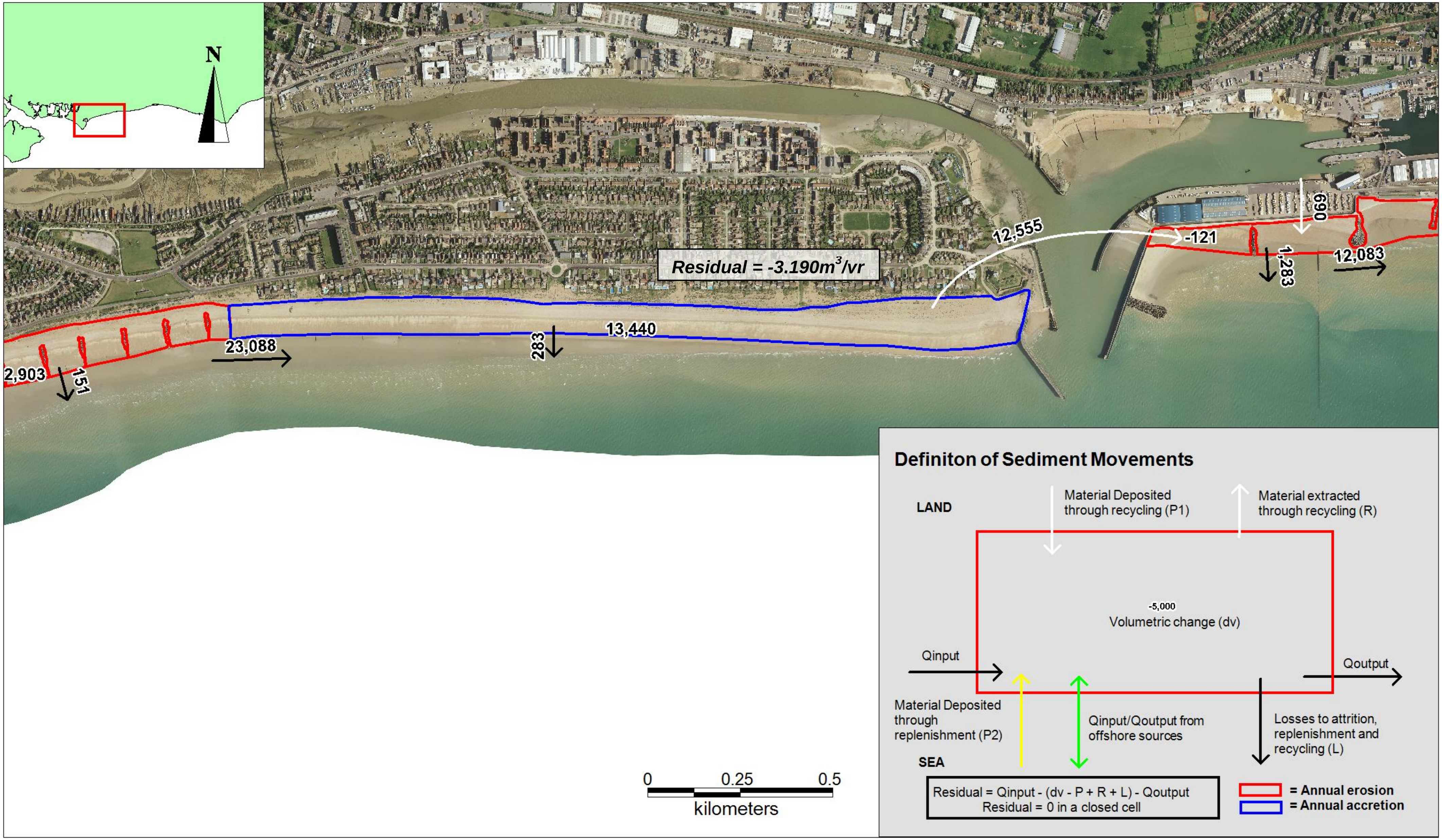


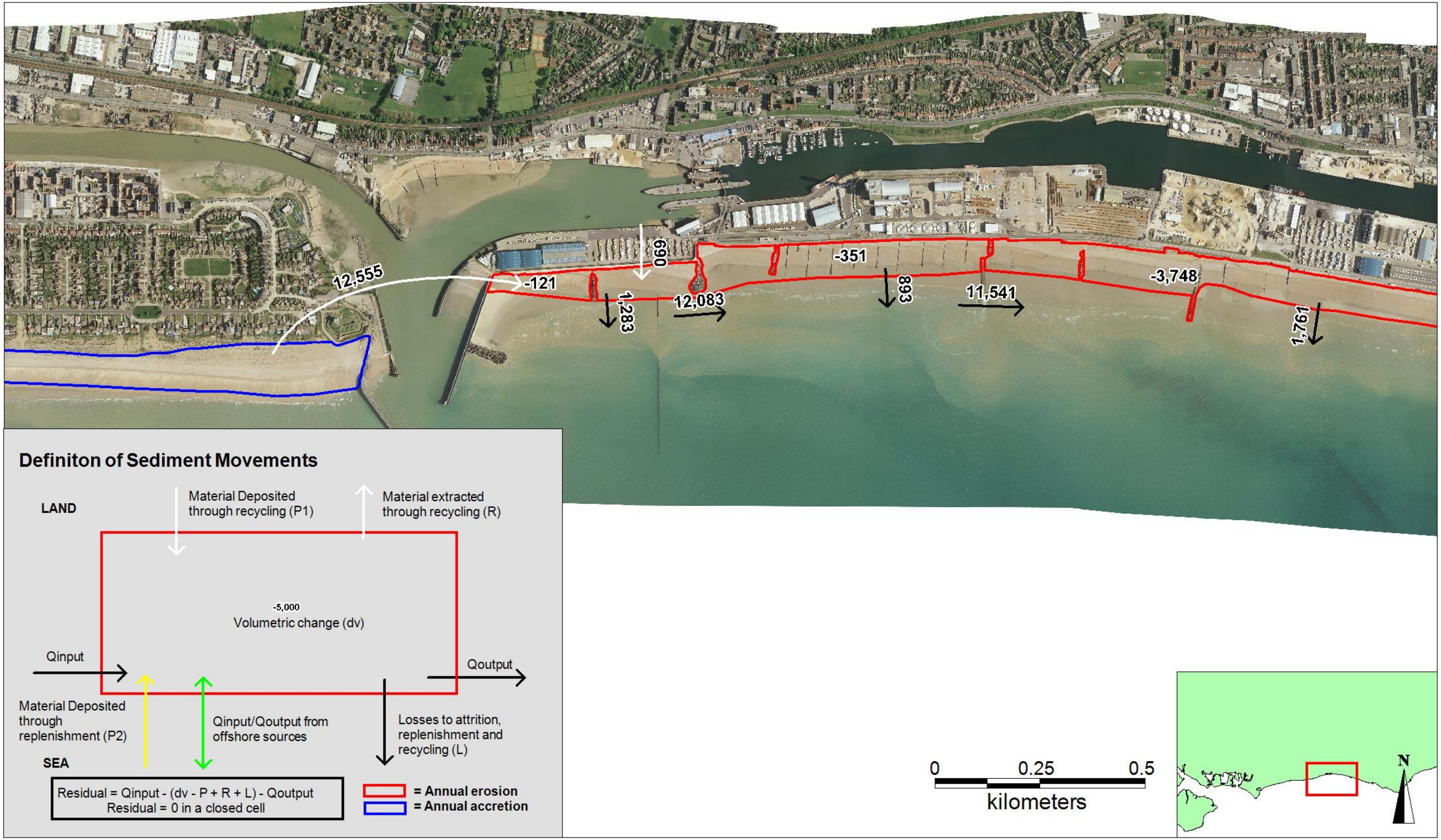
Selsey Bill to Brighton Marina Sediment Budget **Ferring** **Plate 2b (3 of 7)**

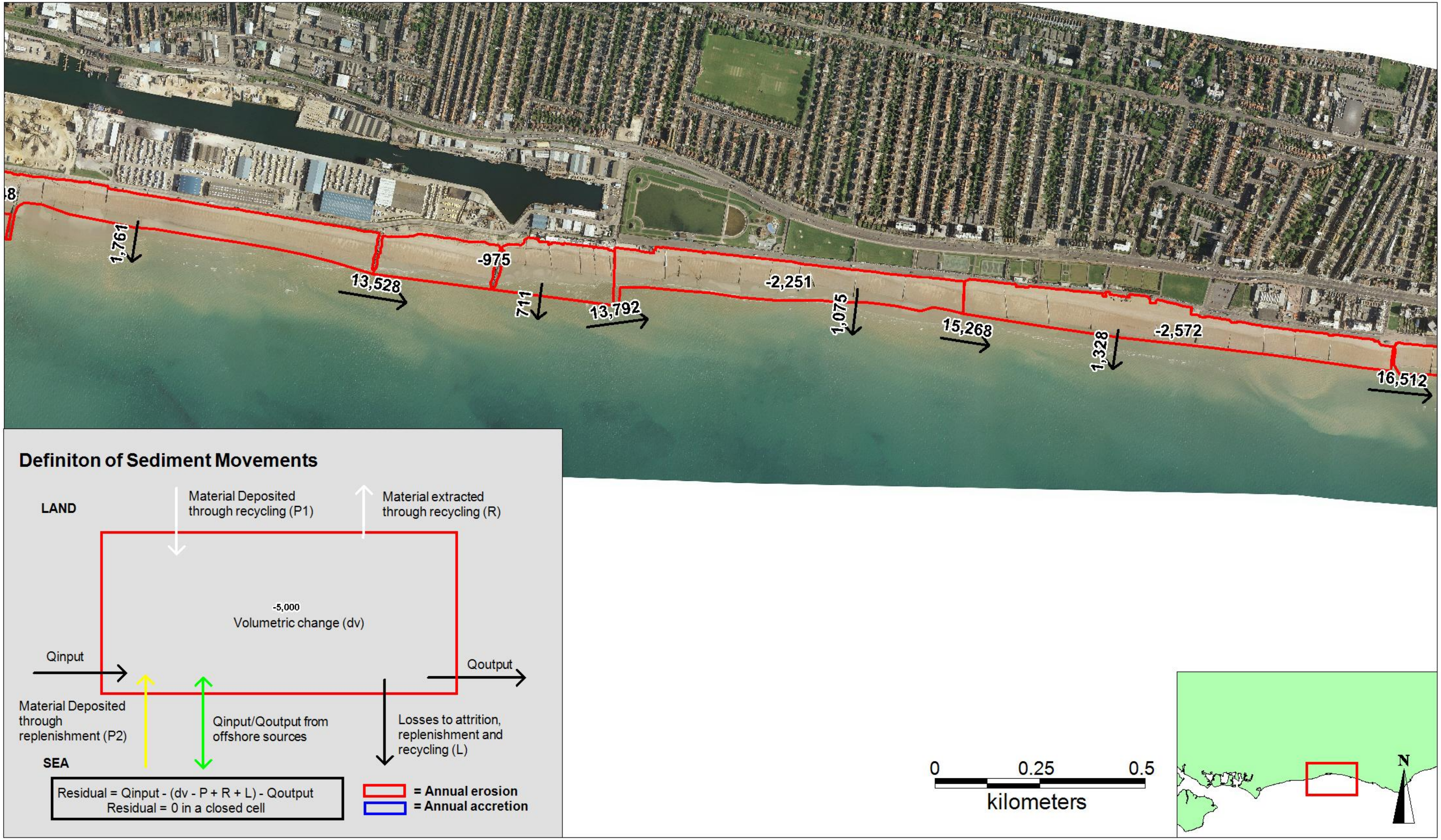

0
0.25
0.5
kilometers
-480
190
200
1,480
-511
1,910
-280
93
2,098
-20
96
2,022
292
60
1,670
-274
158
52
1,735
-1
N
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion

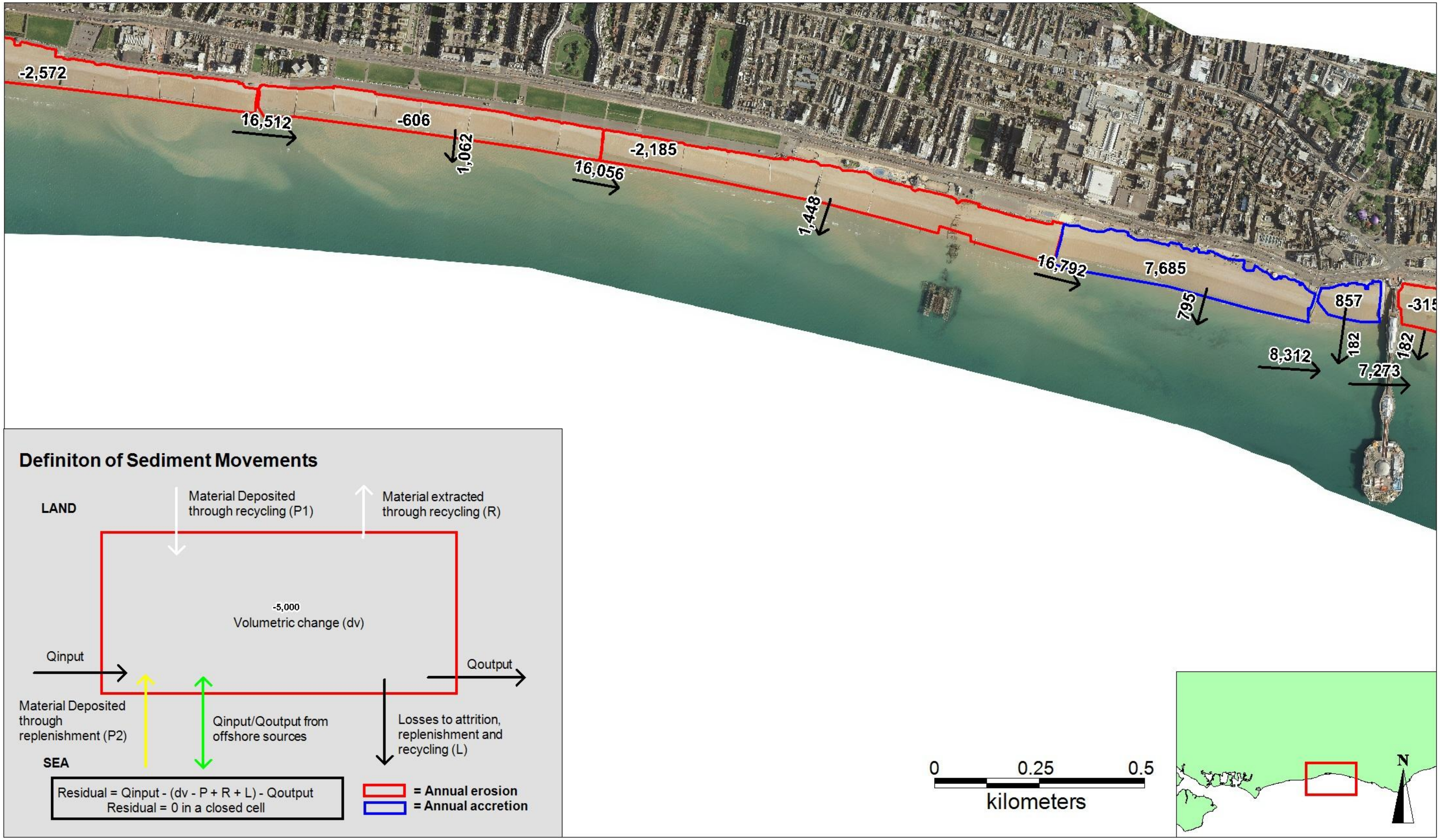

0
0.25
0.5
kilometers
N
7,791
2,777
891
382
4,405
359
1,468
310
1,130
173
142
1,511
1,827
-144
158
1,735
-274
52
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion

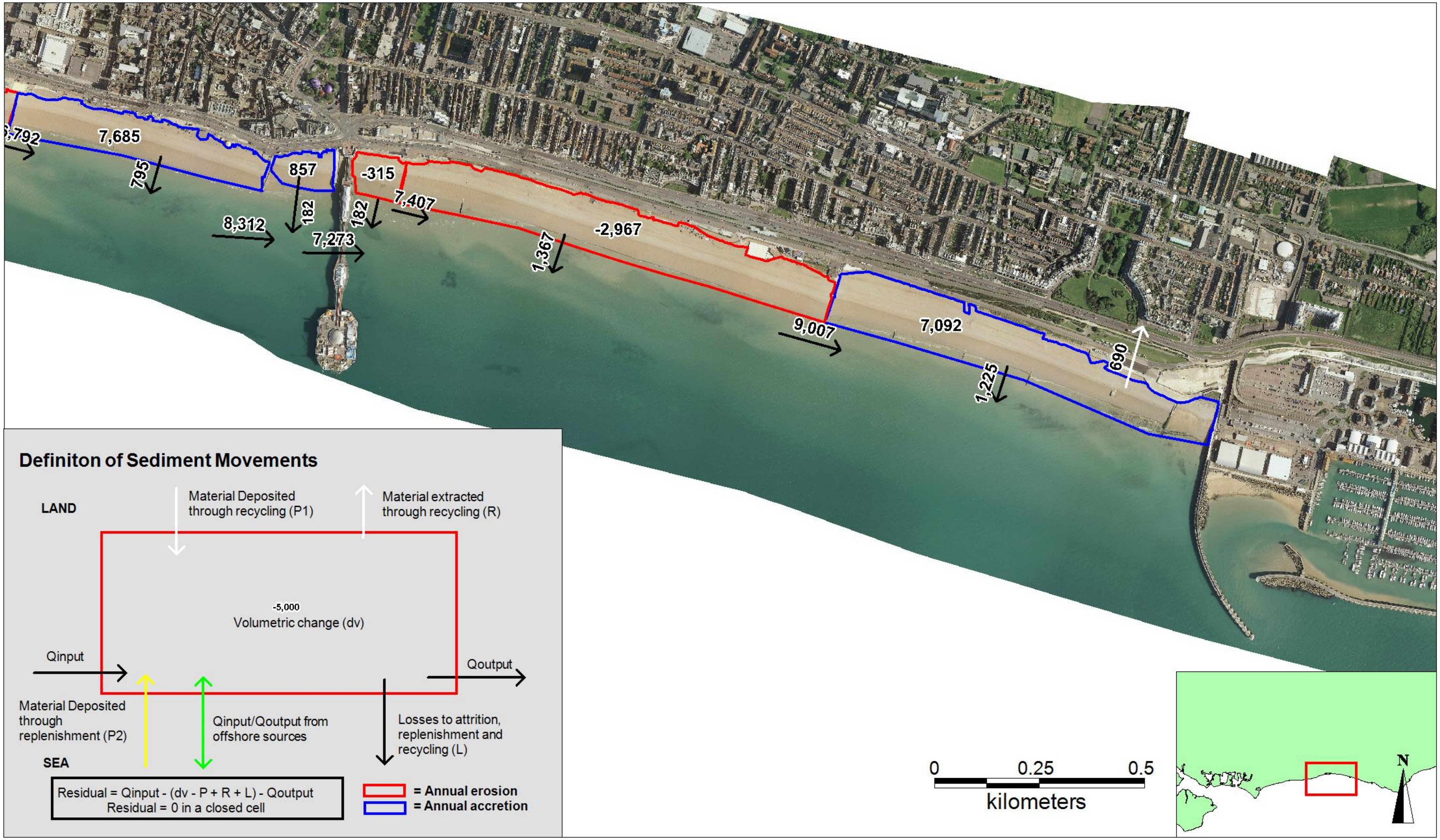

0
0.25
0.5
kilometers
N
-2,903
20,337
2,268
851
7,318
16,138
2,777
3,703
1,283
11,650
12,251
891
2,469
1,059
8,879
7,791
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion


N
12,555
-121
690
1,283
12,083
Residual = -3.190m³/yr
23,088
13,440
283
2,903
151
0
0.25
0.5
kilometers
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion


12,555
-121
690
1,283
12,083
-351
893
11,541
-3,748
1,761
Definiton of Sediment Movements
LAND
Material Deposited
through recycling (P1)
Material extracted
through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited
through
replenishment (P2)
Qinput/Qoutput from
offshore sources
Losses to attrition,
replenishment and
recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion
0
0.25
0.5
kilometers
N


1,761
13,528
-975
711
13,792
-2,251
1,075
15,268
1,328
-2,572
16,512
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion
0
0.25
0.5
kilometers
N


-2,572
16,512
-606
1,062
16,056
-2,185
1,448
16,792
7,685
795
857
8,312
182
7,273
182
Definiton of Sediment Movements
LAND
Material Deposited through recycling (P1)
Material extracted through recycling (R)
-5,000
Volumetric change (dv)
Qinput
Qoutput
Material Deposited through replenishment (P2)
Qinput/Qoutput from offshore sources
Losses to attrition, replenishment and recycling (L)
SEA
Residual = Qinput - (dv - P + R + L) - Qoutput
Residual = 0 in a closed cell
= Annual erosion
= Annual accretion
0
0.25
0.5
kilometers
N



Selsey Bill to Brighton Marina Sediment Budget **Brighton Marina** **Plate 2c (4of 4)**

4.3 Level 4 - Regional Sediment Budget

The level 4 sediment budget has been analysed and displayed in both tabular and visual formats on the following pages to summarise the Level 3 coarse sediment budget.

The total annual average flux for Selsey Bill is 4,815m^3, suggesting the cell is relatively balanced. This is, however, based on several assumptions as there is not a terminal structure at the start of the budget (Selsey). The annual volume transported from Selsey does not satisfy the gain at Pagham. This suggests material is transported onshore at Selsey and Pagham to balance the unit, May et al (2003) supports this. Beach calculations indicate 900m^3 can be traced leaving Pagham spit, eastwards. Foreshore calculations at Pagham (including Inner Owers) indicate an onshore transport rate of 9,000m^3/year; leaving 12,500m^3 unaccounted for. As a result of the drift split in Selsey it is assumed little material (2,500m^3) travels from West Wittering, suggesting 10,000m^3 moves onshore at Selsey Bill. Transport rates reduce between Aldwick and Elmer as a result of timber groynes. The transport rate increases at Climping due to the annual beach recycling, in the region of 30,000m^3. The residual at Littlehampton is 3,838m^3/year which is believed to be transported offshore and accumulate on the high foreshore east of the harbour.

The stretch of coast from Littlehampton to Shoreham Harbour has a total residual of -3,190m^3/year, showing that this sediment cell is relatively well balanced. In general, the western frontages of Rustington, Kingston Gorse and Worthing export sediment that is almost entirely taken up by the beach west of Shoreham harbour. The 12,555m^3/year bypassing round the harbour coupled with the annual gain of 18,978m^3/year makes Shoreham beach a significant importer of sediment. The source of this material is predominantly from the frontages west of the unit, showing that this sediment budget is performing very well.

As explained before, the decision to average the residual for Shoreham to Brighton Marina was taken due to the uniform beaches and morphology. The 10,157m^3/year residual before averaging shows that this cell is not particularly well balanced. This is unlikely to be due to sediment moving into and out of the unit at the eastern and western extents due to the presence of large terminal structures. This residual is more likely to be due to two reasons. Firstly, there could be an offshore movement of sediment, explaining where some of this 10,000m^3 residual is going. Secondly, it could be due to a processing error, with the rules for losses not being applicable over this stretch. The unaccounted losses attempt to quantify this unknown allowing the computation of more realistic transport rates.

Table 4-4 Level 4 - Regional Sediment Budget Selsey to Littlehampton (m^3/yr)

		Selsey Bill	Pagham Harbour	Pagham Harbour (East) - Aldwick	Bognor Regis	Elmer	Climping	Selsey Bill to Climping
Average Annual Change (ΔV)		-3,638	23,434	-6592	-147	-5,691	1,517	8,883
Recharge (P1)		0	0	0	0	0	0	0
Recycling	Deposition (P2)	0	0	0	0	0	24,200	24,200
	Extraction (R1)	0	0	0	0	0	-24,200	-24,200
Losses	Attrition (L1)	-439	-411	-564	-988	-242	-525	-3168
	Recharge (L2)	0	0	0	0	0		0
	Recycling (L3)	0	0	0	0	0	-1,210	-1,210
Average Annual Flux (ΔV-P+R-L)		-3,199	23,845	-6,029	841	-5,449	3,251	13,262
Qinput/Output from/to foreshore*		12,500	9,056	-4,457	0	0	0	17,099
Qinput		0	15,699	909	2,481	1,640	7,089	
Qoutput		15,699	909	2,481	1,640	7,089	3,838	

* Qinput/Qoutput - Negative values represent a loss from the beach to the foreshore. Positive values are the onshore gain from the foreshore to the beach.

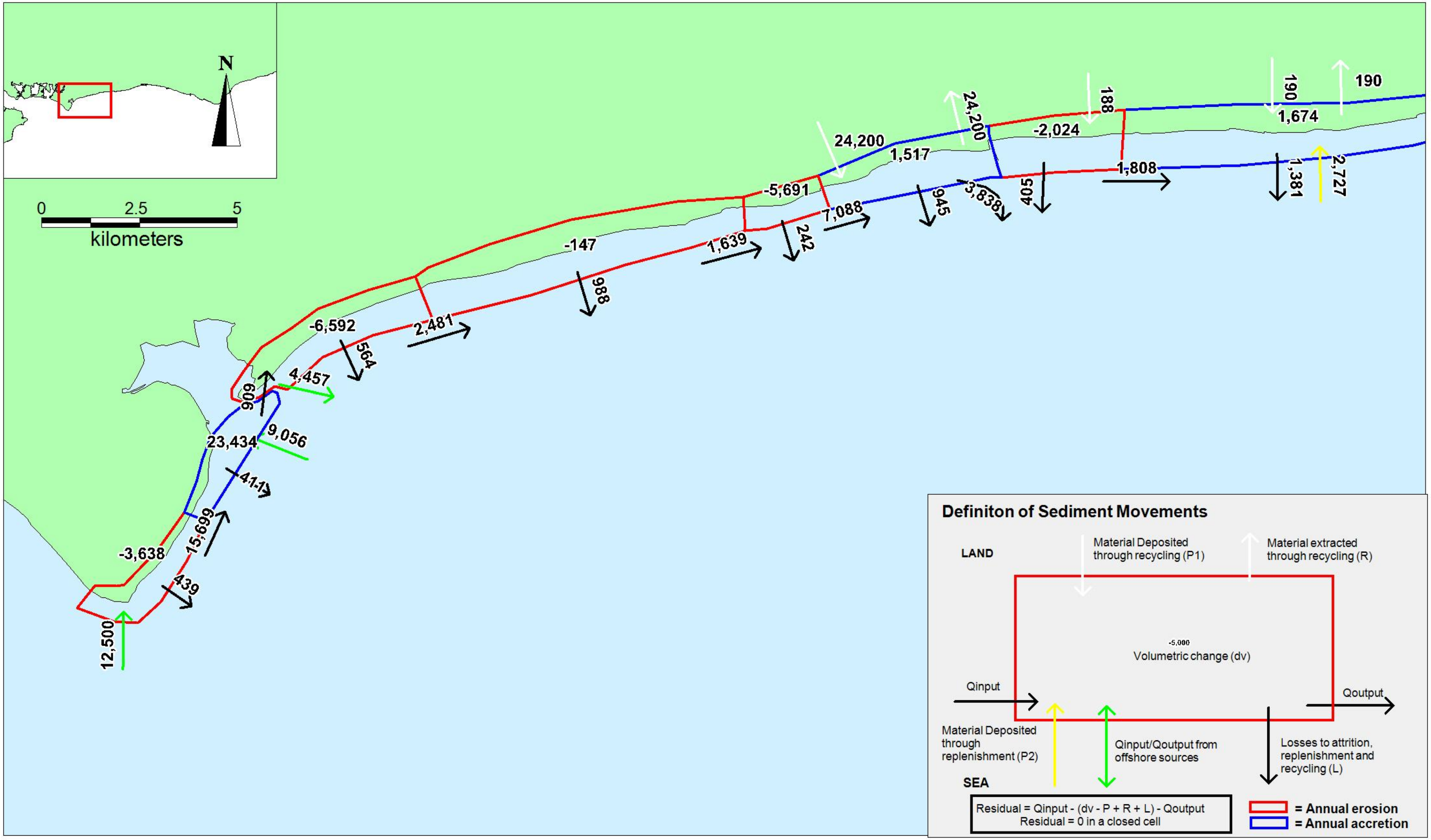
Table 4-5 Level 4 - Regional Sediment Budget Littlehampton to Shoreham (m^3/yr)

		Rustington	Kingston Gorse	Worthing	Shoreham (West)	Littlehampton to Shoreham
Average Annual Change (ΔV)		-2,024	1,674	2,087	18,978	20,714
Recharge (P1)		0	2,727	5,874	27,847	36,448
Recycling	Deposition (P2)	188	190	4,335	0	4,713
	Extraction (R1)	0	-190	-158	-16,223	-16,570
Losses	Attrition (L1)	-395	-1,099	-849	-843	-3,186
	Recharge (L2)	0	-273	-587	-2,785	-3,645
	Recycling (L3)	-9	-9	-217	0	-236
Average Annual Flux (ΔV-P+R-L)		-1,808	327	-6,311	10,981	3,190
Qinput		0	1,808	1,480	7,791	
Qoutput		1,808	1,480	7,791	-3,190	

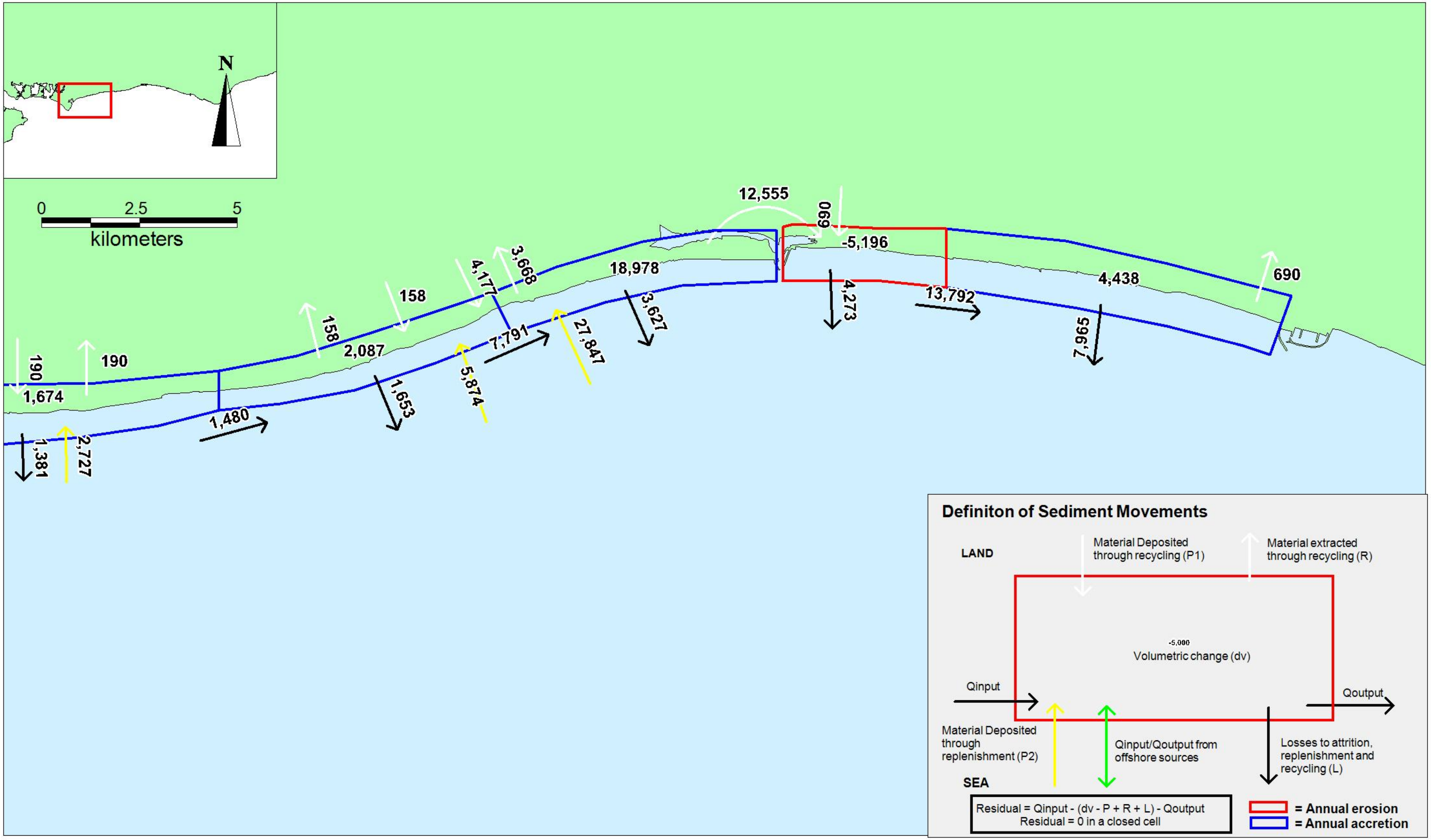
Table 4-6 Level 4 - Regional Sediment Budget Shoreham to Brighton (m^3/yr)

		Shoreham (East)	Brighton	Shoreham to Brighton Marina
Average Annual Change (ΔV)		-5,196	4,438	-757
Recharge (P1)		0	0	0
Recycling	**Deposition (P2)**	13,245	0	13,245
	Extraction (R1)	0	-690	-690
Losses	**Attrition (L1)**	-464	-1,009	-1,473
	Recharge (L2)	0	0	0
	Recycling (L3)	-608	0	-608
DWR**		-3,522	-7,655	-11,177
Average Annual Flux (ΔV-P+R-L)		-17,314	6,137	-11,177
Qinput		0	13,792	0
Qoutput		13,792	0	0

**See Section 4.2



Selsey Bill to Brighton Marina Sediment Budget



Selsey Bill to Brighton Marina Sediment Budget

Plate 1 (2 of 2)

4.4 Level 4 – Beach Volumes

Beach volumes over all timescales were calculated for each frontage to show the actual total volumes of sediment rather than just the volumetric change. The method for the calculation of these volumes is provided in Appendix B. The beach volumes show logical and conceivable beach volumes over the majority of frontages and time scales. This provides confidence in both the methodology for calculating the volumetric change and the methodology for calculating the beach volume.

Table 4-7 Beach Volumes

	BEACH VOLUME (m^3)						
	2012	**2011**	**2007**	**2001**	**1930**	**1910**	**1890**
SELSEY BILL	412,097	411,011	425,388	479,098	1,695,769	2,512,212	2,911,868
PAGHAM	2,699,626	2,686,648	2,672,751	2,586,035	1,083,162	1,418,231	1,314,026
PAGHAM/ALDWICK	1,371,110	1,364,784	1,339,525	1,364,640	993,530	786,325	238,736
BOGNOR REGIS	1,127,100	1,113,944	1,098,339	1,128,713	189,071	364,671	800,943
ELMER	278,095	267,401	294,267	340,700	81,250	252,984	252,141
CLIMPING	657,417	654,616	639,393	640,734	266,809	161,359	135,961
RUSTINGTON	461,952	463,686	470,353	484,218	233,160	142,815	306,766
KINGSTON GORSE	1,345,319	1,342,943	1,335,484	1,326,909	625,772	757,092	999,125
WORTHING	1,415,583	1,414,056	1,405,422	1,396,571	820,329	789,212	758,095
SHOREHAM (WEST)	1,904,013	1,952,327	1,940,624	1,695,258	461,777	953,087	1,444,397
SHOREHAM (EAST)	789,360	816,135	815,191	846,511	173,894	420,607	265,293
BRIGHTON	2,755,384	2,775,680	2,718,696	2,706,563	1,464,354	1,269,302	1,059,247

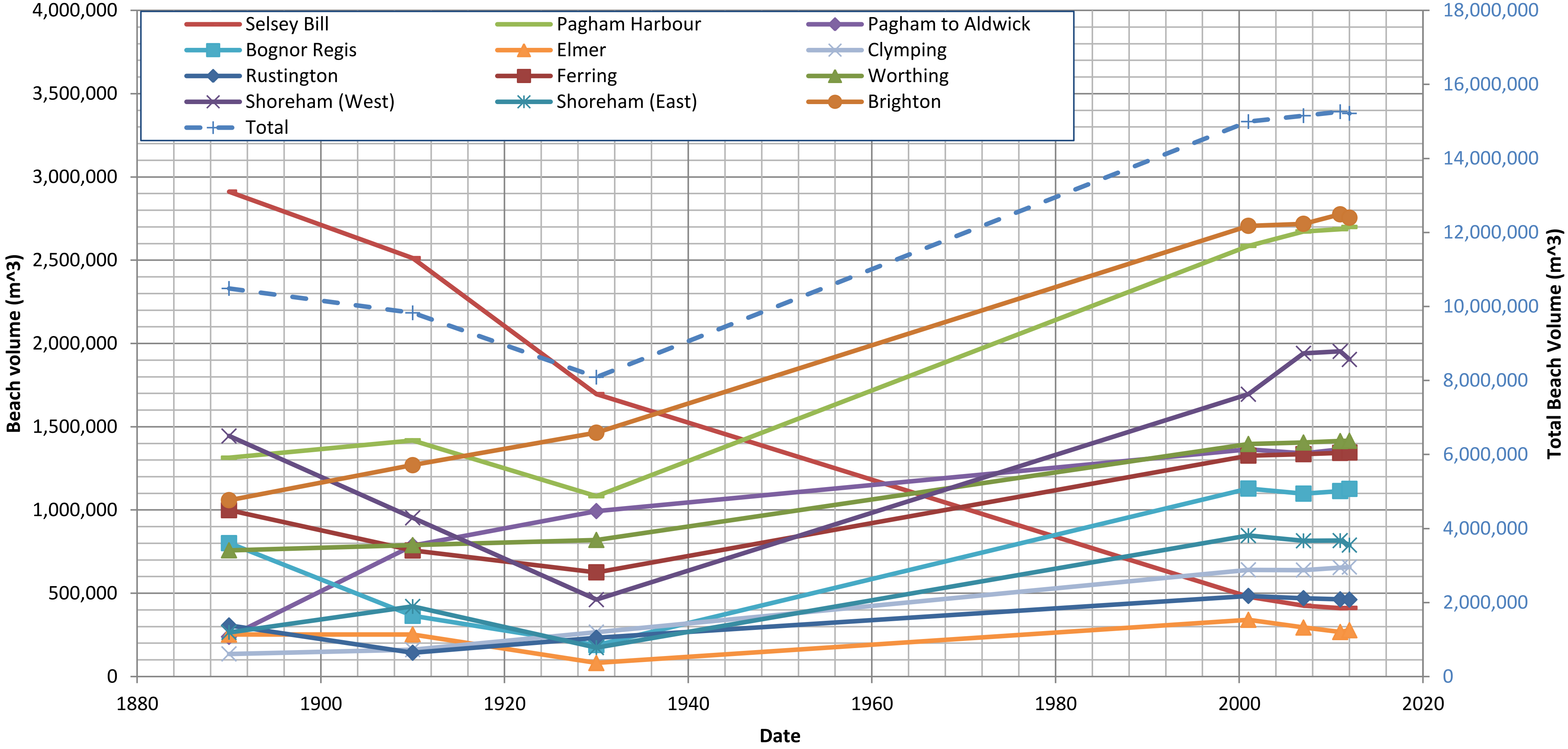


Figure 4-17 Comparison of beach volumes since 1870

Figure 4.17 has been provided to show the relative changes in total beach volume over a longer period of time. This helps to put the more recent volumetric changes explored through the contour plots and sediment budgets into perspective. Taking Shoreham (East) as an example, it shows that the recent loss of material is fairly insignificant when considering the low beach volumes at the turn of the 20th Century.

4.5 Historic Volumetric Change (Level 4)

The historic beach volumetric change has also been provided to help place the most recent changes and sediment budget interpretations into the context of a longer time scale. Stive et al. (2002) identified that the spatial and temporal scale of an analysis are interlinked. When looking over very small timescales, a very fine spatial analysis is possible. As the analysis of historic beach change is over multiple decades, it is unfeasible to view beach volumetric changes on a small spatial scale (Stive et al., 2002). Therefore, analysis of historic beach volumetric change has been undertaken at Level 4 as the most appropriate spatial scale to the temporal period of the analysis.

Table 4-8 Historic beach volumetric change since 1890

	Volumetric Change (m^3)					
	1910-1890		1930-1910		2001-1930	
	Change	Annual Change	Change	Annual Change	Change	Annual Change
Selsey Bill	-399,656	-19,983	-816,443	-40,822	-1,216,671	-17,136
Pagham Harbour	104,205	5,210	-335,069	-16,753	1,502,873	21,167
Pagham to Aldwick	547,589	27,379	207,205	10,360	371,110	5,227
Bognor Regis	-436,272	-21,814	-175,600	-8,700	939,642	13,234
Elmer	843	42	-171,734	-8,587	259,450	3,654
Climping	19,514	976	111,704	5,585	373,925	5,267
Rustington	-163,951	-8,198	90,345	4,517	251,058	3,439
Ferring	-242,033	-12,102	-131,321	-6,566	701,137	9,605
Worthing	-104,866	-5,243	169,610	8,481	576,242	7,894
Shoreham (West)	-443,179	-22,159	-543,954	-27,198	1,233,481	16,897
Shoreham (East)	155,314	7,766	-246,713	-12,336	672,617	9,473
Brighton	210,055	10,503	195,052	9,753	1,242,209	17,496
Total	-500,808	-25,041	-552,830	-27,642	4,676,744	64,804

The annual rate is provided to place volumetric changes into perspective. This assumes a linear rate of change between the known beach volumes which is a significant and erroneous assumption. Consequently, no analysis of annual rates of change is undertaken in the following pages. The analysis of beach volumetric changes since 1890 seeks to justify the figures provided in Table 4.8, rather than explain why those changes occur which was deemed to be outside the scope of this report.

4.5.1 Selsey Bill

Selsey Bill has lost in the region of 2,500,000m^3 since 1890. This loss is directly associated with the 350m eroded coastline during 1890 to the 1950s, averaging a 6m/year retreat rate (Figure 4.19). In the early 1950s a concrete seawall and several timber groynes were constructed to reduce the severely eroding beach front, which has largely controlled beach movement since. Figure 4.18 illustrates the change of MHW in 1890 (green), 1910 (red) and 1930 (blue), based on historic ordnance maps, overlaid onto 2008 aerial photography.

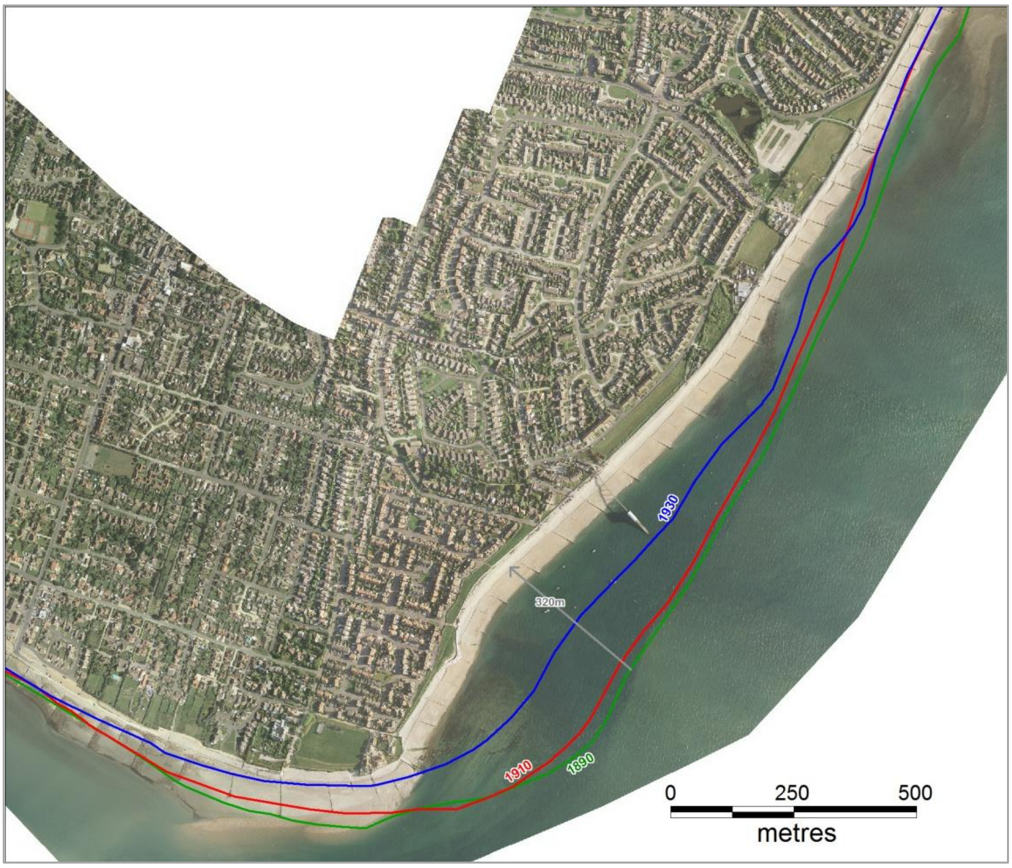


Figure 4-18 Historic MHW (1890, 1910, 1930)

A split in longshore drift is evident within the Selsey unit as material is known to travel round the peninsula towards Worthing and West Wittering. In 1979 Harlow estimated approximately 1,000m^3 is added to the westwards drift from Selsey.

Despite the hard defences, Selsey is a naturally eroding coastline which is currently losing -6,700m^3/year (2001-2012). Recent calculations indicate a shortfall of material leaving Selsey for Pagham Harbour, suggesting an offshore source is adding to the sediment budget. This is supported by Hooke et al. (1996) who calculated 3,000m^3 is added by wave driven onshore transfers to Selsey. Analysis implies this volume to be too low, and closer to 10,000m^3/year.

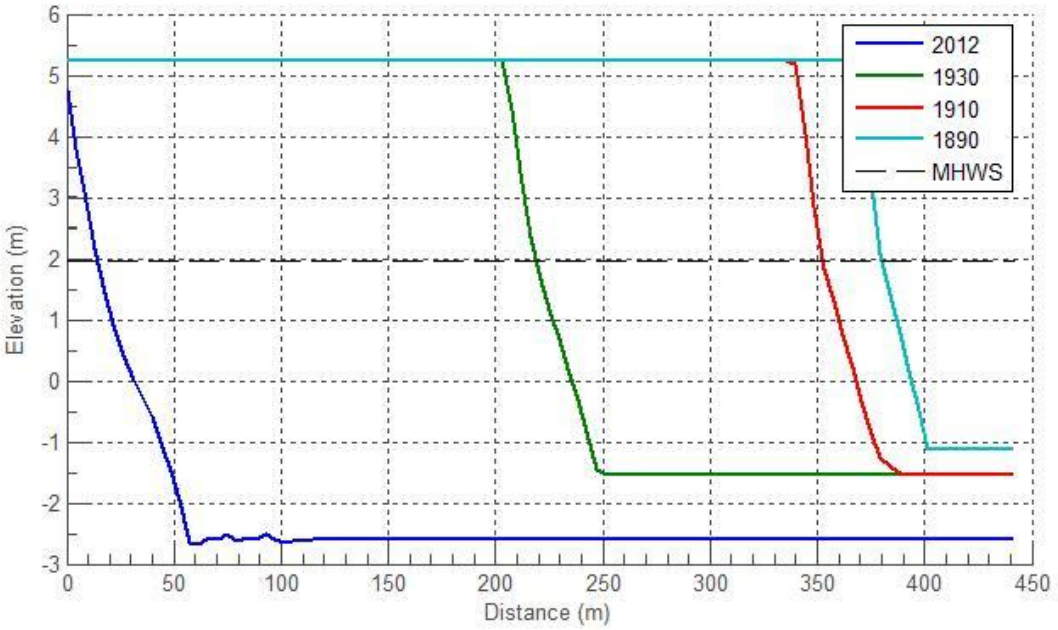


Figure 4-19 Cross section through DTM's south of Lifeboat Station

4.5.2 Pagham Harbour

Pagham Harbour beach is the most dynamic stretch of shingle coastline along this frontage. Originally a solitary spit during the 1700s and late 1800s, it progressed into a bay-bar in the early 1900s which later emerged as a double spit as a direct result of a breach late 1910. May (2003) analysed the spit movement (Figure 4.20), and suggests the severe erosion along the eastern side of Selsey Bill during the 1900s has meant the present area of the harbour mouth has been exposed increasingly to waves approaching from the south.

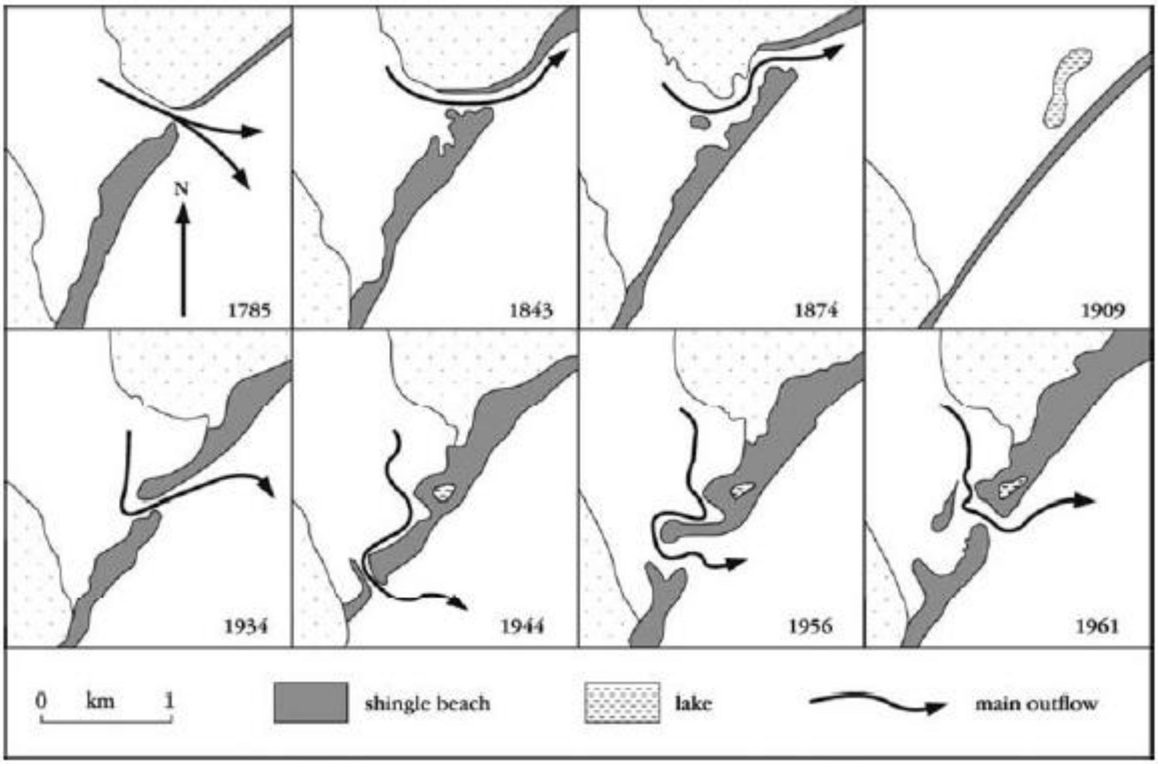


Figure 4-20 Extract from May (2003) illustrating the position of Pagham Harbour

During 1890 and 1910 the beach gained approximately 100,000m^3. Although this volume does not compare to the volume lost at Selsey, the open bar beach had no structures to trap sediment in the unit. When the bar breached in 1910 material would have been lost. Between 1910 and 1930 the Pagham Harbour frontage was losing 330,000m^3. This could be a result of the loss of headland at Selsey which would have reduced protection at Pagham and changed the diffraction of waves around the headland. The geomorphology of the spit noticeably changed within this period, as shown in Figures 4.21 and 4.22. Figure 4.22 is a cross section through the eastern spit, which clearly indicates the presence of the accreting western spit.

Figure 4-21 Historic MHW at Pagham Harbour (1890, 1910 and 1930)

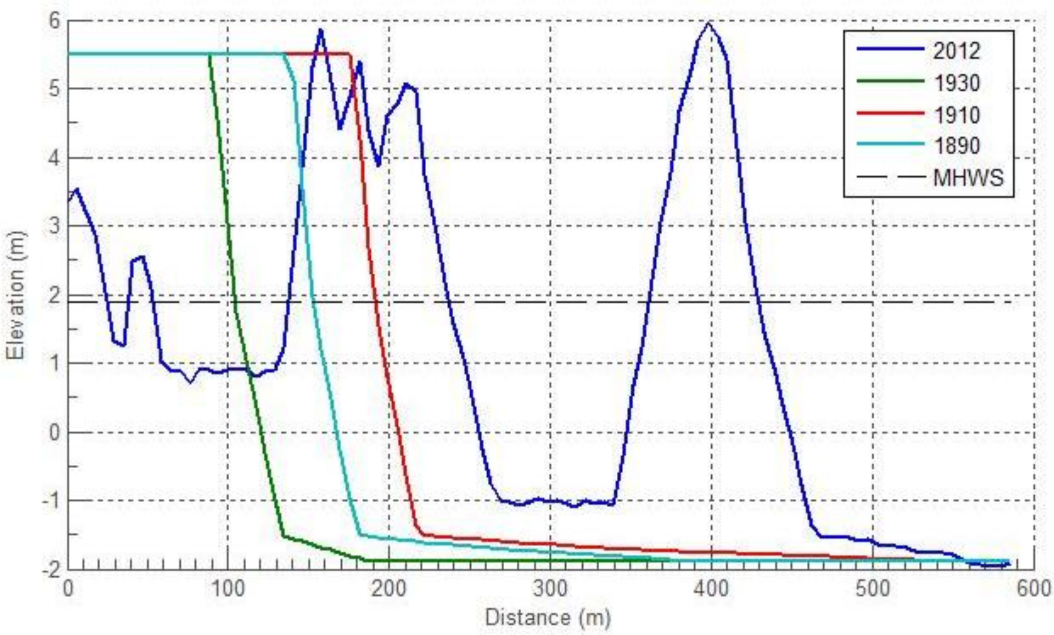


Figure 4-22 Cross section through DTM's at Pagham spit, south

From 1930 to 2001 the beach gained 420,000m^3 as the spit grew towards the south east; since 2001 the beach trend is accreting at 10,000m^3/year. Detailed analysis indicated the spit gains 28,000m^3/year (2001-2012), which is fed by the losses further along the unit. The spit has extended a further 700m since its 2001 position; Figure 4.23 maps the MHW line at 1.9mAOD for the years 2001 to 2012.

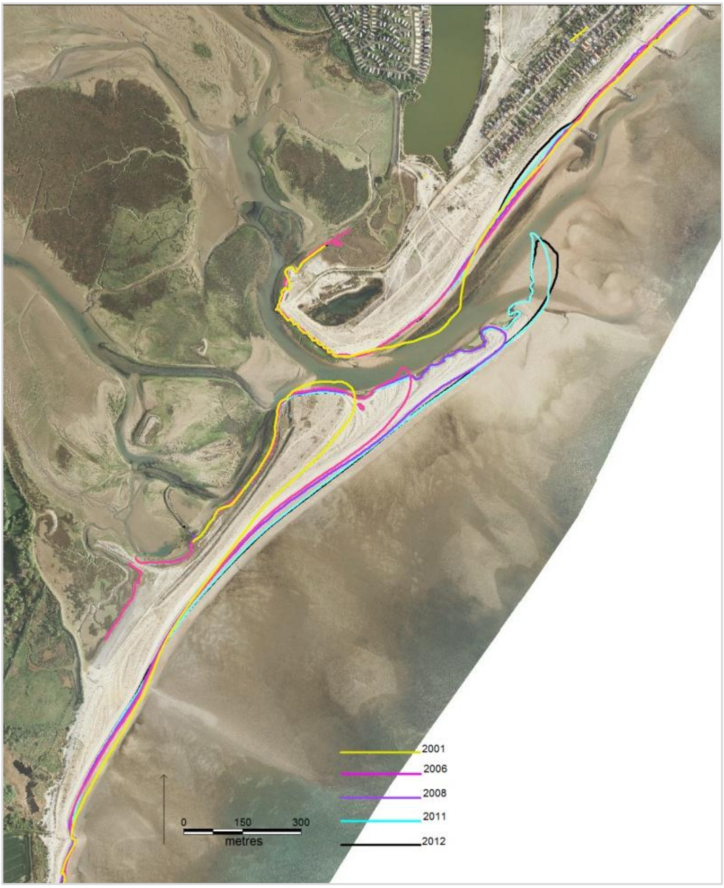


Figure 4-23 MHW at Pagham Harbour (2001, 2006, 2008, 2011 and 2012)

4.5.3 Pagham to Aldwick

The frontage between Pagham and Aldwick gained 1,125,904m^3 during 1890 and 2001. This is split into 547,589m^3 during 1890 and 1910; a gain of 207,205m^3 during 1910 and 1930 and a further gain of 371,110m^3 over the course of 1930 to 2001. Figure 4.24 illustrates the persistently accretive beach face.

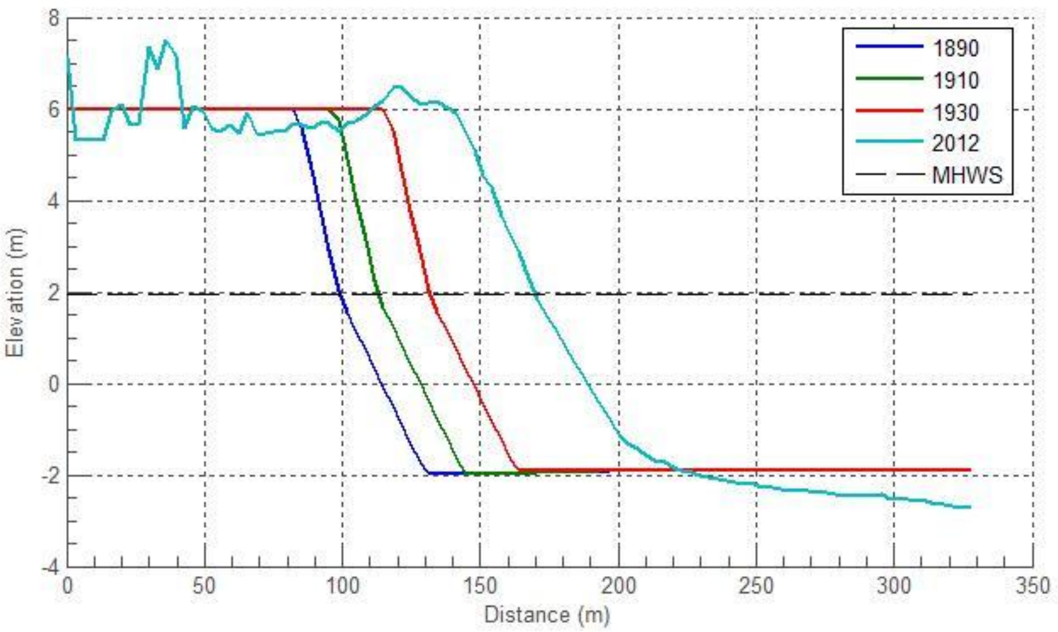


Figure 4-24 MHW at Pagham Harbour (2001, 2006, 2008, 2011 and 2012)

4.5.4 Bognor Regis

The Bognor frontage lost 436,272m^3 during 1890 and 1910, it then lost a further 175,600m^3 during 1910 and 1930 but gained material between 1930 and 2001. Figure 4.25 shows the beach profile retreat between 1890 and 1930 and then advance seaward to 2012.

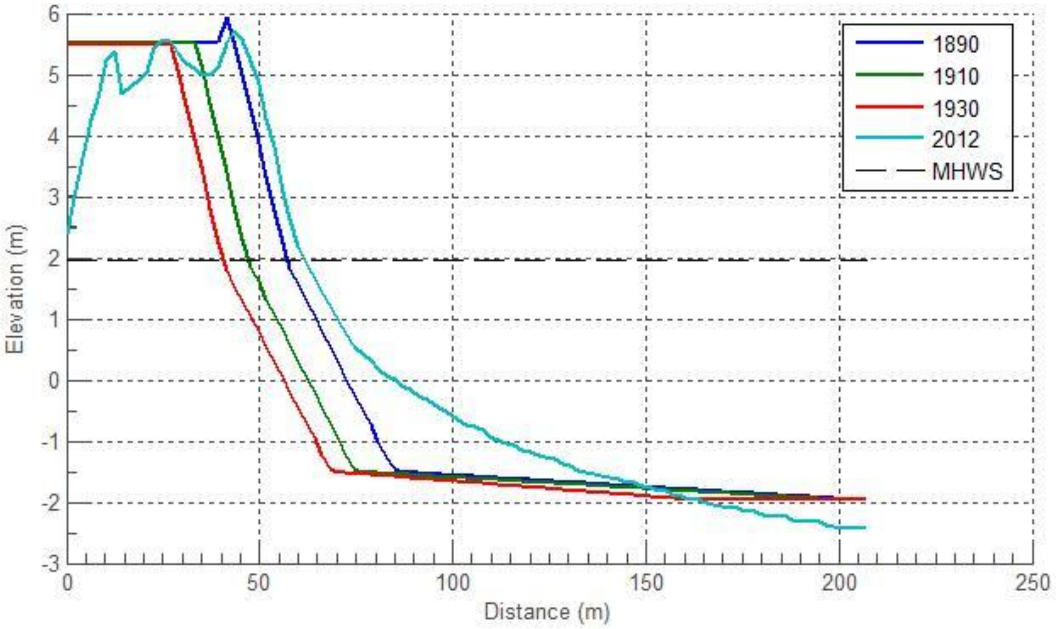


Figure 4-25 MHW at Pagham Harbour (2001, 2006, 2008, 2011 and 2012)

4.5.5 Elmer

The Elmer frontage has gained 520,000m^3 during 1890 and 2012. When deduced, 1890 to 1910 gained 800m^3; 1910 to 1930 lost 172,000m^3 followed by a gain of 260,000m^3 during 1930 and 2001. Historically Elmer beach was losing material (1910 – 1990); in 1993 parallel breakwaters were constructed to reduce the volume of material passing through Elmer by reducing the wave energy along this frontage. In addition to the 100,000 tonnes of rock, 200,000m^3 of beach was imported to raise the levels close to their previous position. There is no post scheme data to evaluate its progress, although the 2001 – 2012 data suggests the beach has lost 62,000m^3 (5,600m^3/year). Since the scheme, crenular bays of shingle have formed, with a rise in foreshore in front of the breakwater; Figures 4.26 and 4.27 represent this.

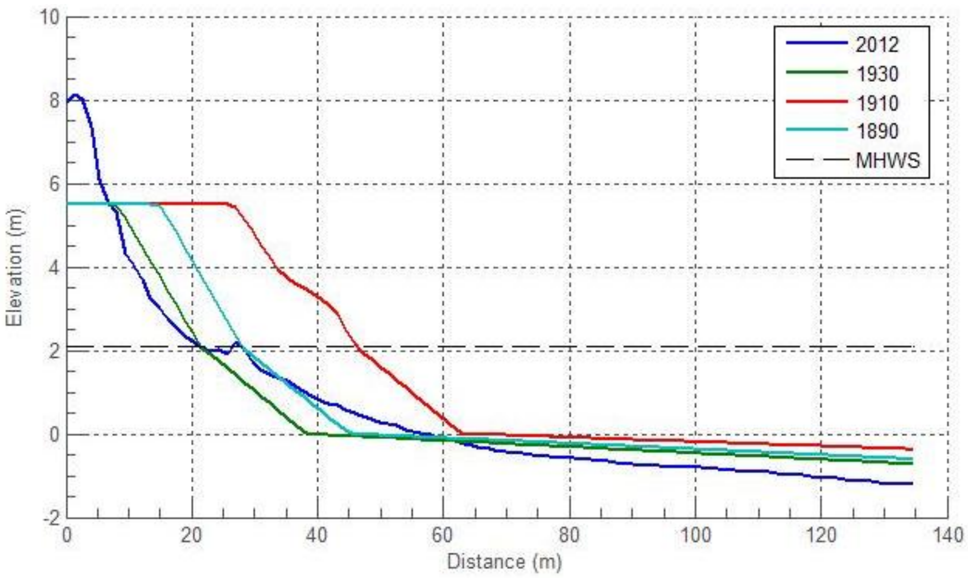


Figure 4-26 Cross section through DTM's at Elmer – mid bay

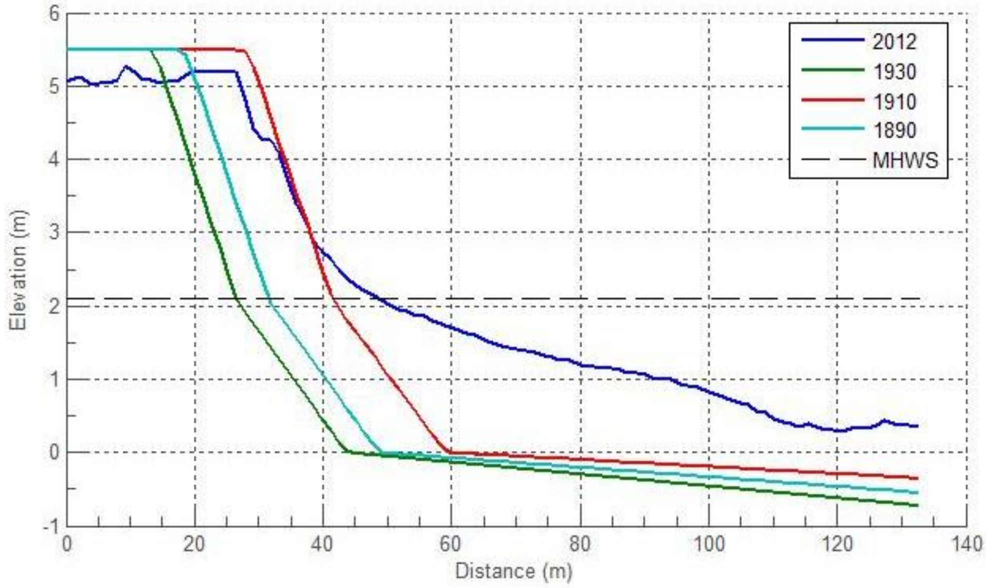


Figure 4-27 Cross section through DTM's at Elmer – to breakwater

4.5.6 Climping

Climping has gained 500,000m^3 since 1890 as the eastern beach has advanced 80m during 1890 and 2012. The terminal structure surrounding the mouth of the River Arun has trapped material transported from the west. Between 1890 and 1910 the beach gained 25,000m^3 and a further 105,000m^3 during 1910 and 1930. The largest gain of 375,000m^3 accumulated throughout 1930 to 2001. Figure 4.26 indicates the large accretion towards Littlehampton Harbour during 1930 to 2001, extended to 2012. The dunes have increased and beach has migrated seaward by near 80m and the dunes have raised the beach profile from +5.5mAOD to +11.5mAOD.

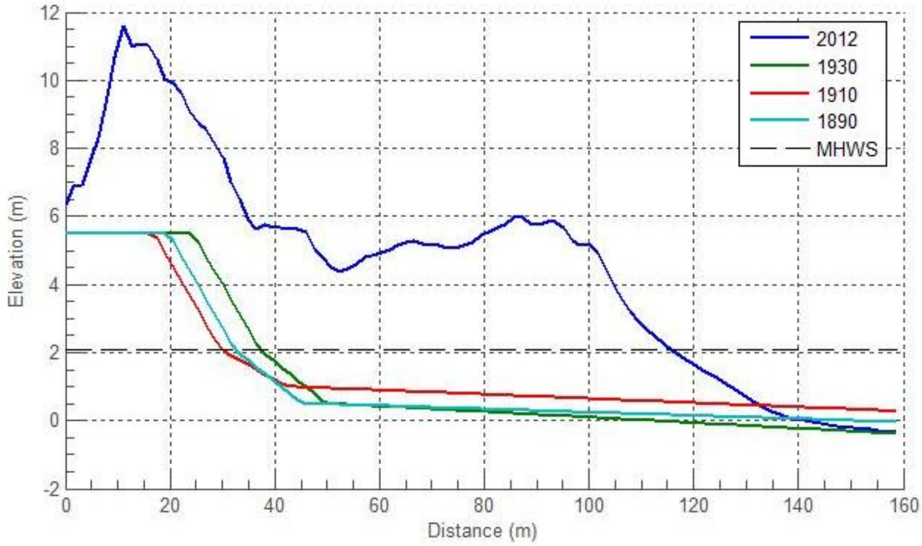


Figure 4-28 Cross section through DTM's at Climping

4.5.7 Rustington

Rustington has gained 180,000m^3 since 1890. Despite this large gain, there was a significant loss of 160,00m^3 from 1890 to 1910. This large loss can be seen in the Profile below taken through the beach 200m east of the pier. The beach retreated 30m between 1890 and 1910; this is contrasted by a seaward movement of 25m during 1910-1930. The beach has moved further seawards by 2001, residing 7m further out at the MHW mark than in 1890. This profile matches well with the trend for the whole unit, retreating from 1890 to 1910 the returning to an accretive trend from 1910-2001. This large scale gain puts the small scale loss over the past 10 years into perspective.

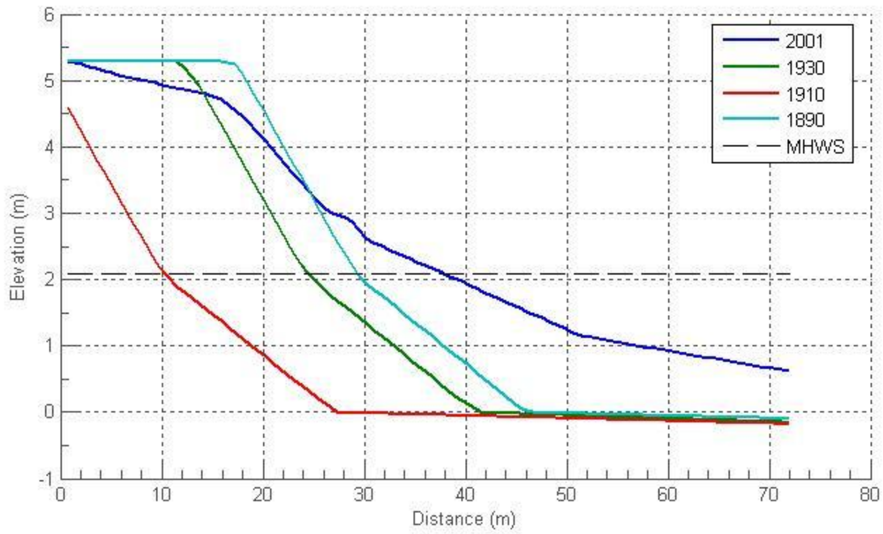


Figure 4-29 Cross section through DTM's in Rustington

Further evidence can be drawn from looking at historical images of the beach at Littlehampton from the Pier. The beach in 1890 is narrower, with the present day photo showing a much wider and flatter beach. This corresponds well to Figure (4.29) showing a higher and wider crest in 2001 than in 1890.

Figure 4-30 Rustington Beach from Littlehampton Pier 1890 (left); Littlehampton 2003 (right)
Source:Goldenagepaintings.blogspot.co.uk (2011); ivebeenthere.co.uk. (2009)

4.5.8 Ferring

Ferring showed losses of 240,000m^3 and 130,000m^3 between 1890-1910 and 1910-1930 respectively. This contrasts the trend since 1930 showing a large accumulation of 700,000m^3, producing the total change since 1890 of 330,000m^3. This profile at West Kingston shows the profile cutting back by 15m from 1890 to 1910 and 40m between 1910 and 1930. However, by 2001 the beach has returned to the 1910 beach profile accreting by 40m.

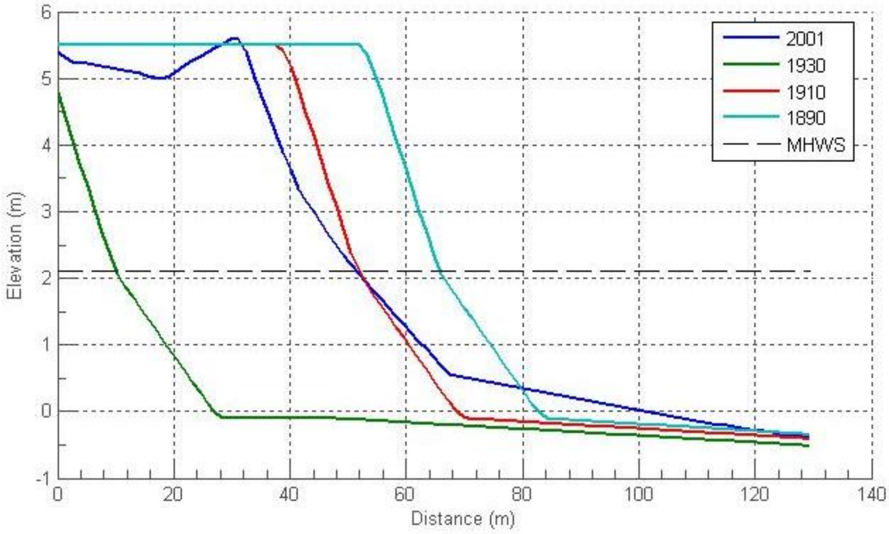


Figure 4-31 Cross sections through DTM's in Ferring

4.5.9 Worthing

The Worthing frontage has shown relative stability over the last 90 years, showing consistent gains and a total gain of 630,000m^3 since 1890. Despite this trend of stability, spatial variation exists, with bands of erosion and accretion present with distance alongshore. For example in the cross section shown overleaf, the 2001 profile has roughly maintained its position, but showed a large loss between 1930 and 1890 with the crest cutting back by 38m. This is compared to an area further along the coast, where there was a build up of material over the same time period. This produces the low net change of 60,000m^3 between 1930 and 1890.

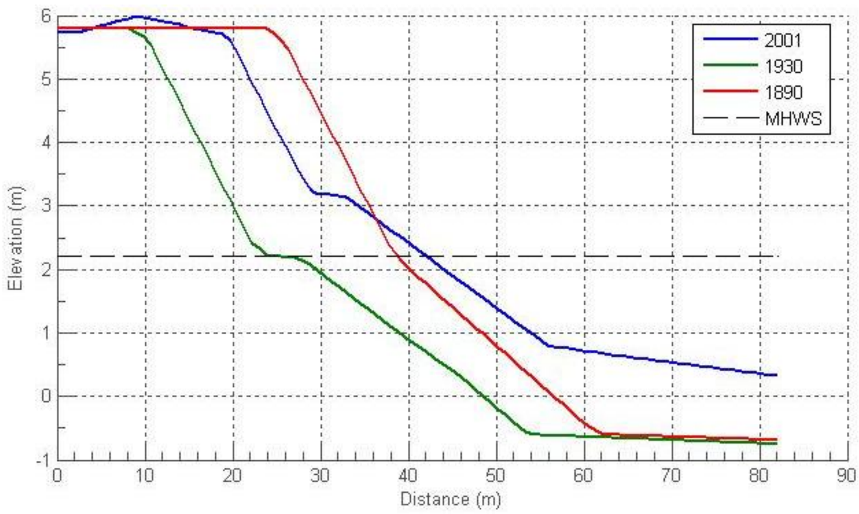


Figure 4-32 Cross sections through Worthing DTM's

4.5.10 Shoreham (West)

West of Shoreham harbour lost 980,000m^3 from 1890 to 1910, it then gained a further 1,230,000m^3 to 2001 producing a net increase of 250,000m^3 since 1890. In the respective difference model calculations, a consistent loss and gain across the whole beach is noted. However, the open beach immediately west of the harbour entrance gained a significant volume of material. This cross section shows a retreat of the beach face of 30m between 1890 and 1930. However, the beach face has advanced by as much as 70m by 2001 as material is trapped by the terminal structure at Shoreham Harbour.

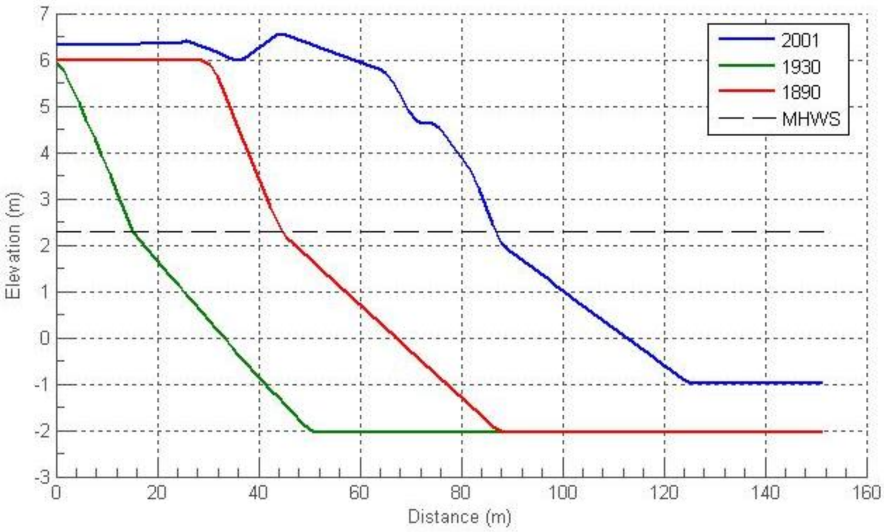


Figure 4-33 Cross sections through Shoreham DTM's

4.5.11 Shoreham Harbour (East)

Just east of Shoreham Harbour gained 150,000m^3 to 1910, lost 250,000m^3 to 1930 and gained 670,000m^3 to 2001. The images below show how the beaches have change over the last 80 years. In 1918, the beaches are very narrow offering minimal flood protection at high tide. The beaches get wider with distance alongshore, also shown in the more recent image. The beaches are on the whole wider and higher than in the early 1900's possibly as a result of bypassing works to address the sediment starvation from the terminal structures at Sovereign Harbour.

4.5.12 Brighton

Brighton beach shows year on year gains, producing a total increase of 1,600,000m^3. These gains are shown across the whole beach but are particularly focussed at the Brighton Marina end where the terminal structures have caused a build up of material.

The figure below shows a cross-section through the beach at Kemp Town. After retreating 15m from 1890 to 1910, the beach remained fairly stable to 1930 before translating seawards by 35m to 2001. This large-scale accretion is most likely due to increased volumes of sediment entering the beach from sediment bypassing at Shoreham Harbour.

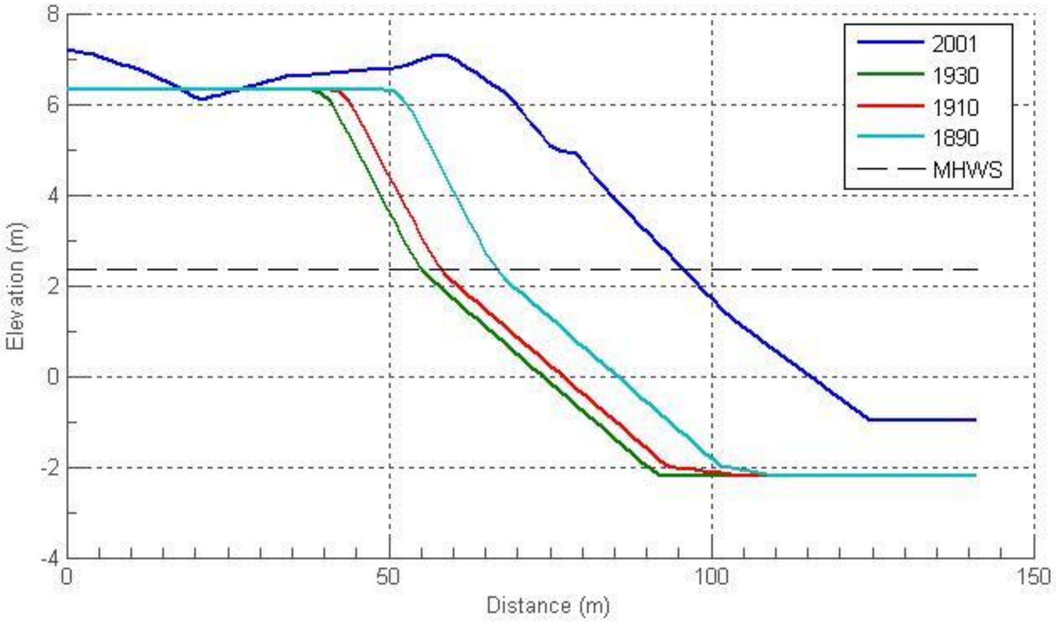


Figure 4-34 Cross sections through Brighton DTM's

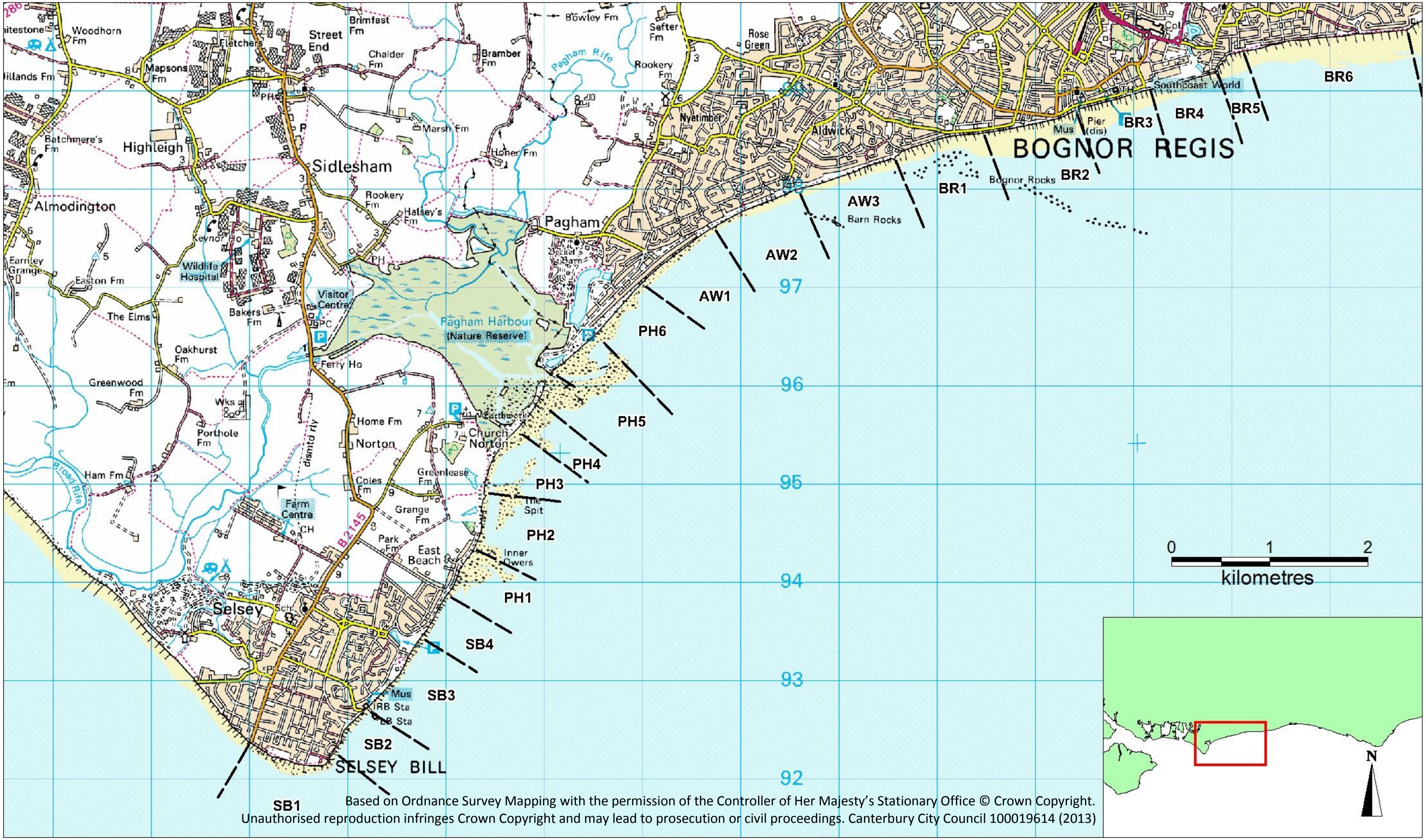
5.0 Available data

The data that can be provided with regards to the above analysis is shown in the table below. The data will be provided in CD format when the report has been finalised.

Table 5-1 Available GIS data

Data	Type	Description
GIS (1)		**AVAILABLE FROM CANTERBURY CITY COUNCIL**
	DTMs	2012 -2003 DTMs for all frontages
	Difference Models	For all frontages
	Analysis Polygons	Level 1 - 50m length
		Level 2 - SRCMP Polygons
		Level 3 - Coarse Polygons
		Level 4 - Regional Polygons
	Historic	Historic feature lines for all frontages
		Historic DTMs for all frontages in 1890, 1910 and 1930
		Historic difference models, 1910-1890, 1930-1910, 2011-1930
	Sediment Budget	Polygons as above
		Level 3 sediment movements
		Level 4 sediment movements
GIS (2)		**AVAILABLE FROM THE ENVIRONMENT AGENCY**
	Lidar	All available Lidar data sets
SPREADSHEETS		**AVAILABLE FROM CANTERBURY CITY COUNCIL**
	Level 1	All Level 1 data in .txt format
	Level 2-4	All levels data in .xlsx format
PLATES		**AVAILABLE FROM CANTERBURY CITY COUNCIL**
	1 and 2	All plates in .jpg format
REPORT		**AVAILABLE FROM CANTERBURY CITY COUNCIL**

6.0 Sub-cell Location Diagrams


SB1
SB2
SB3
SB4
PH1
PH2
PH3
PH4
PH5
PH6
AW1
AW2
AW3
BR1
BR2
BR3
BR4
BR5
BR6
Selsey
SELSEY BILL
Pagham Harbour
(Nature Reserve)
Pagham
Sidlesham
Aldwick
BOGNOR REGIS
Bognor Rocks
Barn Rocks
Church Norton
The Spit
Inner Owers
East Beach
0
1
2
kilometres
N


Yapton
Ford
LITTLEHAMPTON
East Preston
Hangleton
Flansham
Felpham
Middleton-on-Sea
Climping
Atherington
Rustington
Kingston Gorse
BR5
BR6
BR7
BR8
E1
E2
CL1
CL2
CL3
CL4
R1
R2
R3
R4
KG1
KG2
KG3
KG4
0 1 2
kilometres
N

South East Regional Coastal Monitoring Programme

Level 3 - Sub-cell Location Diagrams


SHOREHAM-BY-SEA
SOUTHWICK
PORTSLADE-BY-SEA
HOVE
BRIGHTON
SW4
SW5
SE1
SE2
SE3
SE4
B1
B2
B3
B4
B5
B6
B7
B8
B9
0
1
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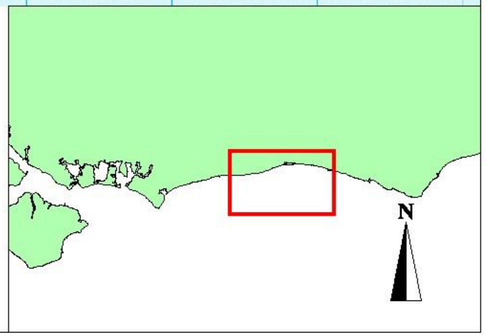
N

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