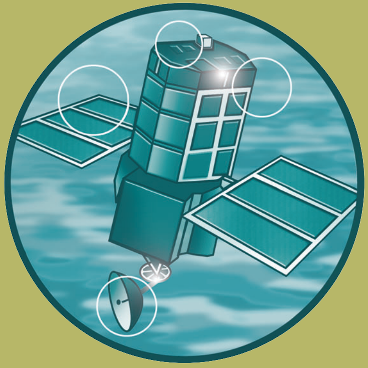
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

# Development of estuary morphological models

## Annex D: Development of a Lagrangian morphodynamic model for sandy estuaries and coasts

R&D Project Record FD2107/PR



Environment Agency

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Food and Rural Affairs

HR Wallingford
Working with water

TR 159

# Development of a Lagrangian morphodynamic model for sandy estuaries and coasts

Report TR 159
Release 1.0
July 2007

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# Document Information

| | |
|---|---|
| **Project** | Development of a Estuary Morphological Models |
| **Report title** | Development of a Langrangian morphodynamic model for sandy estuaries and coasts |
| **Client** | NERC/POL |
| **Client Representative** | Dr J Huthnance |
| **Project No.** | DDS0214 |
| **Report No.** | TR 159 |
| **Project Manager** | R L Soulsby |
| **Project Director** | R J S Whitehouse |

# Document History

| Date | Release | Prepared | Approved | Authorised | Notes |
|---|---|---|---|---|---|
| 27/04/07 | 1.0 | rls | rjsw | mpd | |

**Prepared** RL Soulsby

**Approved** Richard Whitehouse

**Authorised**

# Summary

Development of a Lagrangian morphodynamic model for sandy estuaries and coasts

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A new estuarine and coastal morphodynamic model has been developed, by extending the existing SandTrack model to have a morphodynamic capability. The particles which are moved by the tidal currents in SandTrack have a volume of sediment assigned, which is deposited in a diffuse lens, followed by flow updating. The radius of the lens is determined by the number of particles and the overall model area, while the thickness of the lens was calibrated against the Van Rijn TRANSPOR sediment transport model. The resulting model has been named MorphoSandTrack.

The model was applied to the case of the Thames Estuary. Morphodynamic runs were made using annual bed/flow updates over a 50-year period, starting with the present day bathymetry. Comparisons with another prediction approach, using extrapolation of measured bathymetric surveys to 2030 performed in the TE2100 project, found only limited agreement. A sensitivity analysis was performed on the effect of variations in grainsize, mean sea level, and bathymetry on particle positions over the whole modelled area, and sediment fluxes at four North-South flux curtains.

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# 1. Aims and rationale

HR Wallingford has a well-established random-walk Lagrangian particle-tracking model for the dispersal of suspended muddy sediments, primarily dredged spoil, SEDPLUME-RW (Mead and Rodger, 1991). Subsequently a sister-model (SandTrack) for Lagrangian particle-tracking of sand-grains was developed including bedload, suspended load, incipient motion and burial processes (Soulsby *et al*, 2007). The models operate by tracking the movement of "tagged" grains of mud or sand, each representative of billions of similar grains. Runs over times of typically a few weeks to a few decades give predictions of where the tagged grains end up. Sites that the SandTrack model has been applied to include the north coast of Scotland, Morecambe Bay, the Dee Estuary, and the central North Sea.

This report describes the extension of the SandTrack model to associate a volume of sediment with each tagged grain, and deposit it on the bed in a diffuse fashion as a sediment "lens" with a defined maximum thickness and extent. The sum of the lenses gives the morphodynamic development of the estuary. If this process is repeated at intervals of say 1 year or 10 years, and the hydrodynamics re-calculated at each step, this is in effect a hybrid morphodynamic model. The resulting model has been named "MorphoSandTrack".

It has the advantage over other hybrid models that in areas of deposition (tidal flats, salt-marshes) the *source* of the deposited sediment is known as well as its thickness. The tagged particles can carry a marker to indicate whether they are polluted with heavy metals, for example. Thus this approach to morphodynamics leads directly to information which is additionally valuable for biological, ecological and water quality purposes, such as whether a newly deposited area of sediment is contaminated. The new morphodynamic development has been tested on the Thames estuary. The developments were done in collaboration with the Proudman Oceanographic Laboratory, who have their own rather different Lagrangian model, whose behaviour and applicability is complementary to those of SandTrack. Sensitivity tests were made with respect to grainsize, initial seeding location, mean sea level and initial bathymetry.

# 2. The SandTrack model

Traditional sediment transport models (such as HR Wallingford's SANDFLOW) treat sand grains as interchangeable: if one grain lands on the sea-bed surface and is then buried, there is always a similar grain to take its place and be transported. Thus the quantity that is predicted is the mass of sand transported across unit width of bed (transverse to the flow) per unit time. The grains have no individual identity.

For the case in which it is necessary to track the movement of, for example, contaminated sediments it is essential to track individual particles: in essence each particle is "tagged". If a tagged particle becomes buried, perhaps for an hour, a day or a year, then it is important to take this into account when predicting its long-term dispersion. Likewise, if a particle is on the bed surface, and a proportion of grains are moving, then it is important whether it is the tagged grain, or a similar sand grain, that is moving. So-called particle tracking models exist (such as HR Wallingford's PLUME-RW), but these relate to "particles" of fluid or mud or oil. SandTrack has been devised to model the transport of grains of sand (or hydraulically similar particles).

It is, of course, impossible to model precisely what every tagged grain does in a fully deterministic manner, so the approach adopted is stochastic. The SandTrack algorithms simulate, as exactly as possible, the behaviour of sand grains in response to currents and waves, in an average sense but with a random element.

The aim of the original development of SandTrack was to devise a particle-tracking algorithm applicable to sand grains and industrial metal particles transported by current and wave mechanisms. This needed to be at a level of sophistication that would represent the processes of burial/re-emergence, bedload and suspended load transport accurately, but be capable of application in computer models for 30-year simulations or longer. The algorithm had to be consistent with existing tried and tested sediment transport formulae/models.

The HR Wallingford model SEDPLUME-RW already contained most of the elements needed for a particle tracking model. However, it was designed for mud, so it needed to be adapted to represent the rather different processes involved in sand transport. Some of the underlying processes were drawn from the book "Dynamics of Marine Sands" by Soulsby (1997).

Transport of sand grains involves the following processes which are included in the SandTrack algorithm:

- burial (or "trapping" in the seabed) and re-emergence, due to passage of ripples and sandwaves, general bed movement, bioturbation and "anthroturbation"
- alternate movement and resting of particles on the seabed (that is, in a layer comprising the top few grains of the bed)
- bedload transport by rolling and hopping (mainly coarsest grains)
- suspended transport (mainly finest grains).

The following driving processes are important for sand movement in the marine environment, to varying degrees:

- tidal, residual and mean currents
- waves.

At some sites, currents alone (even if acting all together in the same direction) are rarely able to mobilise sand grains or industrial particles alone. In such cases, the wave stirring effect can be the main process mobilising the grains, which are then advected by the current. In a model run, thousands or tens of thousands of tagged particles are released at a single point over a period of time (e.g. a few complete tidal cycles). In the extension of the model to estuarine morphodynamics, the seeding is instead implemented by seeding the tagged particles at random locations scattered evenly across the study area. In doing so, particles must also be seeded well outside the area of greatest interest, so that they can, if required, travel into that area as the model run proceeds.

# 3. Development of morphodynamic capability

To extend SandTrack to predict morphodynamic evolution of the seabed or estuary bed, a volume of sediment is assigned to each of the tagged particles. If a particle is picked up by the flow, this volume of sediment is removed from the initial bathymetry, and deposited at the location of the tagged particle at some later time. The volume is given the shape of a diffuse "lens", so that its effect on the bed is distributed over an area of the bed rather than just at the precise location of the particle. The lens was given a circular plan-shape, and a vertical cross-section (of maximum height $h$) corresponding to the cosine of distance from the particle, extending out to a certain radius of influence $a$ outside which the effect on the bathymetry is zero (Figure 3.1).

The finite-element-based flow model TELEMAC was used for the study. TELEMAC, developed originally by EDF-LNHE, Paris, uses a completely unstructured mesh of triangular elements, which enables accurate modelling of complex coastlines and bathymetric features, with detail focussed in areas of key interest.

In order to update the bed levels according to the sediment transport model results, HR Wallingford's bed update module TELEMORPH was modified to allow the reading of initial and final particle locations. For each particle location, TELEMORPH checks through all the nodes in the model to see if any lie within the radius of influence of the particle. This radius is defined such that all points in the model are influenced by at least 30 particles, to ensure statistical stability. Thus, if $A$ is the area of the model then ideally the number of particles, $N$, and the radius of influence, $a$, are chosen such that $(N/A)\pi a^2 \geq 30$, or roughly $Na^2 \geq 10A$.

If a node lies within a particle's radius of influence then a bed level change is assigned by TELEMORPH, the exact change depending on a cosine function of the distance from the particle to the node, with the maximum possible change occurring at the particle location. The assigned volume has a maximum thickness $h$ (Figure 3.1) which can be determined by the "mean mobile thickness", which is the mean thickness of a layer of sediment (across the area of interest) that can be mobilised during a morphological timestep. In initial tests, the value of the "mean mobile thickness" was specified arbitrarily, choosing a large value so that significant changes to the bed morphology occurred quickly. Subsequently, the value of $h$ was calibrated against a widely-used sediment transport predictor (see Section 4), so that SandTrack can be used in applications without further calibration or arbitrary specification. However, as with any sediment transport predictions, site-specific calibration can improve results if suitable data are available.

The contributions at each node from each particle are summed by TELEMORPH, and the difference between the initial and final sums constitutes the total bed change. The bed level change is applied to the flow model bathymetry so that the flow field can be recalculated and the whole morphodynamic process repeated.

The morphodynamic process, from the calculation of a flow field through to the bed-update stage, constitutes one morphological timestep. This process is summarised in the flow diagram shown in Figure 3.2.

# 4. Calibration of lens thickness

For the initial model runs, the mean mobile thickness was arbitrarily set at a larger than natural value, in order to exaggerate the bed level changes, and hence the flow distribution changes. During the model development, a more quantitative approach was adopted, whereby lens thicknesses were established through calibration of the model using known sediment transport rates. A uniform square test bed was used for the calibration, measuring 500m by 500m, with a constant water depth of 5m. A uniform steady flow was imposed at every point in the model, and the current speed was varied as detailed in the test sequence list below. Three different grain sizes $d_{50}$ were tested: 0.125mm, 0.25mm, and 0.5mm, and the sensitivity to three different timesteps was checked. In all the tests, 10,000 particles were seeded randomly across the 500m x 500m test area. Details of the tests are given in Table 4.1, which includes the test results in terms of fluxes of model particles in the direction of the specified current.

**Table 4.1 Details of the model calibration tests**

| Test | $d_{50}$ (mm) | timestep (s) | U (m/s) | SandTrack Flux (particles/m/s) | TRANSPOR Flux (kg/m/s) | Lens height, h (mm) |
|---|---|---|---|---|---|---|
| 04 | 0.25 | 60 | 0.4 | 0 | 0.0006 | |
| 05 | 0.25 | 60 | 0.8 | 0.00331 | 0.143 | 3.4 |
| 06 | 0.25 | 60 | 1.2 | 0.0131 | 1.05 | 6.3 |
| 07 | 0.25 | 60 | 1.6 | 0.0230 | 4.33 | 14.8 |
| 08 | 0.25 | 60 | 2 | 0.0361 | 10.9 | 23.7 |
| 09 | 0.125 | 60 | 0.4 | 0 | 0.0012 | |
| 10 | 0.125 | 60 | 0.8 | 0.0106 | 0.301 | 2.2 |
| 11 | 0.125 | 60 | 1.2 | 0.0312 | 2.5 | 6.3 |
| 12 | 0.125 | 60 | 1.6 | 0.0463 | 11.7 | 20.0 |
| 13 | 0.125 | 60 | 2 | 0.0602 | 48 | 62.7 |
| 14 | 0.5 | 60 | 0.4 | 0 | 0.0001 | |
| 15 | 0.5 | 60 | 0.8 | 0.00189 | 0.0551 | 2.3 |
| 16 | 0.5 | 60 | 1.2 | 0.00901 | 0.455 | 4.0 |
| 17 | 0.5 | 60 | 1.6 | 0.0176 | 1.81 | 8.1 |
| 18 | 0.5 | 60 | 2 | 0.0267 | 4.44 | 13.1 |
| 19 | 0.25 | 10 | 1.2 | 0.0131 | | |
| 20 | 0.25 | 600 | 1.2 | 0.0131 | | |

Tests 19 and 20 gave the same fluxes as the equivalent Test 06, showing that the fluxes were independent of the timestep. The results of Tests 4 to 18 were compared with results from the widely used sediment transport predictor TRANSPOR (Van Rijn, 1993), as follows. The sediment transport rate expressed as volume of settled bed (including pore space) was derived from the TRANSPOR fluxes by dividing by the typical bulk density of a sand bed = 1600 kg/m$^3$. Dividing this by the SandTrack flux (particles/m/s) yields the effective volume of bed sediment per SandTrack particle. The volume of a lens whose cross-sectional shape is cosinusoidal is (by analytical integration) approximately $a^2h$. If the number of particles in the model is N, and the model area is $A$, then the area of one lens is $A / N = \pi a^2$, yielding $a = (A / \pi N)^{1/2} = 2.82$m for A = 500x500m$^2$ and N = 10,000. Equating the volume of the lens with the volume per particle deduced above yields the value of $h$ (Table 4.1).

It was deduced that the calibrated lens height $h$ for the uniform test bed varies from 2mm to 63mm, depending on the grain size and the current speed. Ideally, the value of $h$ would be independent of grain size and current speed, but this does not appear to be the case. As a compromise, when setting up a model at a particular study site, the value of $h$ should be fixed using Table 4.2 for the grainsize under consideration and a current speed which is typical of the site, taking a value close to the peak of the mean spring tide (when the majority of sediment transport takes place). For example, for the test cases on the Thames described in Section 5, a value of $h$ = 5mm was used, which is typical of a current speed of 1.0m/s for both 0.125mm and 0.25mm grains.

# 5. *Test case – Thames Estuary*

## 5.1 SET UP

### Flow model

The work undertaken used an existing flow model of the Thames Estuary and adjacent coastal waters, based on TELEMAC-2D, and covering the area shown in Figure 5.1. The model contains approximately 9000 elements, with a grid size of around 250m in the narrow sections of the River Thames, rising to over 5km at the offshore boundary.

The model's boundary condition consists of water levels for a mean spring tide imposed on the offshore boundary. For the present study, the model was run for two consecutive tides, which was sufficient for the flow field to converge. The second tide of each test case was then extracted for use in the particle tracking simulation. This tide was repeated for the duration of the run, or for the required interval between bed updates (typically one year).

### Particle Tracking

The SandTrack model was used with 10,000 particles seeded randomly across the area of interest (see Table 5.1). The model was run for various periods of time, as detailed in Sections 5.2, 5.3 and 5.4. Unlike the uniform flow model test case, the particles were not constrained to a specific "active area", and were free to move around the entire flow model domain.

### Bed update

The bed update stage of the process used the TELEMORPH program discussed in Section 3.

## 5.2 PARTICLE TRACKS OVER 3 YEARS

The SandTrack model was used to predict the transport of particles around the model area over a three-year period. Three scenarios were tested, each with different areas of the model initially seeded with 0.25mm diameter particles of density 2650kg/m$^3$, as summarised in Table 5.1.

**Table 5.1 Specification of the Thames Estuary test cases**

| Test | Number of particles | Initial random seeding |
|---|---|---|
| 01 | 10,000 | area to the west of a line 625km E |
| 02 | 10,000 | area to the east of a line 625km E |
| 03 | 30,000 | entire model area |

For these simulations, no bed updates were incorporated into the model. Figure 5.2 shows the particle distribution variations over three years of simulation for the three different initial seedings. It should be noted that the flow field used in Test 1 was a repeating spring-neap cycle, whereas the flow fields in both Tests 2 and 3 were repeating mean spring tides.

Particle accumulations tended to occur along the coastlines in the initially-seeded areas, and in a relatively small number of localised areas offshore. The linear features evident in Figure 5.2 appear to be preferred particle transport pathways, which tended, in Tests 2 and 3, to persist until most of the model particles were in localised areas of long-term accumulation. It is probable that such accumulations did not occur in Test 1 due to the higher maximum current speeds associated with the use of a spring-neap cycle of flow model results, as opposed to a single mean spring tide. The transport pathways in all three tests tended to lie along the tops and flanks of the existing sandbanks, and were aligned with the residual flow patterns, as shown in Figure 5.3, which is a more detailed presentation of one of the frames of Figure 5.2. Accumulation points may occur for various reasons, such as in areas where the current speed is frequently below the threshold of motion, near the centres of eddies, or at convergence zones of sediment transport.

## 5.3 ANNUAL BED UPDATES

A further Thames Estuary model simulation was carried out including bed updates, using morphological timesteps of one year, with a total simulation length of 3 years. The SandTrack model was seeded with 10,000 particles scattered at random to the west of 625km E. After one year, the bed elevations were altered using TELEMORPH, based on the initial and final particle locations, as described in Section 4.1. The flow field was then re-calculated and the process repeated for the updated bed.

This simulation was carried out before the means of making quantitative lens thickness estimates was established (Section 4.3). The mean mobile thickness used was 30cm, with a corresponding lens thickness of 3.2cm and a radius of influence of 2.4km. The evolution of the bed over the three years is shown in Figures 5.4 and 5.5. Positive bed level changes tended to occur along the coastlines in the initially-seeded area, in the outer Thames to the north of the Medway Estuary, and along some of the transport pathways mentioned in the previous Section. The magnitudes of the changes were much larger than one would expect in nature over similar time scales, reflecting the relatively large lens thickness, which was an order of magnitude greater than that indicated by the calculations described in Section 4.3 (see Section 5.4).

## 5.4 TIDAL BED UPDATES

A further morphodynamic simulation was carried out as described in Section 5.3, but with the morphological timestep reduced to one month and the total simulation length set to one year. A different strategy was also employed at the bed update stage, as described further below. The volume of sediment associated with each lens was based on the calculations described in Section 4.3; that is the thickness of each lens at its centre was 5mm.

The TELEMORPH program was modified so that particle locations were read in at the start and end of each tide, instead of each year. Bed level changes were then worked out at the end of each tide, but the bed was not modified until the end of each month, when the final bed level was calculated based on the accumulation of all the changes over the course of the month. A smoothing was applied to the final bed level change before its application to the model bathymetry.

Figure 5.6 shows the level changes applied to the bed at the end of each month over one year, and Figure 5.7 shows the overall bed change after one year. It can be seen that banks of up to 8m above the original bed level formed around 625km E, with adjacent troughs up to 14m below the original bed level. These results do not appear to be realistic, indicating that the tidal update method is not a promising approach. It was also noted that the smoothing applied to the bed level changes could determine the magnitude of the total change. For this reason, and as there is no theoretical basis for the number of smoothings applied, it was decided that such smoothing would not be employed in further applications of the modelling technique. Furthermore, the tidal bed updates required much more computational time than the annual updating. Since the results looked less plausible than for the annual updating, the tidal updating was not pursued further.

## 5.5 50-YEAR MORPHODYNAMIC EVOLUTION

A 50-year morphodynamic simulation was carried out using annual bed updates as for the test described in Section 5.3, but with a median grain diameter of 0.15mm. This was the representative grainsize used in modelling for the Thames Estuary 2100 (TE2100) project. The volume of sediment associated with each lens was based on the calculations described in Section 4.3, with each lens thickness set to 5mm at its centre.

The bed evolution is shown every five years in Figures 5.8 to 5.12. In each plot, the cumulative change in bed elevation over the five years is also shown. The cumulative changes in the Inner and Outer Thames Estuary over 30 and 50 years are shown in Figures 5.13 and 5.14 respectively (these being based on 29 and 49 morphological updates respectively).

For the first 20 years of simulation, positive bed level changes tended to occur along the coastlines in the initially-seeded area, and in the outer Thames to the north of the Medway Estuary. In a small number of localised areas, the magnitudes of the changes were larger than one might expect in nature over similar time scales, with a maximum accretion depth of around 11m occurring to the north of the Medway Estuary in the five years between years five and 10 (see Figure 5.8). However, over the latter half of the simulation, the rate of accretion diminishes in the areas of deposition along the southeast coast of Essex.

# 6. *Sensitivity tests*

The three year particle-tracking model was tested for sensitivity to a number of parameters:

- grain size
- mean sea level increase
- sea bed elevation.

The sensitivity tests are described in Sections 6.1 to 6.4.

## 6.1 BASELINE CASE

A baseline case for the sensitivity tests was established, based on the findings of Section 5, with 10,000 particles of median grain diameter 0.15mm, initially seeded randomly over an area to the west of national grid easting 625,000. As for the tests presented in Section 5.2, no bed updates were incorporated into the model. Figure 6.1(i) shows the particle distribution variations over three years of the baseline simulation, which was carried out for a repeating mean spring tide.

For this and each of the subsequent simulations, the number of particles moving east and west past a set of four "flux curtains", or north-to-south lines, were recorded. The flux curtains were located within the River Thames at:

- Barking Reach (546,232mE)
- Tilbury (564,838mE)
- Blyth Sands (574,147mE)
- Southend (588,294mE).

The flux curtain locations are shown in Figure 6.2.

Table 6.1a shows the number of particles crossing the flux curtains for the 0.15mm grain (baseline) test. The gross fluxes increase eastwards, reflecting the eastward-increasing width of the estuary. It can be seen from the net fluxes that overall there is a tendency for sediment to be carried westward from the outer estuary into the river. There is a closer balance between transport in and out of the estuary for the easternmost flux curtains. However, the numbers of particles are relatively small, given that 10,000 particles were seeded initially, and that this was a three-year simulation. This suggests that an increase in the number of particles seeded within the estuary would have been beneficial. However, this would only have been worth doing if the grid resolution was finer than the rather coarse grid used in the pre-existing flow model. Generating a purpose-built flow model was outside the scope of the present project.

**Table 6.1 Flux curtain data for 0.15mm grains**

| Flux curtain | Width of curtain (m) | Number of particles crossing flux curtain | | |
|---|---|---|---|---|
| | | Eastward | Westward | Net westward |
| 1. Barking Reach | 530 | 0 | 3 | 3 |
| 2. Tilbury | 745 | 36 | 118 | 82 |
| 3. Blyth Sands | 2370 | 177 | 177 | 0 |
| 4. Southend | 7340 | 810 | 822 | 12 |

## 6.2 SENSITIVITY TO GRAIN SIZE

The three-year baseline simulation was repeated using particles representing sand grains of 0.1mm and 0.2mm median grain diameter. Figures 6.1(ii) and 6.1(iii) show the particle distribution variations over three years of simulation for these two simulations.

Generally, as might be expected, the 0.1mm diameter grains are more mobile than the larger 0.2mm grains and the original 0.15mm grains. Over the course of the simulation, a small number of the particles representing 0.10mm grains (less than 0.1%) are lost from the flow model area, whereas all the particles in the 0.15mm and 0.2mm grain tests remain within the model area after three years.

Despite the varying mobility of the particles with grain size, the overall distributions of particles are similar for the three grain diameters tested, with particle accumulations tending to occur adjacent to the coastlines in the initially-seeded areas, and in localised areas offshore, as for the three-year simulations of Section 5.2.

The number of particles crossing the flux curtains during the simulations are shown in Tables 6.2a and 6.2b for the 0.1mm and 0.2mm grains respectively. There are no consistent patterns of variation of the fluxes with grain size. Overall there is a tendency for all grain sizes of sediment to be carried westward.

**Table 6.2a Flux curtain data for 0.1mm grains**

| Flux curtain | Number of particles crossing flux curtain | | |
|---|---|---|---|
| | Eastward | Westward | Net westward |
| 1. Barking Reach | 0 | 3 | 3 |
| 2. Tilbury | 54 | 130 | 76 |
| 3. Blyth Sands | 90 | 114 | 24 |
| 4. Southend | 2368 | 2531 | 163 |

**Table 6.2b Flux curtain data for 0.2mm grains**

| Flux curtain | Number of particles crossing flux curtain | | |
|---|---|---|---|
| | Eastward | Westward | Net westward |
| 1. Barking Reach | 0 | 3 | 3 |
| 2. Tilbury | 33 | 108 | 75 |
| 3. Blyth Sands | 669 | 670 | 1 |
| 4. Southend | 935 | 951 | 16 |

## 6.3 SENSITIVITY TO MEAN SEA LEVEL

A three-year particle-tracking simulation was carried out using a flow model in which the mean sea level was increased by 0.3m (the agreed standard value to be used by all the modelling partners in the present project, based on values used in the TE2100 project).

Figure 6.3 shows a comparison between the particle distribution variations over three years for this simulation and the original 0.15mm grain baseline test. Most of the main features of the particle distributions are similar in the two tests, although there are some noticeable differences. Comparison of Table 6.3 with Table 6.1 shows that, whilst the overall net transport trend is similar in both tests, the increase in mean sea level has increased the gross transport at all locations except Barking Reach. This increased particle mobility is most likely due to the marginal changes in current speed that result from the increased water depths. Thus an increase in Mean Sea Level produces an increase in the mobility of the sediments, which would allow them to re-distribute more readily towards a new (quasi-) equilibrium morphology.

**Table 6.3 Flux curtain data for 0.15mm grains, with mean sea level raised by 0.3m**

| Flux curtain | Number of particles crossing flux curtain | | |
|---|---|---|---|
| | Eastward | Westward | Net westward |
| 1. Barking Reach | 0 | 3 | 3 |
| 2. Tilbury | 47 | 139 | 92 |
| 3. Blyth Sands | 422 | 424 | 2 |
| 4. Southend | 1450 | 1457 | 7 |

## 6.4 SENSITIVITY TO BATHYMETRY

Additional particle-tracking simulations were carried out for two of the predicted bathymetries derived from the 50-year morphodynamic simulation presented in Section 5.5. Bathymetries from 2030 and 2050 were selected for the purposes of testing.

Figure 6.4 shows a comparison between the particle distribution variations over three years for the baseline 0.15mm grain test and the two bathymetry sensitivity tests. In general there is a greater tendency for the particles to be retained in the inner estuary for the “2030” and “2050” bathymetries, with particular accumulation along the coastlines. These areas of accumulation coincide with areas that have already accreted sediment over the course of the 50-year morphodynamic simulation, as can be seen in Figures 5.14 and 5.15.

The flux curtain data for the bathymetry sensitivity simulations, shown in Tables 6.4a and 6.4b, show that for “2030” the net transport trend is largely similar to the baseline case. The mobility further up the Thames is reduced, whilst the mobility further eastward is increased over the baseline case.

For “2050”, there is a marked difference in the overall sediment fluxes across the curtains. The net sediment transport into the river from the estuary is increased, and the mobility of grains around Blyth Sands has been increased.

**Table 6.4a Flux curtain data for 0.15mm grains, with predicted “2030” bathymetry**

| Flux curtain | Number of particles crossing flux curtain | | |
|---|---|---|---|
| | Eastward | Westward | Net westward |
| 1. Barking Reach | 0 | 3 | 3 |
| 2. Tilbury | 25 | 114 | 89 |
| 3. Blyth Sands | 114 | 127 | 13 |
| 4. Southend | 1141 | 1175 | 34 |

**Table 6.4b Flux curtain data for 0.15mm grains, with predicted "2050" bathymetry**

| Flux curtain | Number of particles crossing flux curtain | | |
|---|---|---|---|
| | Eastward | Westward | Net westward |
| 1. Barking Reach | 0 | 3 | 3 |
| 2. Tilbury | 70 | 229 | 159 |
| 3. Blyth Sands | 1946 | 2028 | 82 |
| 4. Southend | 804 | 1051 | 247 |

# 7. Discussion

## 7.1 COMPARISON BETWEEN MORPHOSANDTRACK AND TE2100 THAMES PREDICTION

A comparison was made between the morphology of the Thames Estuary in 2030 predicted by MorphoSandTrack (as described in Section 5.5) and the morphology deduced using a form of Historical Trend Analysis (based on extrapolation of existing repeat bathymetric surveys) as part of the Thames Estuary 2100 (TE2100) project. The evaluation given in Appendix 1 was made as part of the present project by Graham Siggers (project manager for HR Wallingford's work on the TE2100 project), acting as an independent evaluator of the SandTrack results.

Within the Thames Estuary *per se*, little similarity was found between the 2030 morphologies from the two methods of prediction. For SandTrack, the results suffer from a lack of resolution in the region examined, as noted in the Appendix. This applies both to the cell size of the flow model, and the limited number of tracked particles, in the examined region. Increasing the number of particles would only be productive if the flow mesh was considerably refined. Although a more refined mesh TELEMAC model was developed for the TE2100 project, this was not available at the time of the MorphoSandTrack runs, and re-establishing SandTrack on the TE2100 flow model was beyond the scope of the FD2107 project.

However, in the Outer Thames Estuary, where the level of flow resolution for resolution is more appropriate, the MorphoSandTrack predictions for the linear sandbanks does agree with observations. Here, the model predicts a stable and self-reinforcing pattern of banks, with a tendency to extend northeastwards, as is indeed observed.

Sediment fluxes were measured in the Thames in 2004 at the locations shown on Figure 6.2. The compared flux distributions displayed little similarity (Figures A1.4 and A1.5). However, it was noted that the SandTrack results assume uniform 0.15mm sand everywhere, whereas the measured fluxes included silt and mud which became increasingly dominant in the upper parts of the estuary. Thus the comparison is not of like with like.

## 7.2 PROS AND CONS OF THE MORPHOSANDTRACK MODEL

The developments to the model have achieved some of the intended objectives, but some aspects were less successful than anticipated. A list of the positive and negative attributes is given below.

**Positives**

- Modular nature (easy to separate and individually analyse the different stages of a morphodynamic simulation)
- Flexibility (not every simulation has to be morphodynamic - can also set up pure particle-tracking runs)
- Lagrangian approach (the user can easily see the evolution/preferred pathways of particles)
- Makes use of state-of-art software (SandTrack)
- Relatively quick to execute (depending on flow model resolution).

**Negatives**

- Currently requires individual setting up of a number of steering files for each simulated morphological timestep (would require automation if going to be used frequently)
- Modular nature means that many independent output files are generated
- Sediment is lost at boundaries (e.g. if a lens overlaps with the coastline, or if a particle leaves the flow model mesh)
- The calibration of the lens thickness against the Van Rijn TRANSPOR predictions is not fully independent of grain size or flow velocity
- In one morphological timestep, sediment can only be eroded to a depth limited by the thickness of the sediment lens and the random distribution of particles, but deposition can occur to a depth of many lens thicknesses in areas where there is a large accumulation of particles
- In order to accurately convert particle locations into areas of accretion and erosion, a relatively fine grid flow model is required (although this is possibly also true of more traditional Eulerian approaches)
- The choice of morphological timestep duration (e.g. one tide, one month, or one year) is rather arbitrary (also true of Eulerian approaches).

# 8. *Conclusions*

The existing Lagrangian particle-tracking model SandTrack for predicting the movement of sand grains in tidal estuaries and coastal locations has been extended to have a morphological capability, resulting in a new model named MorphoSandTrack. This was achieved by assigning a volume of sediment to each tracked grain, and depositing it in a diffuse lens at the end of specified time steps (typically one year). The bed bathymetry is updated accordingly, and the new flow pattern computed. A large number of grains (typically a few tens of thousands) are distributed randomly over the study area at the start of the simulation, and again after each new bathymetry/hydrodynamic update. This is repeated for a desired overall duration (typically a few decades) to give the model the capability of making predictions of long-term morphological development.

The volumes of sediment to be assigned to each tracked particle were calibrated against a well-established sediment transport model. The height and diameter of the cosine-cross-sectioned lens of sediment were related to these calibrated volumes, the number of modelled particles, and the area over which the particles are distributed, as an algorithm that determines the model inputs.

The model was tested on the Thames estuary to give predictions of the morphological evolution over 50 years (with annual bed updates). A model run seeded west of a North-South line at 625km East showed preferential particle paths in the outer estuary and the adjacent North Sea that cluster on, and run northeastwards along, the tops and flanks of the linear sand banks found in this area. After some years, some of the particles return southwards down the outer edge of the bank system, then head westwards to rejoin the stream of particles along the bank crests. After approximately 18 months, particles start to leave the model area northwards at about the latitude of 52.1°N. No particles leave the model area eastwards, and none travel along the North Kent coast or into the Dover Straits. A second model run with particles seeded East of the same line showed particles travelling into the Outer Thames Estuary. The predicted morphological evolution over 50 years showed accretion on the Maplin and Foulness Sands, and in The Swale, South of the Isle of Sheppey.

Calculations of the gross and net sediment fluxes through four North-South “flux curtains” showed net westward (up-estuary) fluxes through all curtains, with both the gross and net fluxes increasing eastwards (i.e. with increasing curtain width).

A sensitivity analysis for three-year (non-morphodynamic) runs on the Thames Estuary was performed. The results showed:

- For variations in grainsize of 0.10mm, 0.15mm and 0.20mm (representative of various parts of the estuary), (a) the rate of movement of grains was greater for finer grains, but the overall patterns were similar; (b) no consistent pattern variation with grainsize of fluxes through the flux curtains.
- For an increase of 0.3m in mean sea level, (a) accumulation of sediment at points less far offshore, (b) increased gross fluxes (allowing more rapid adjustment to rising sea level), but little change in net fluxes.
- For initial bathymetries set at the predicted 2030 and 2050 distributions, (a) greater retention of particles inshore, especially for 2050 bathymetry, (b) for 2030, decreased fluxes in inner estuary, increased fluxes in outer estuary, (c) for 2050, increased fluxes all round, especially the gross fluxes at Blyth Sands and net fluxes at Southend.

A detailed comparison between the modelled morphology in the Thames Estuary for 2030 and a prediction made by extrapolation of historical trends in the TE2100 project showed little correspondence, but this is at least partly due the coarse resolution of the available flow model used by SandTrack. It should also be understood that the extrapolated morphology for the TE2100 project is itself a form of prediction.

We conclude that the morphological extension of SandTrack has achieved some benefits, although it is not as yet a tried and tested methodology and has some limitations. It would be advantageous to trial the model alongside a more conventional Eulerian model in a few study areas. The similarities and differences between the long-term predicted morphologies can be noted. The SandTrack model is expected to have the following advantages over the Eulerian model:

- Quicker to run, due to fewer bed updates and hydrodynamic re-calculations
- Less prone to instabilities in bed evolution

- Ability to detect the provenance of deposited sediments, and to track the movement and accumulation of contaminants.

Disadvantages are:

- Tendency to limit erosion depths, but not deposition thicknesses
- Less well-tested methodology.

Future enhancements which can be easily incorporated are:

- Adding wave effects (already incorporated in SandTrack and needs trialling on MorphoSandTrack)
- Adding markers to particles to indicate the presence of one or more contaminants (this would require a simple bit of coding).

# 9. References

Mead, C.T. and Rodger, J.G. 1991. Random Walk Simulations of the Dispersal of Dredged Spoil, in *Environmental Hydraulics*, Lee, J.H.W. & Cheung, Y.K. (Eds)., Balkema, Rotterdam, 783-788.

Soulsby R.L., Mead C.T. and Wild B.R 2007. A model for simulating the dispersal tracks of sand grains in coastal waters - "SandTrack". In: Coastal and Shelf Sediment Transport, eds P.S. Balson and M.B. Collins, Geological Society of London, Special Publications, 274, 65-72.

Van Rijn, L. C. 1993. Principles of Sediment Transport in River, estuaries and Coastal Seas. Aqua Publications, Amsterdam, NL. ISBN 90-800356-2-9.

# *Figures*

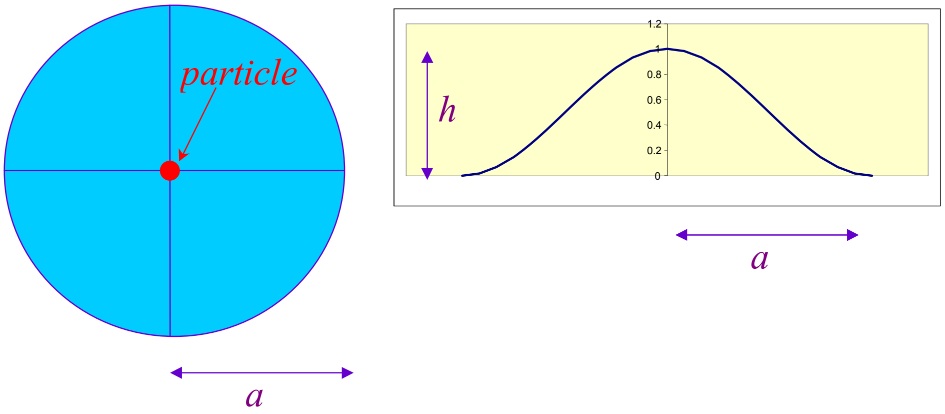

**Figure 3.1** **The particle "lens" form used at the bed-update stage. Plan view and cross-section**

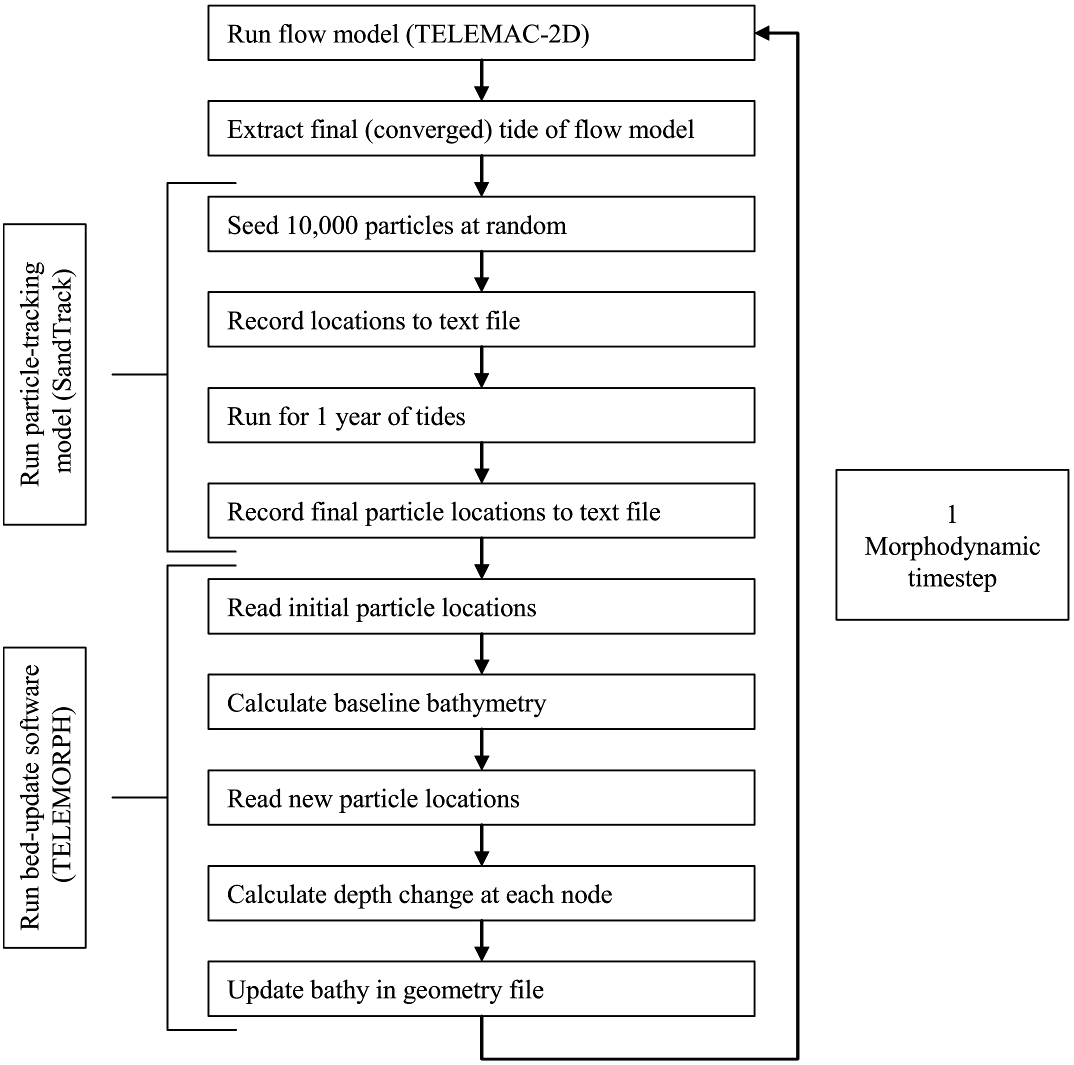

**Figure 3.2 The morphodynamic model algorithm (HR Wallingford's specific models are given in parentheses)**

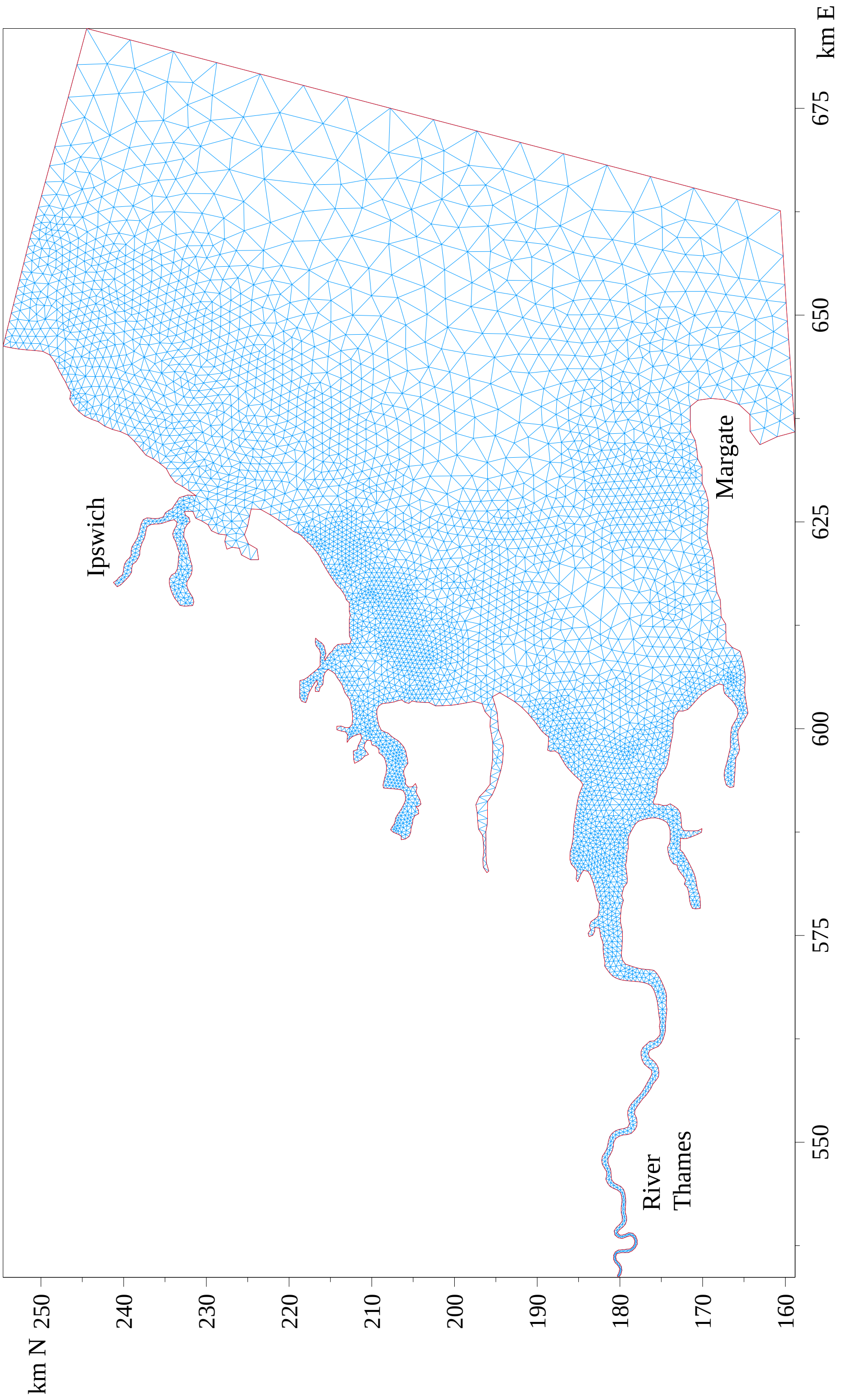

**Figure 5.1 The Thames model area and mesh**

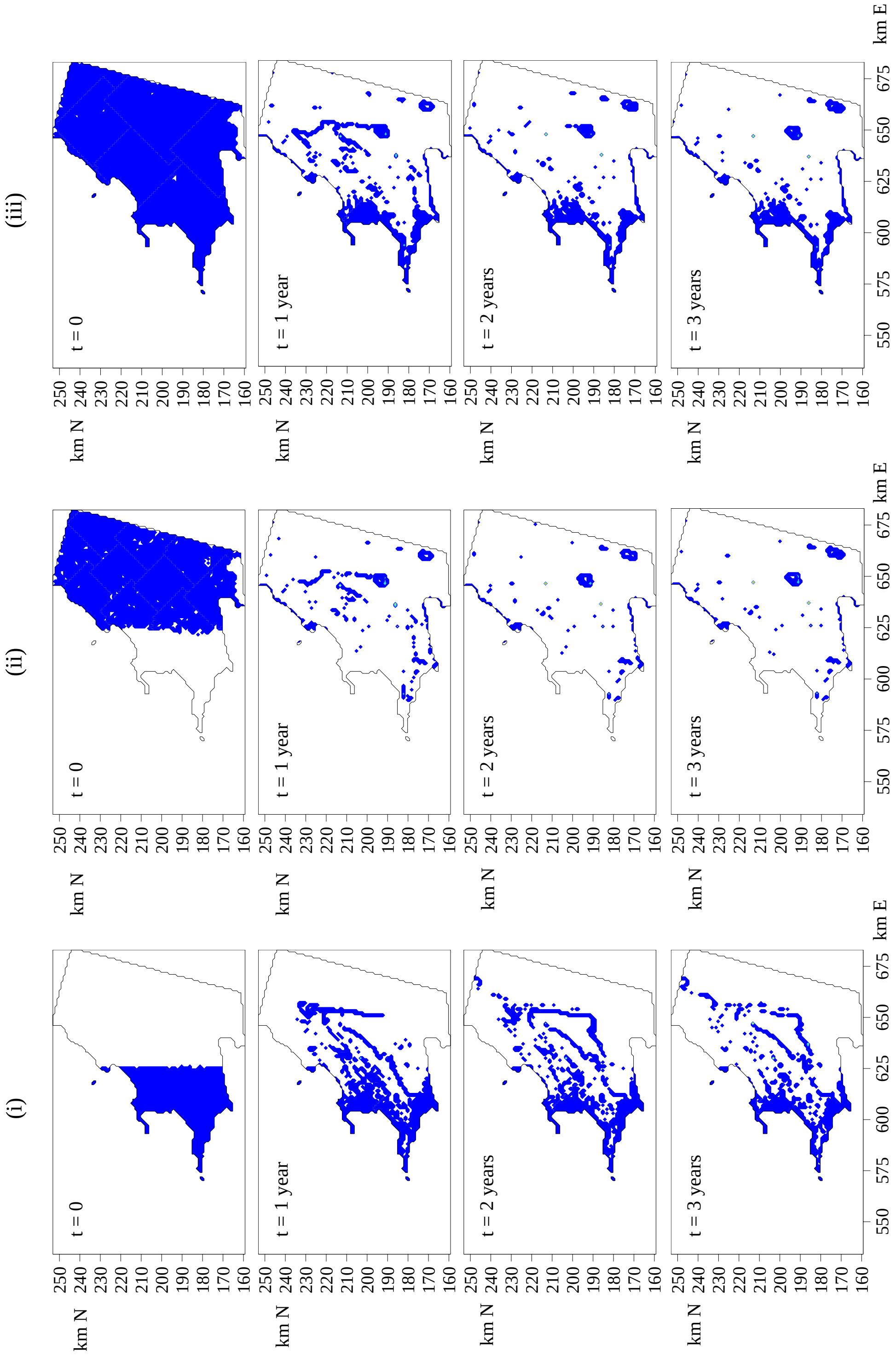

**Figure 5.2** Particle distribution variations over three years of simulation for models with: (i) 10,000 particles seeded in the area to the west of a line 625km E; (ii) 10,000 particles seeded in the area to the east of a line 625km E; (iii) 30,000 particles seeded over the entire model area

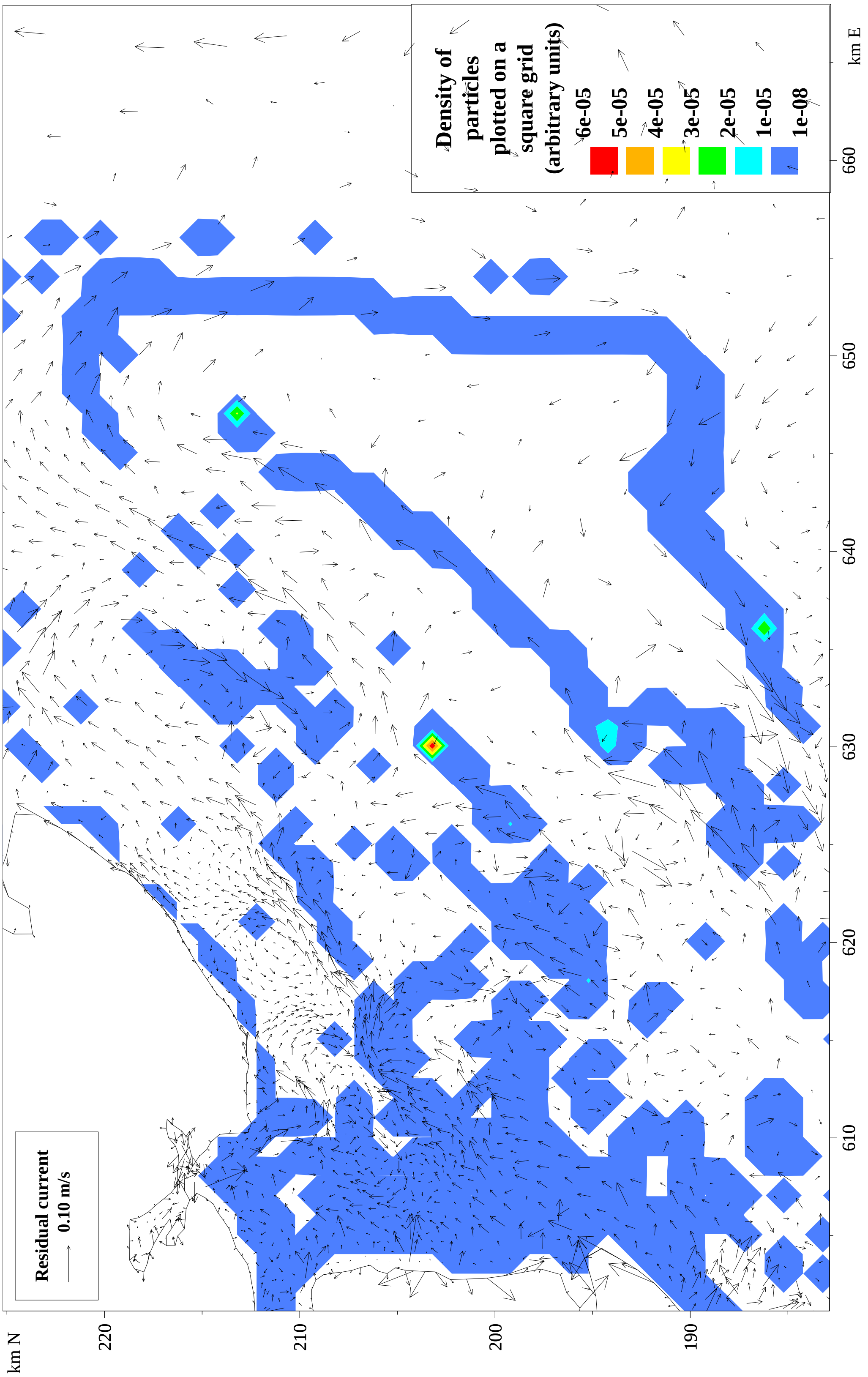

**Figure 5.3** Particle locations for Test 1 after two years of simulation, along with the residual current vectors. Particle densities have been plotted on a regular square output grid

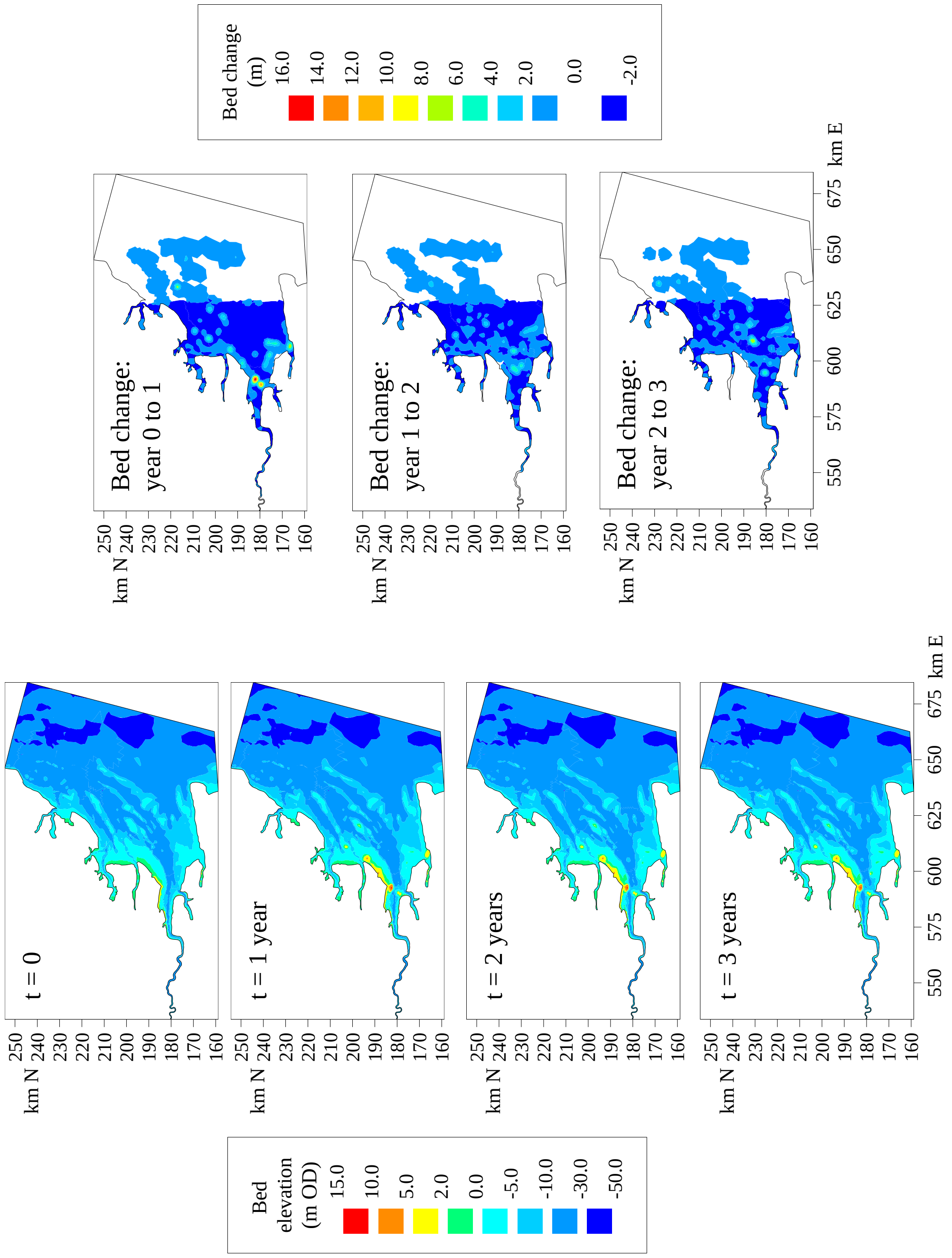

**Figure 5.4** Evolution of the Thames model bed over three years (exaggerated mobile layer thickness)

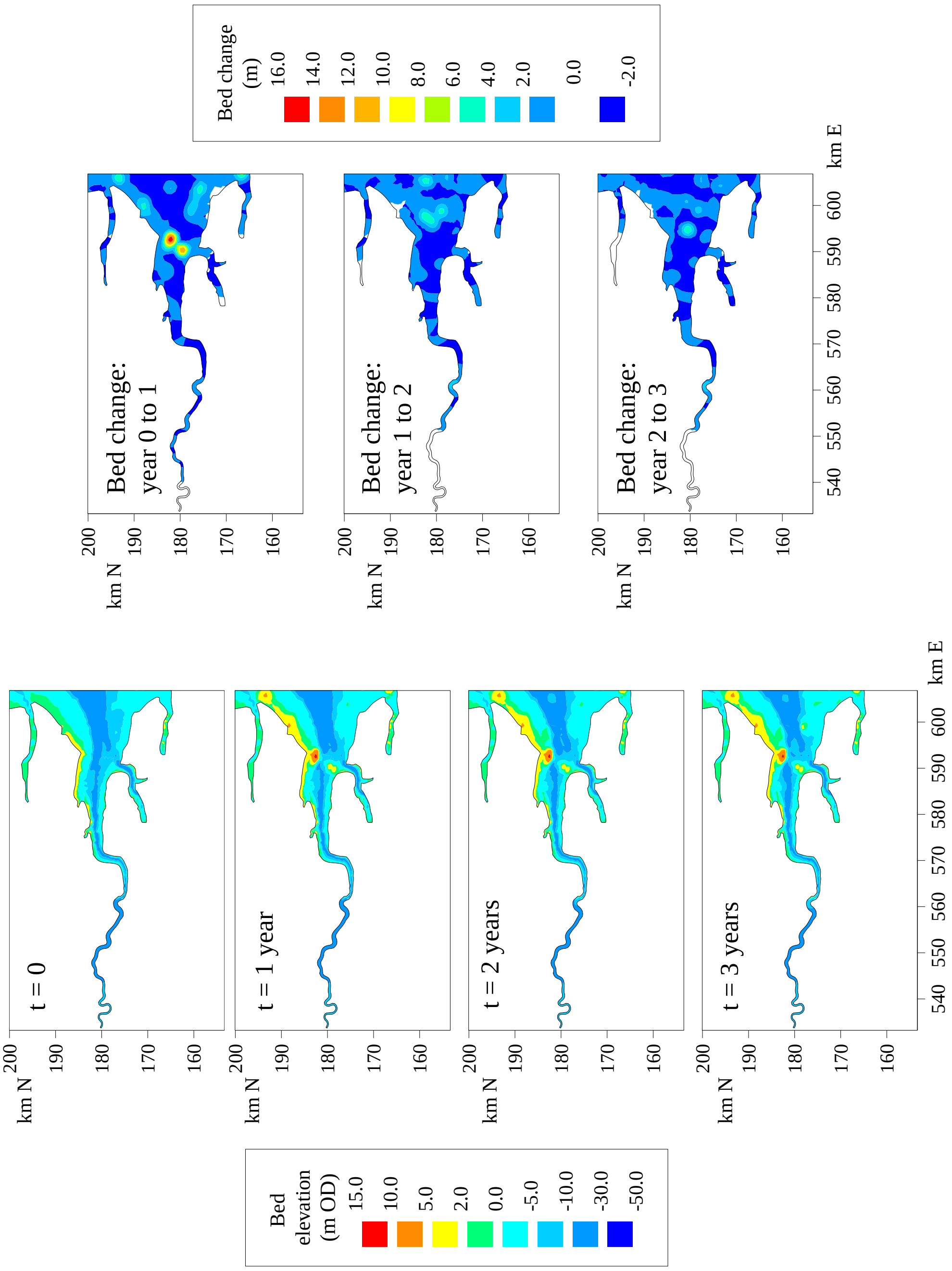

**Figure 5.5** Evolution of the Thames model bed, with enlarged detail around the mouth of the Thames Estuary (exaggerated mobile layer thickness)

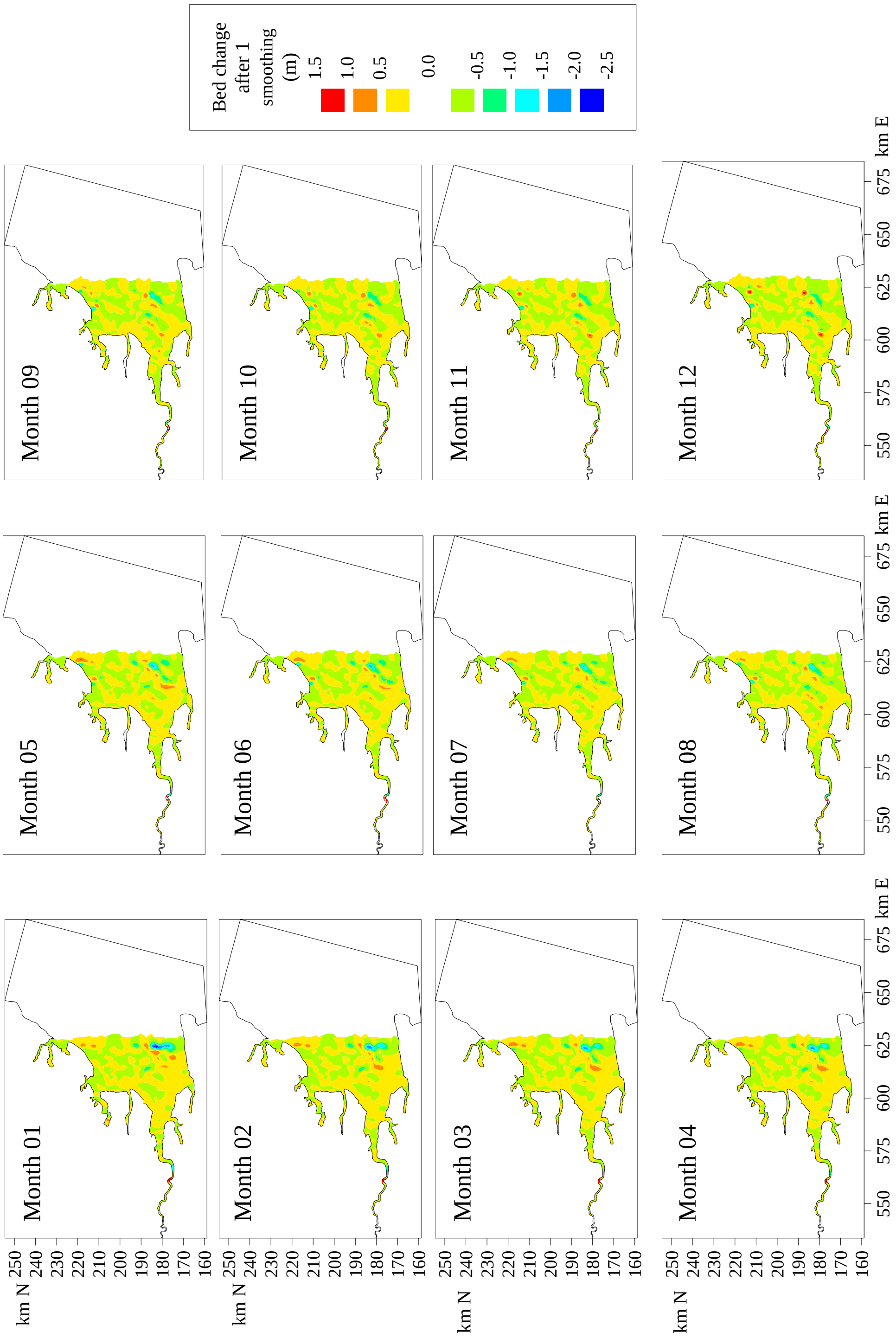

**Figure 5.6** Evolution of the Thames model bed over one year of simulation, using monthly bed updates based on the accumulation of bed level changes after each tide

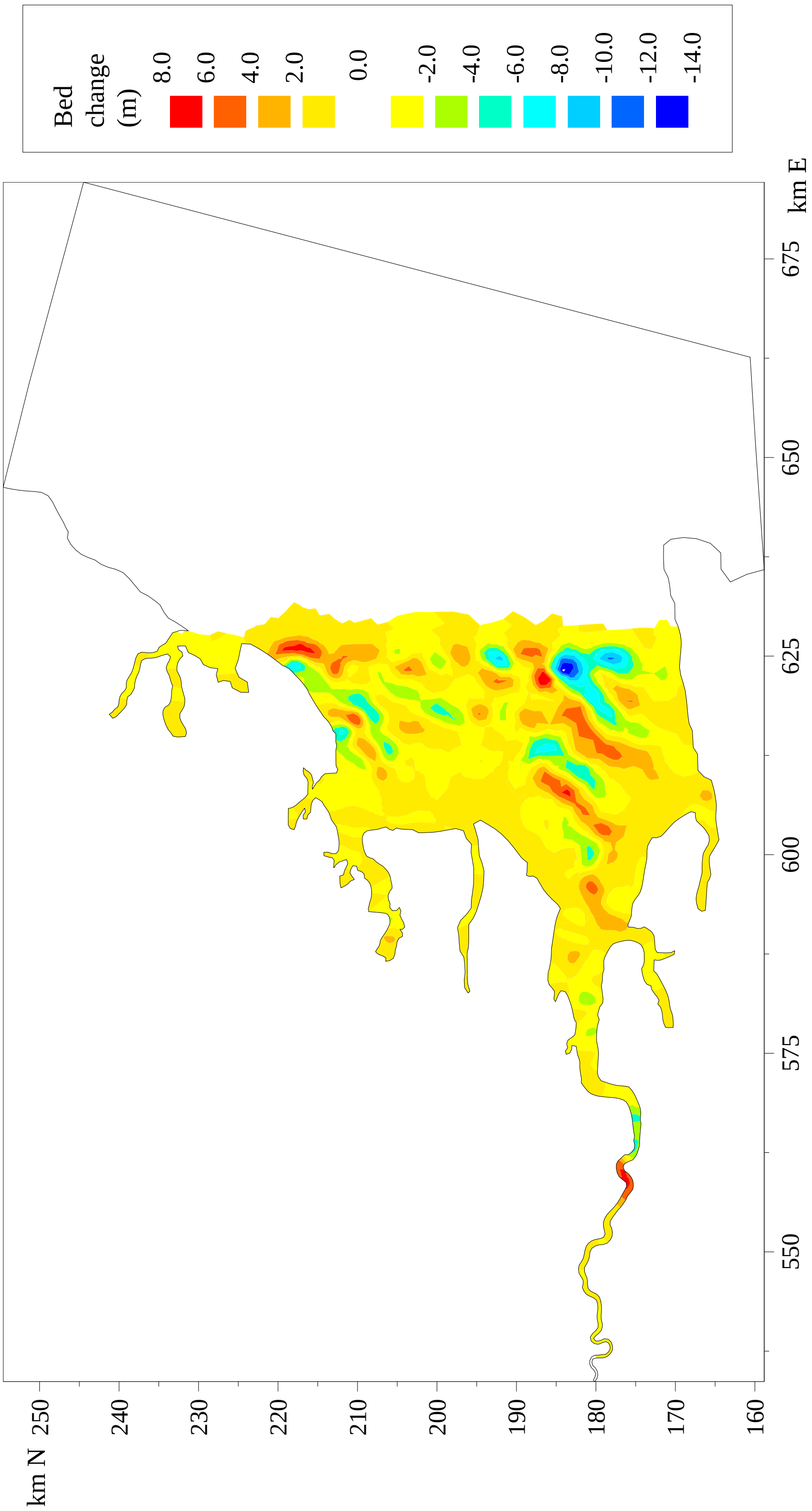

**Figure 5.7** Overall change in the Thames model bed over one year of simulation, using monthly bed updates based on the accumulation of bed level changes after each tide

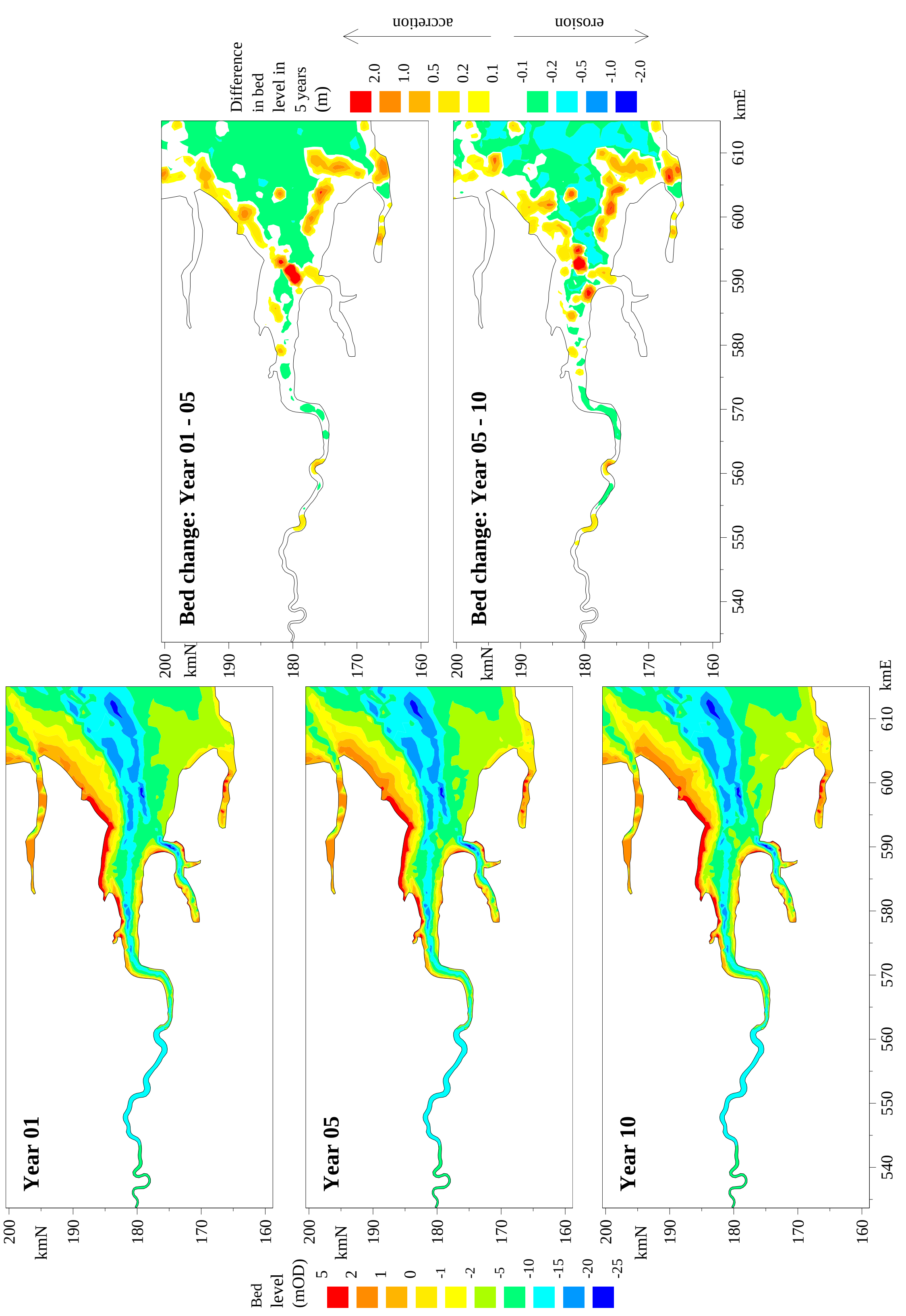

Figure 5.8 Evolution of the Thames model over year 1 to year 10 of a 50-year morphodynamic simulation, using yearly bed updates

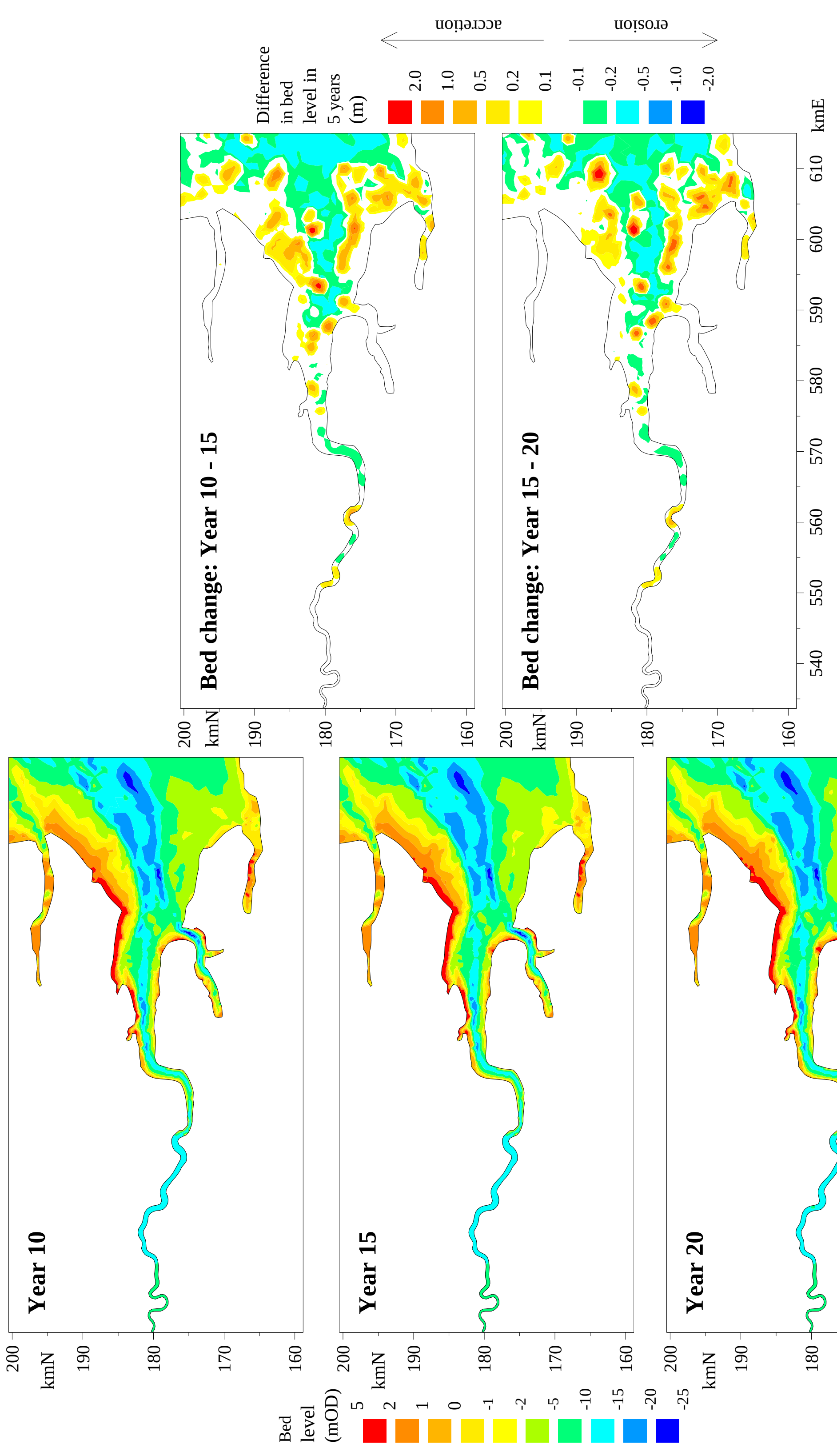

**Figure 5.9** Evolution of the Thames model over year 10 to year 20 of a 50-year morphodynamic simulation, using yearly bed updates

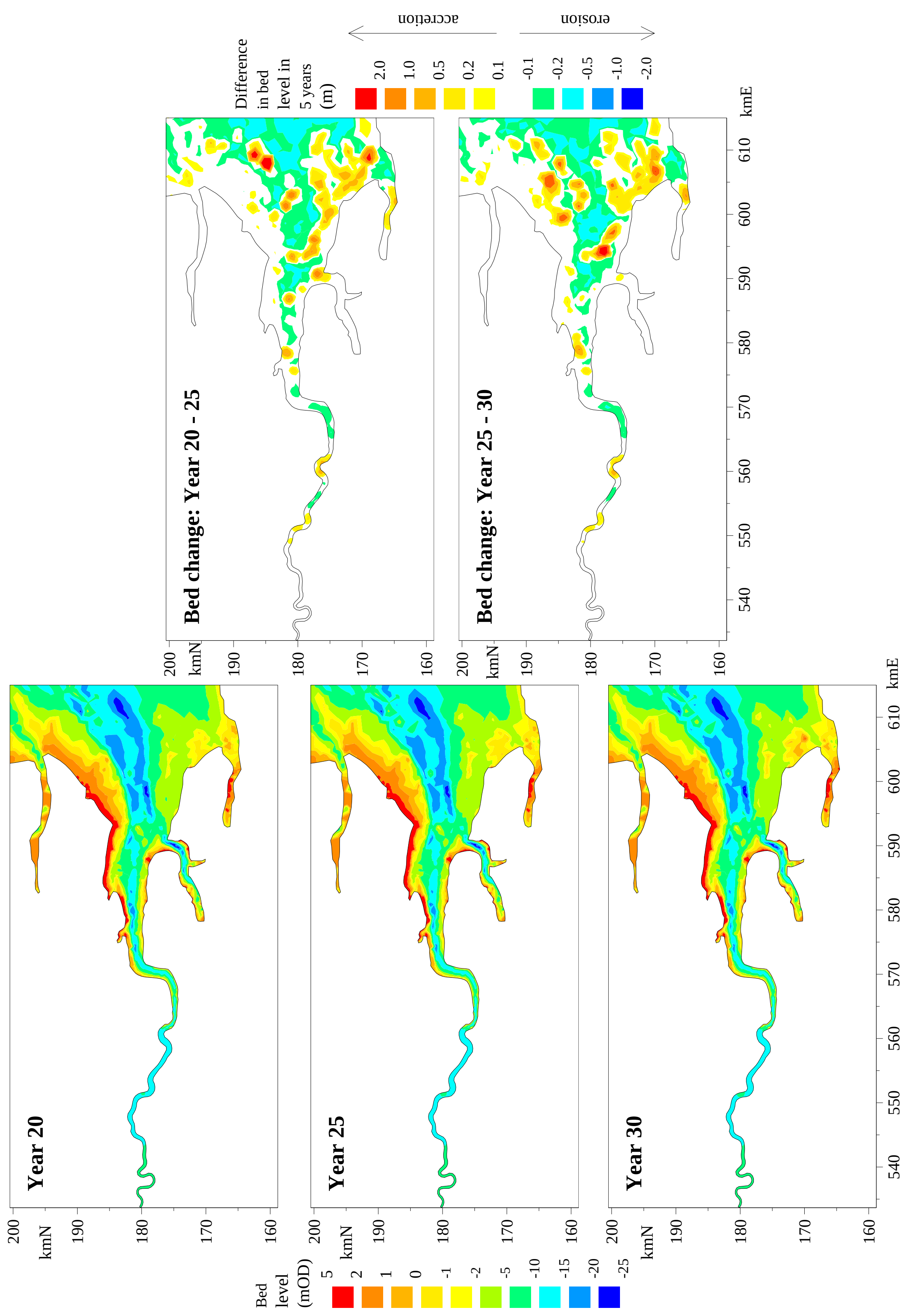

**Figure 5.10** Evolution of the Thames model over year 20 to year 30 of a 50-year morphodynamic simulation, using yearly bed updates

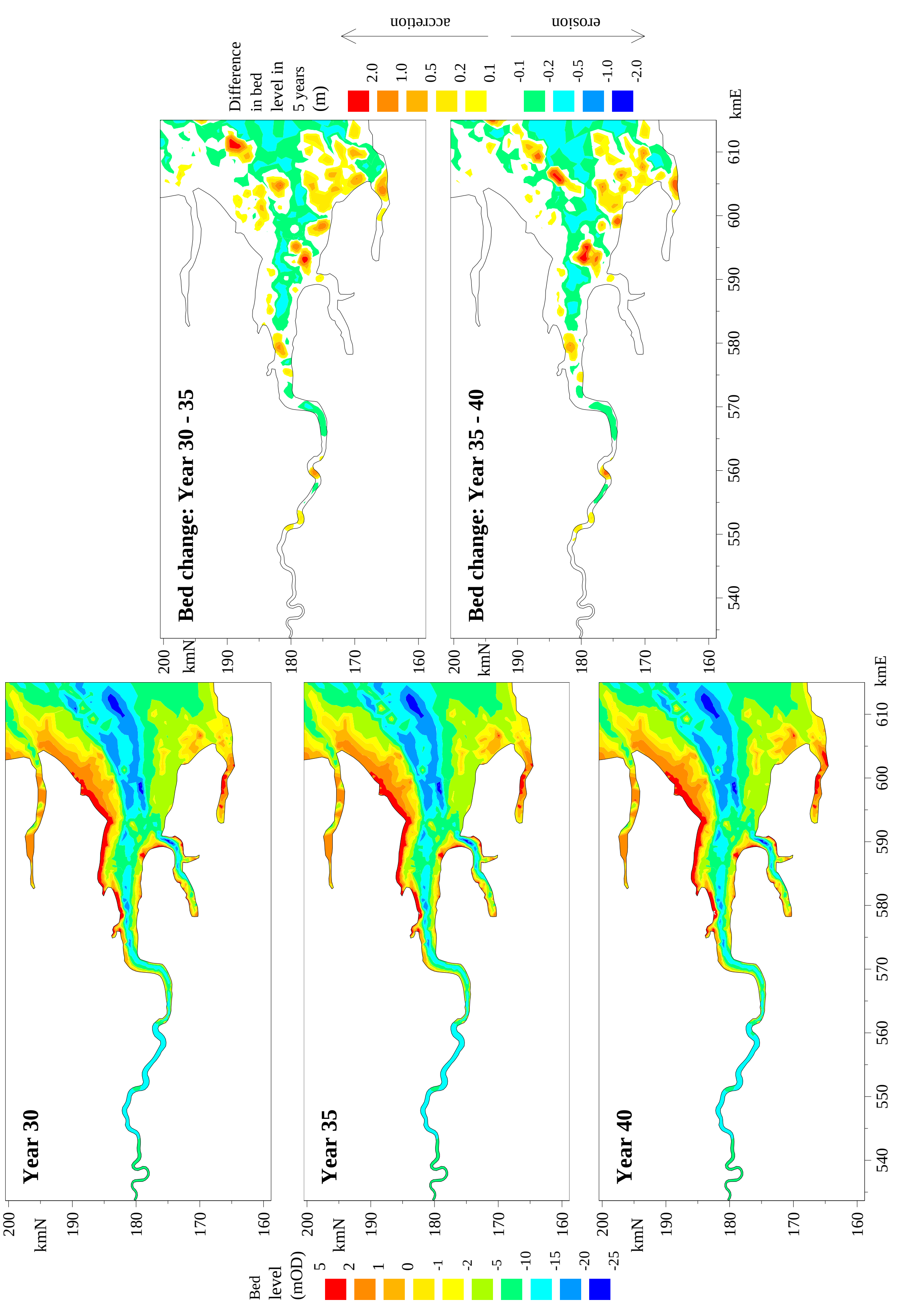

**Figure 5.11** Evolution of the Thames model over year 30 to year 40 of a 50-year morphodynamic simulation, using yearly bed updates

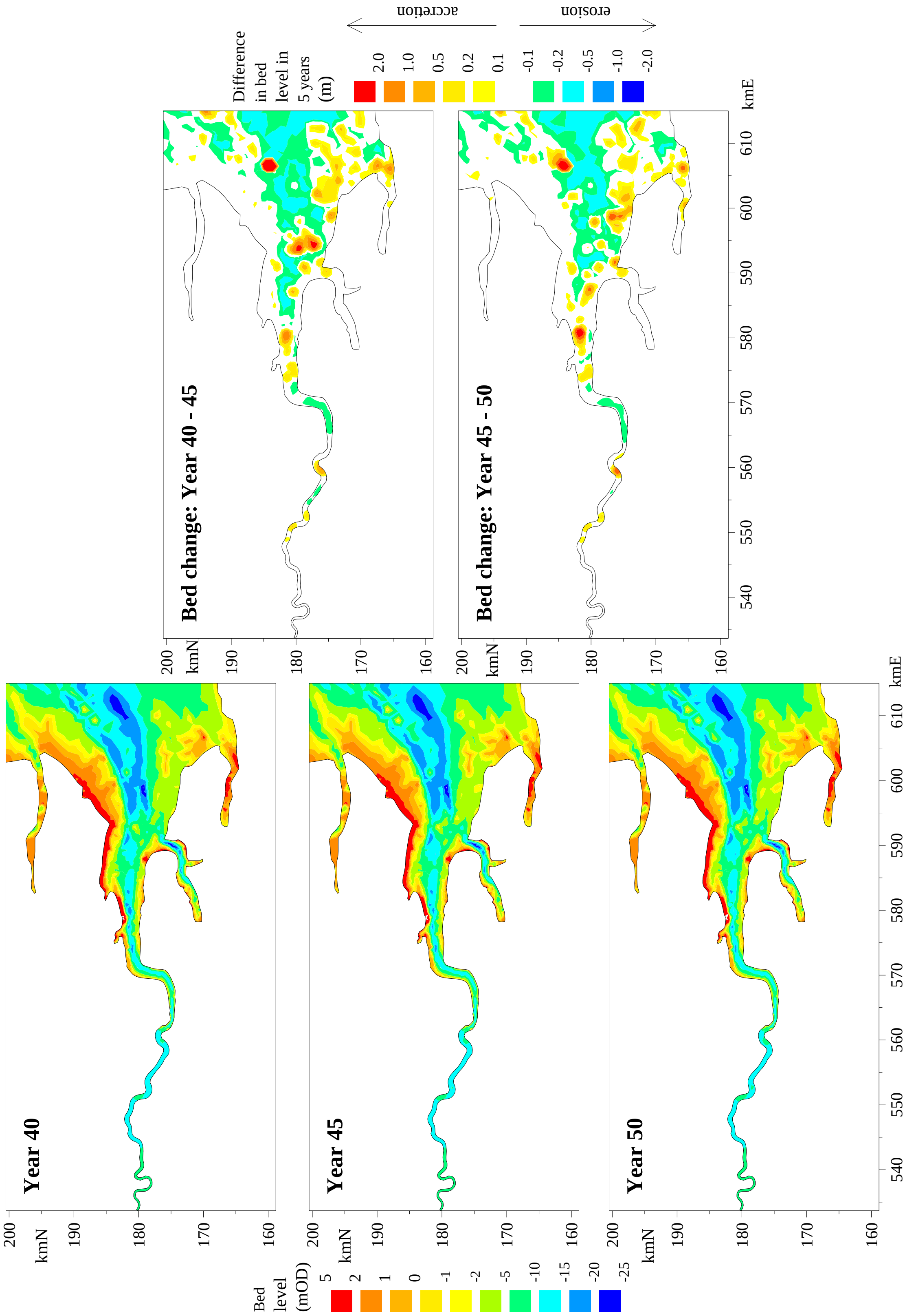

**Figure 5.12** Evolution of the Thames model over year 40 to year 50 of a 50-year morphodynamic simulation, using yearly bed updates

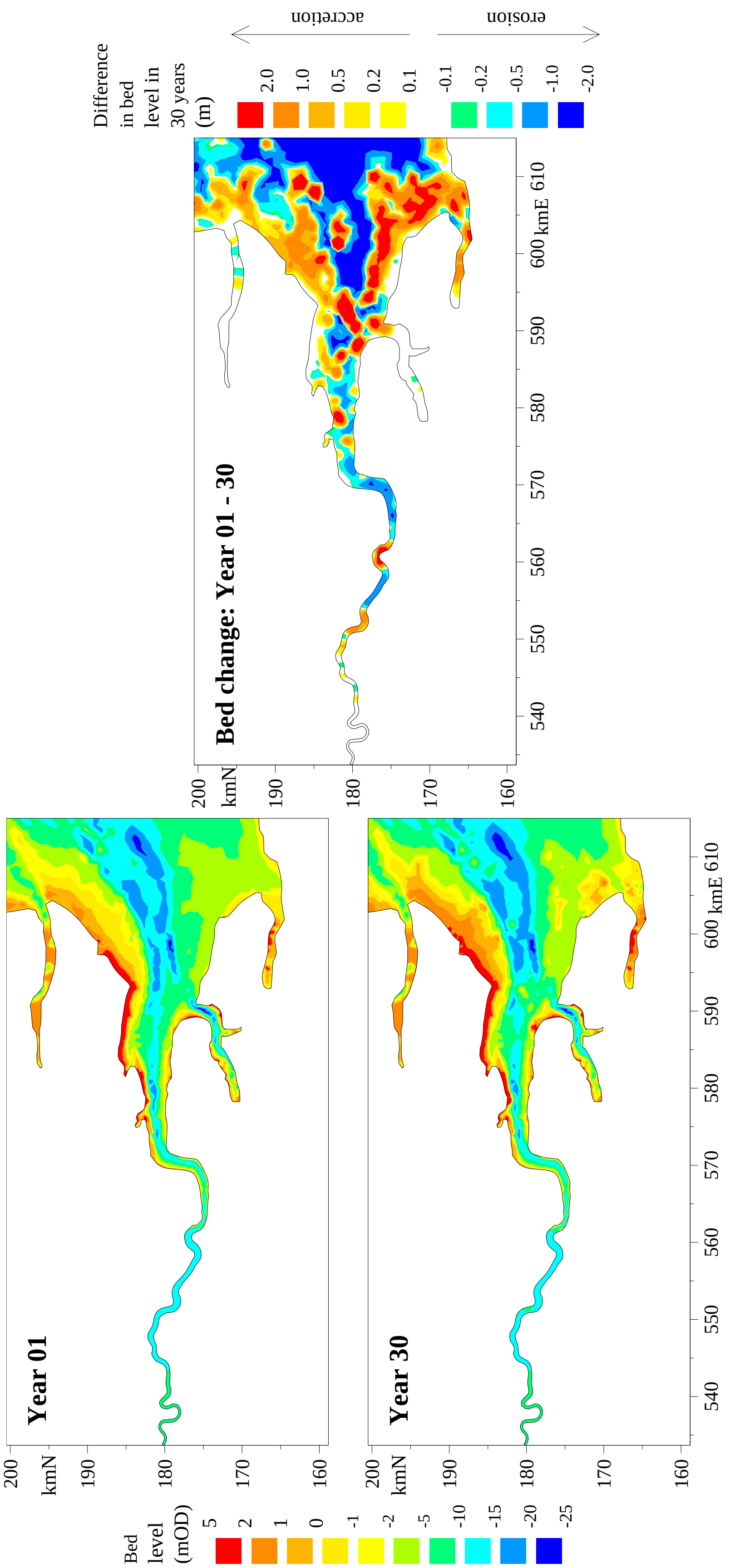

**Figure 5.13** Evolution of the Thames model over year 1 to year 30 of a 50-year morphodynamic simulation, using yearly bed updates

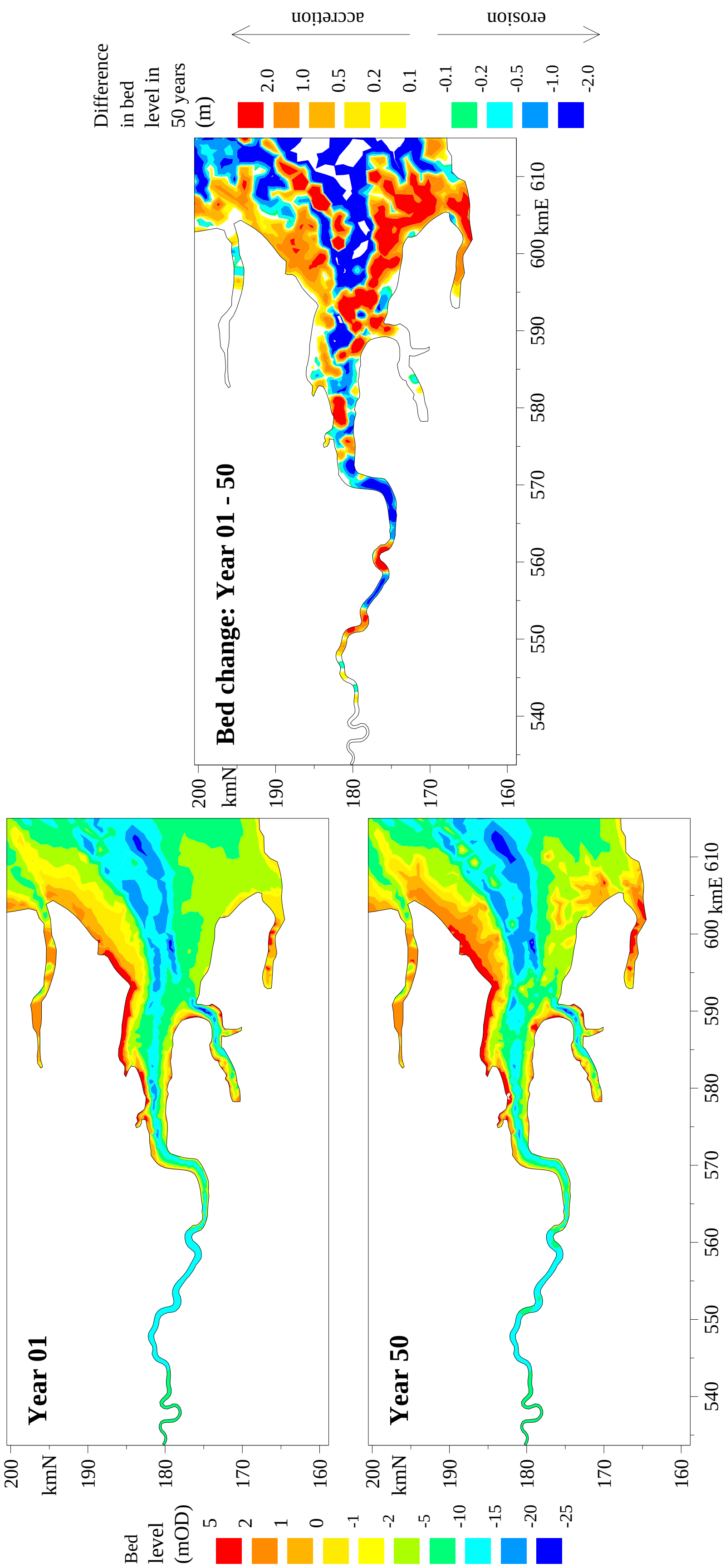

**Figure 5.14** Evolution of the Thames model over year 1 to year 50 of a 50-year morphodynamic simulation, using yearly bed updates

**Figure 6.1** Particle distribution variations over three years of simulation for models with 10,000 grains of diameters: (i) 0.15mm, (ii) 0.1mm, (iii) 0.2mm, seeded in the area to the west of a line 625km E

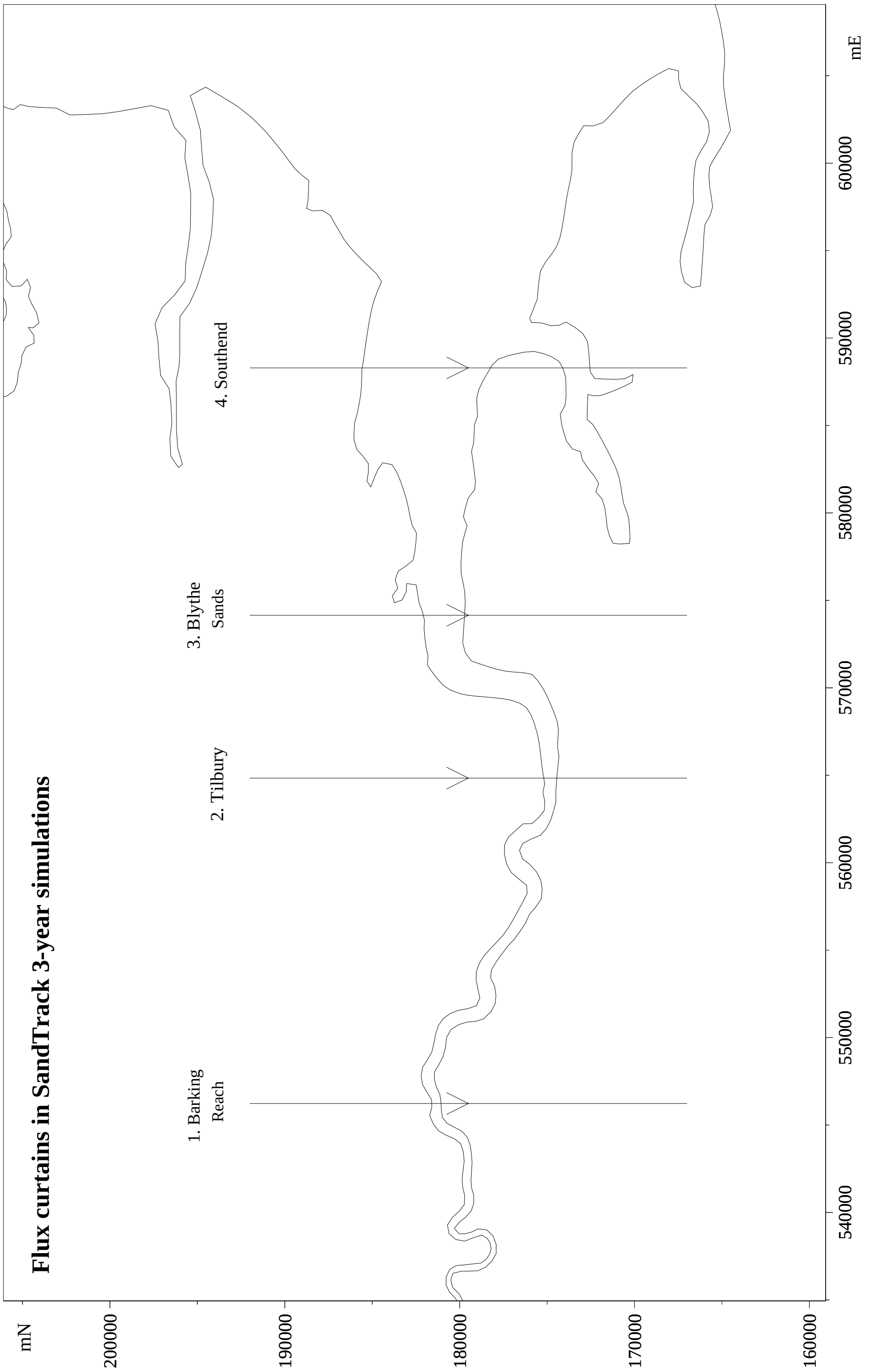

Figure 6.2 Flux curtain locations

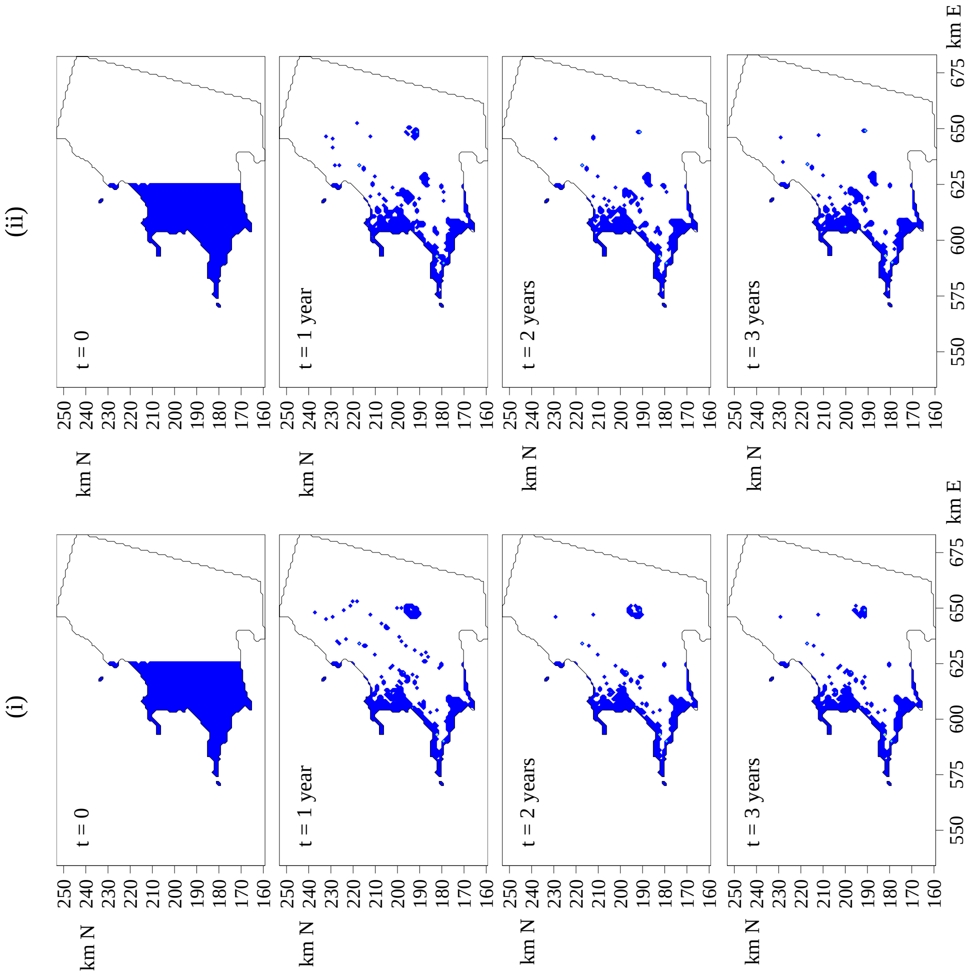

**Figure 6.3** Particle distribution variations over three years of simulation for 0.15mm grains with (i) the original mean sea level; (ii) mean sea level raised by 0.3m

**Figure 6.4** Particle distribution variations over three years of simulation for models with: (i) baseline bathymetry; (ii) predicted "2030" bathymetry; (iii) predicted "2050" bathymetry

# Appendix

# Appendix 1 Comparison of future (2030) morphologies for the Thames Estuary as derived from SandTrack modelling and TE2100 predictions

**Thames Estuary 2100 Estuary Processes studies – Morphological Change**

The Thames Estuary 2100 (TE2100) is an Environment Agency led project to develop a flood risk management strategy for the Thames Estuary, including London, to 2100. As part of the overall study, a number of projects were undertaken to investigate a number of key physical processes in the Estuary. This included detailed studies into morphological changes over the last 100 years, both in the Thames Estuary upstream of Southend as well as the Outer Thames Estuary system of channels and banks. An evaluation of a number of different geomorphological approaches including bottom-up and top-down methods were evaluated against historical observations, and a hybrid method adopted to provide a prediction of morphology to the year 2030. Any such prediction is, of course, subject to a very large degree of uncertainty, although this was partially managed by not attempting to predict very far into the future (it was felt that 2030 was about as far ahead as one could reasonably attempt).

**TE2100 morphological prediction to 2030**

The following provides a summary of the method adopted to predict a future morphology within the TE2100 programme. For a full description of the method, the reader should refer to (HR Wallingford, 2006a). However, based upon an evaluation of the performance of various geomorphological tools against historical morphological change in the Thames Estuary, the method essentially used an extrapolation of the Historical Trends Analysis (HTA). The extrapolation basically meant adding the change in bed level between 1970 and 2000 to the 2000 bathymetry. However, adding the change in bathymetry in this manner is insufficient by itself to generate a realistic bathymetry for the following reasons:

- Changes in the position of the lower foreshore of the channel will often lead to large vertical changes of a few metres. Extrapolation of this change will lead to (in the case of accretion) unrealistic banking on the lower intertidal or (in the case of erosion) unnaturally high erosion of the channel near the foreshore.
- Subtidal changes in the channel can be due to dredging or other capital works and changes in bed levels of a few metres can be incorrectly extrapolated several metres.
- The bathymetry of declared navigation channels in the Estuary is principally a function of the management of navigation rather than natural Estuary response.

For this reason the extrapolated bathymetry was further modified as follows:

- No subtidal erosion of more than 2m was allowed
- Subtidal accretion was not allowed to increase the bed level above 0mOD (roughly mid-tide).

The predicted differences in bathymetry result in the following features:

- Continued accretion in the Leigh Channel
- Continued accretion along the foreshore of Blyth Sands
- Continued accretion in the entrance to Holehaven Creek

- Continued accretion on Mucking Flats
- Continued deepening of the navigation channel in Sea reach and in Lower Hope Reach
- Continued accretion along the northern foreshore at Coalhouse Point
- Continued intertidal accretion between Broadness and Woolwich
- Continued deepening of the navigation channel between Broadness and Woolwich
- Varied and localised subtidal and intertidal changes between Woolwich and Putney
- Continued overall erosion of the subtidal foreshore between Putney and Richmond
- Localised accretion of the deepest part of the Low Water channel between Putney and Richmond.

A second prediction was undertaken where it was assumed that the navigation channel below Charlton would be maintained at the current depth (no change). This is presented as Geometry2 here, but is considered no further in this report.

### Comparison of SandTrack and TE2100 Thames Estuary morphological prediction to 2030

#### Thames Estuary

A comparison of the two methods is not a simple task. While the methods used in TE2100 are empirically based, supported by an understanding of the natural and anthropogenic changes that have occurred in the recent past, the SandTrack method uses modelling, with no attempt to alter the predictions to account for any drivers of change not represented in the model. Nevertheless, a comparison of Figures A1.1 to A1.3 (TE2100 2030 prediction) against Figure 5.14 produced from the SandTrack modelling is discussed below.

Firstly, it must be stated that the resolution adopted for SandTrack is not sufficient to permit a sensible comparison of the predicted morphological change. Based upon recent observed changes in the stretch between Lower Hope Point and Southend, certain distinct changes have been observed, including the growth of the intertidal areas at Blyth Sands and the deepening of the channel. Indeed, as one moves further upstream, a similar pattern has generally been observed, with a deepening and narrowing of the subtidal channel at the same time as an increase in the plan area of intertidals.

Unfortunately, the resolution of the model used for the SandTrack prediction is only 3-4 nodes across at Blyth Sands (excluding the shoreline), which has immediately limited the potential of the model to represent such an effect, should this be its aim. Visual comparison of the two predictions upstream of Southend does not conclusively lead to any areas of potential similarity. Rapidly developing accretion along Grain Spit is shown (extending further eastwards), which seems quite extreme (downstream of limit of TE2100 predictions) and may also be a side effect of the limited resolution.

#### Outer Thames Estuary

Looking at the SandTrack predicted changes further into the Outer Estuary (Figure 5.4 shows modelled changes in the first three years), however, does lead to a rather interesting finding. Viewing this figure seems (the scale is obviously quite small) to reveal a relatively stable system of channels and banks in the Outer Estuary, with the exception of the region (about 625,000E, 180,000N) around the Edinburgh Channels crossing Long Sand. The TE2100 studies examined the morphological changes over the last Century in the Outer Estuary and concluded that the system of channels and banks appeared relatively stable with extension of some of the banks seawards by up to a few km, except for the region around the Edinburgh Channels which appeared quite dynamic. The channels crossing Long Sand exist through the generation of a head difference across Long Sand through the action of the tide wave which generally propagates down the Eastern coast into and out of the Estuary, while at the same time continuing around the SE Coast.

It would appear that the SandTrack model bathymetry has responded to the simplified hydrodynamic boundary conditions by developing a wider channel in this region. The dynamic zone identified through the model test appears to be an area which is dynamic in practice.

**Sediment Fluxes**

The baseline number of particles passing through four cross-sections in the Thames (Table 6.1) in the SandTrack model was compared against the total fluxes integrated through time from the TE2100 River Characteristics survey in Autumn 2004 (HR Wallingford, 2006b). The comparison is presented in Figure A1.4 and A1.5.

While the SandTrack numbers show a strong correlation to cross-sectional area, this is not true of the observations which demonstrate peak fluxes to occur in Gravesend/Lower Hope Reach. No correlation of the two data sets is therefore observed, whether for gross or net values. It is important to note that the observations have limitations in their estimate of near bed sediment transport, while the SandTrack model has assumed 0.15mm sand for the modelling (transport of fine material is probably more important upstream of Lower Hope).

**References**

HR Wallingford, 2006a. Thames Estuary 2100 – Morphological Changes in the Thames Estuary. HR Wallingford Report Number EX5335 prepared for the Environment Agency.

HR Wallingford, 2006b. Thames Estuary 2100 – The Dry River Characteristics Survey (2004). HR Wallingford Report Number EX5285A prepared for the Environment Agency.

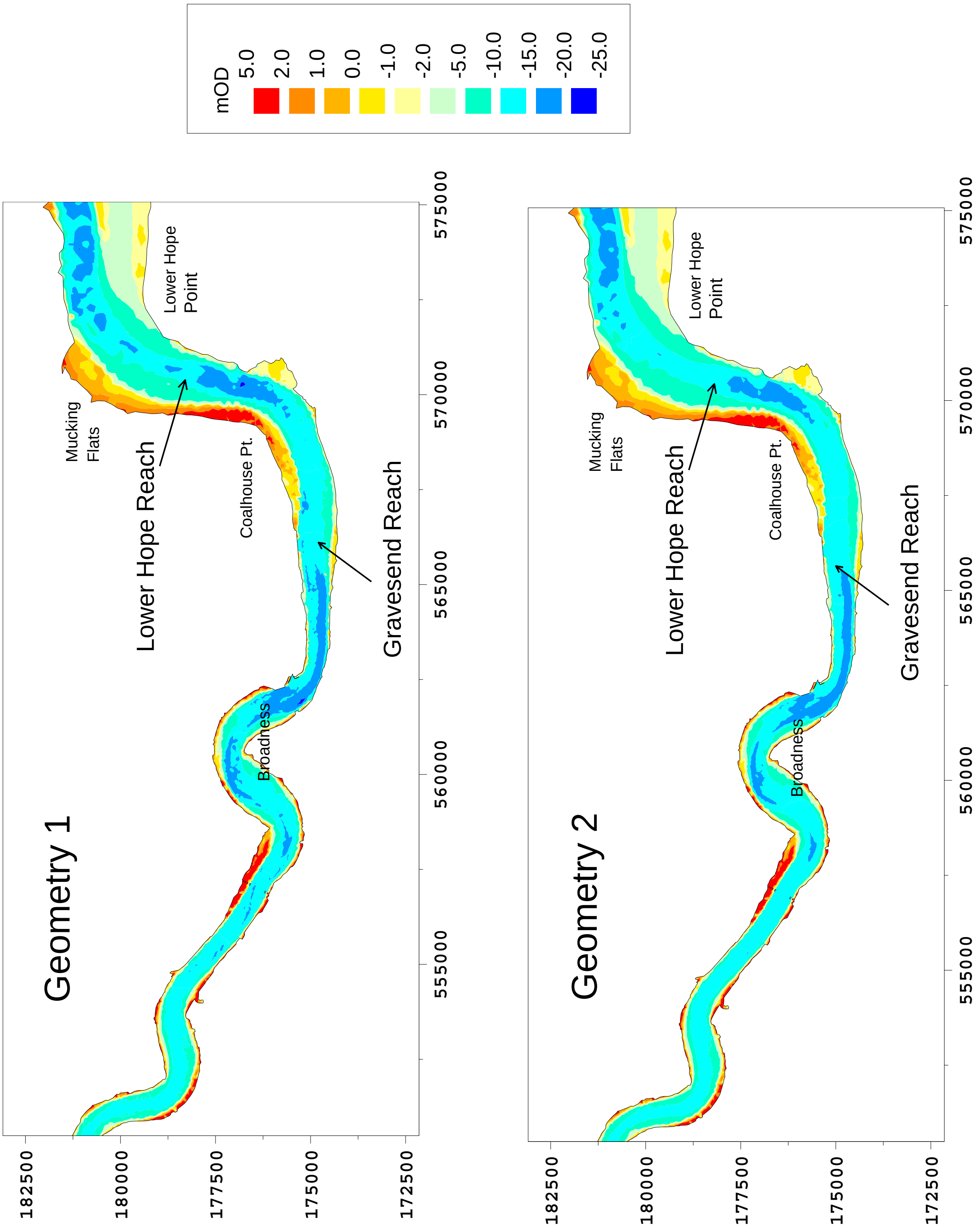

Figure A1.1 Predicted 2030 bathymetry between Lower Hope Point and Erith

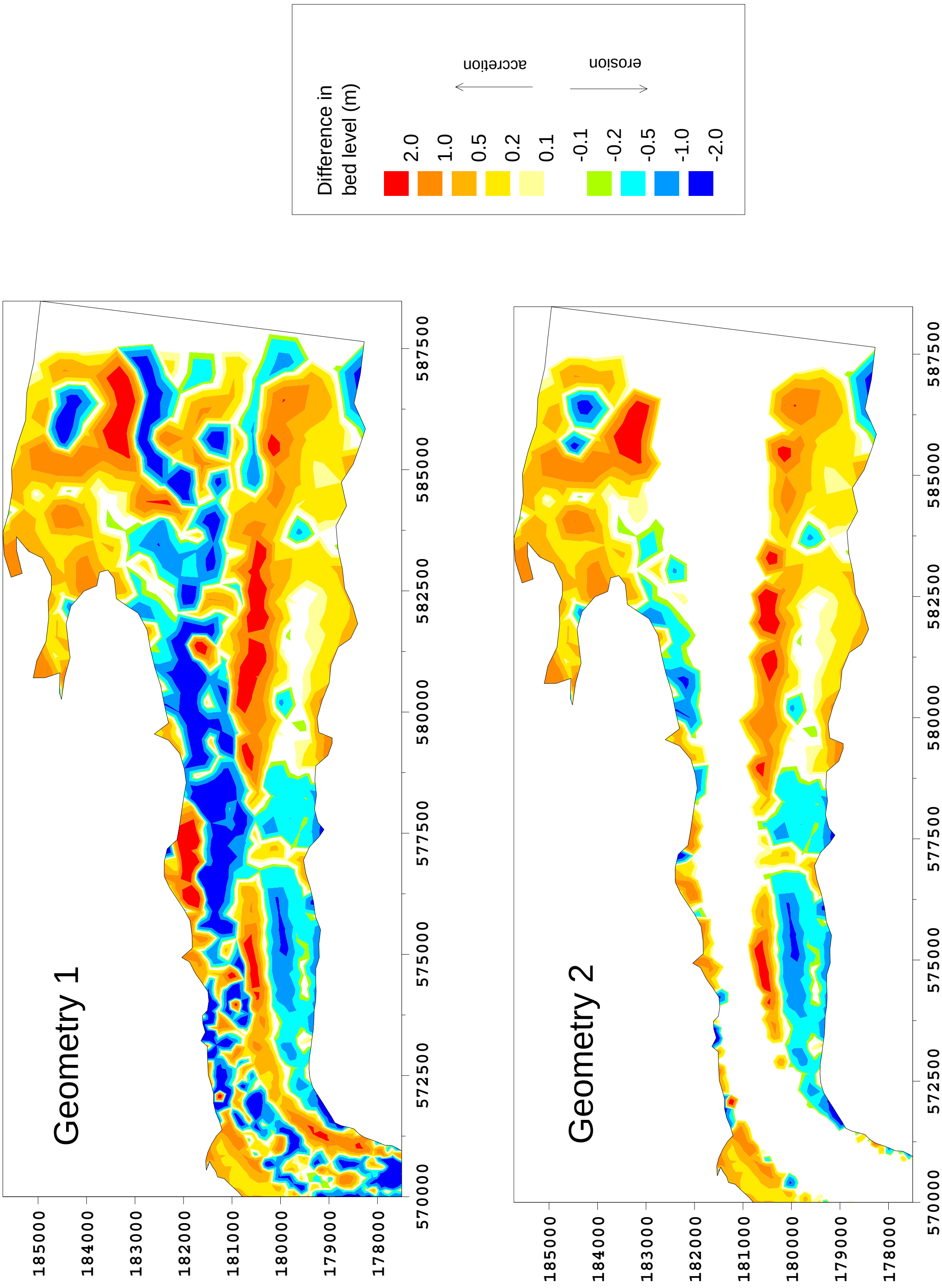

Figure A1.2 Predicted changes in bathymetry over the period 2000 to 2030, Lower Hope Point to Southend

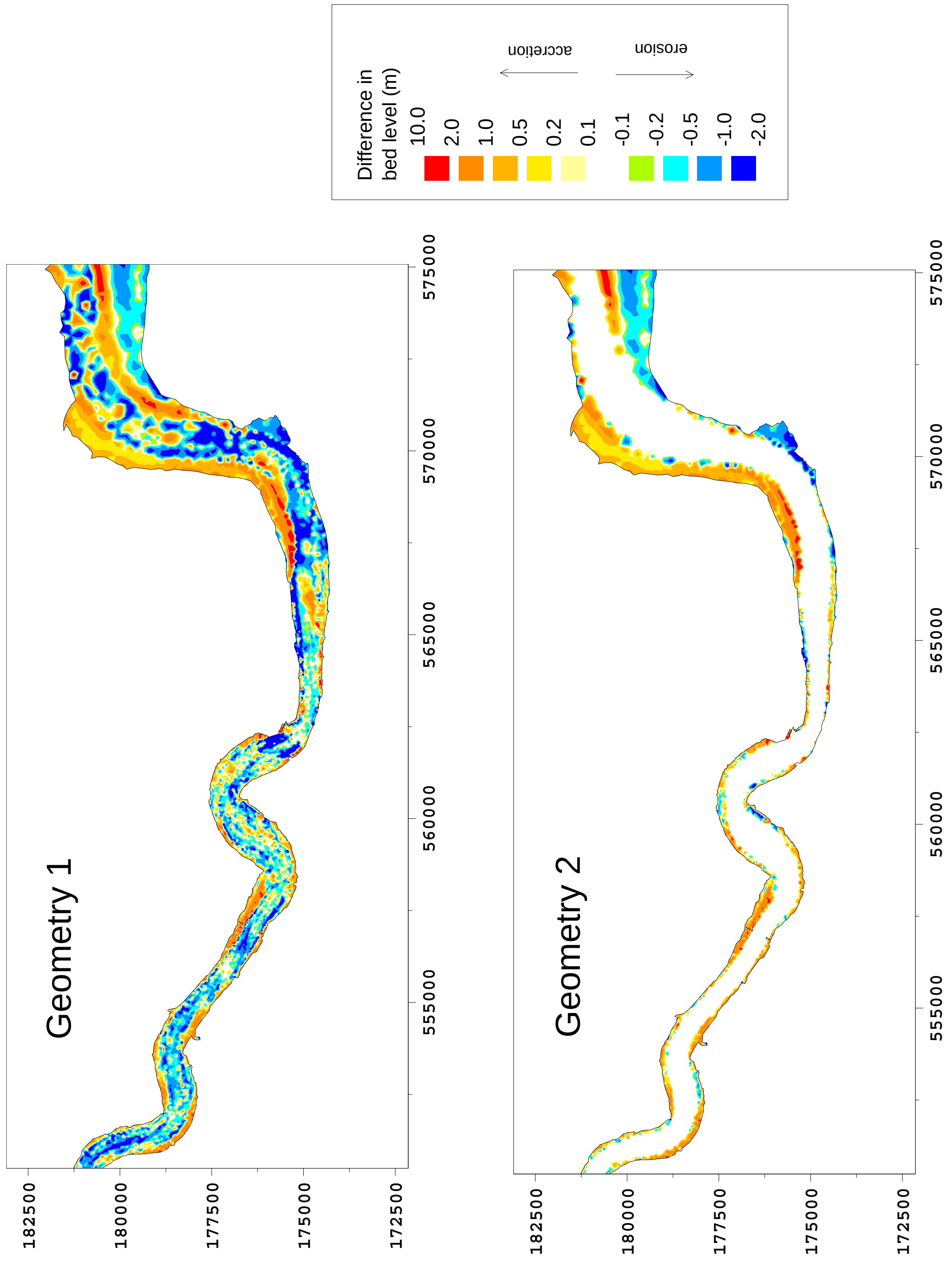

**Figure A1.3** Predicted changes in bathymetry over the period 2000 to 2030, Erith to Lower Hope Point

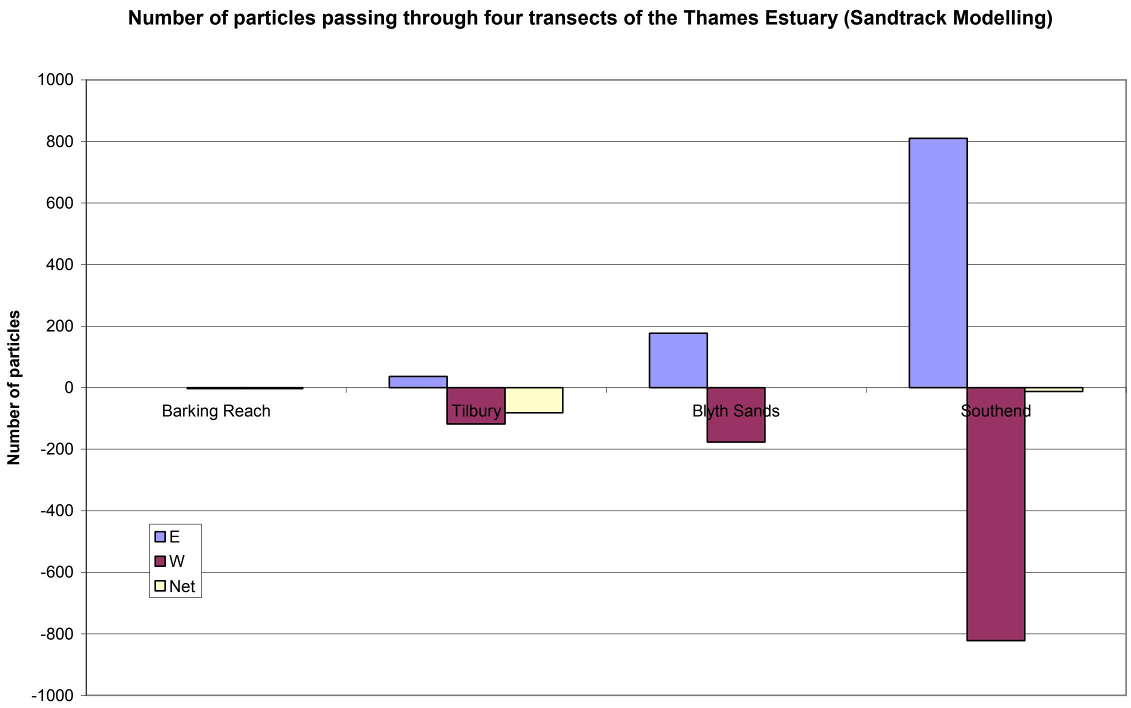

**Figure A1.4** SandTrack modelled number of particles passing Thames Estuary transects

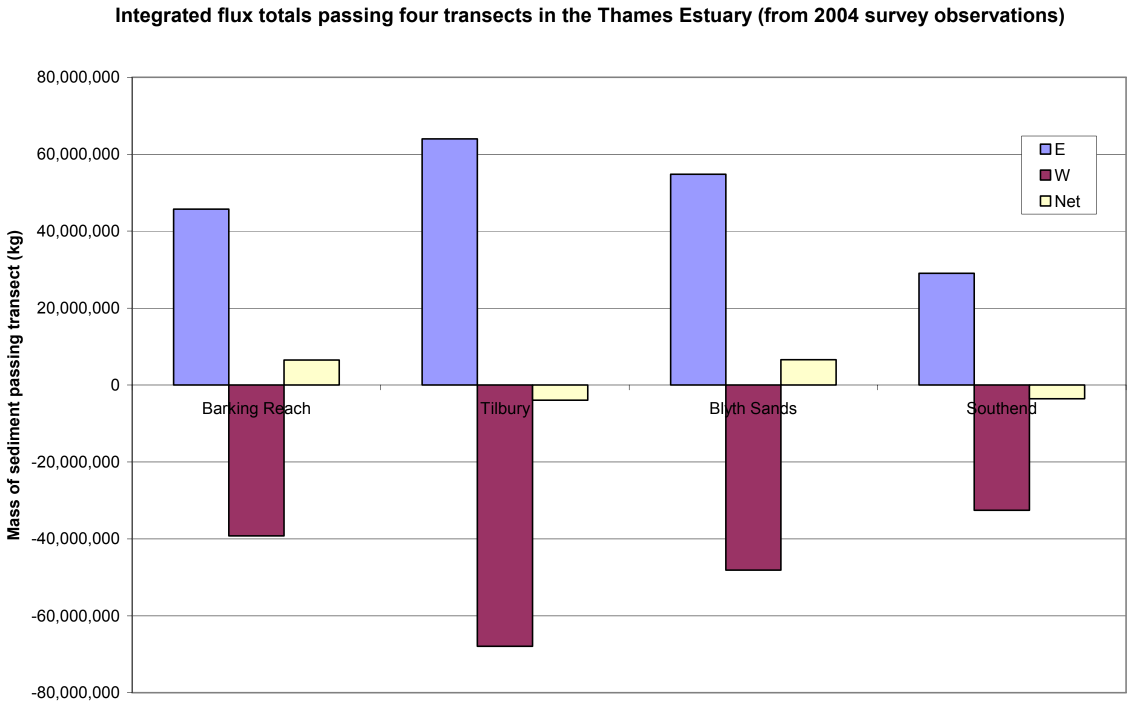

**Figure A1.5** Integrated gross and net fluxes passing Thames Estuary transects (from 2004 River Characteristics Survey)

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