Evidence

Parameter values used in coastal dispersion modelling for radiological assessments

Report: SC060080/R3

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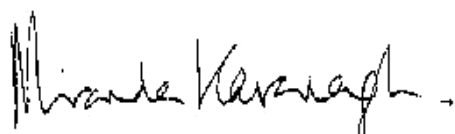
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Miranda Kavanagh

Director of Evidence

Executive summary

Under the Environmental Permitting Regulations 2010 (EPR 2010), the disposal or discharge of radioactive waste to the environment requires prior authorisation. In England and Wales, the Environment Agency is responsible for determining whether such an authorisation should be granted, subject to appropriate limits and conditions. The Environment Agency must be satisfied that the waste discharged will not give rise to a radiation dose to members of the public greater than the UK dose limit of 1 mSv (millisievert, a measure of the effective dose). In addition to this limit, the Environment Agency must have regard to constraints on the dose which may arise from individual sites and sources.

The Environment Agency has an initial radiological assessment system for providing an assessment of radiation exposures from proposed discharges. The assessment system uses environmental dispersion data to provide a more realistic assessment of the predicted levels of radionuclides in the environment. More detailed assessments may also be undertaken with more sophisticated models such as PC-CREAM. For discharges reaching the marine environment, a key dispersion parameter used by the initial assessment system is volumetric flow in the vicinity of the release point.

This report provides improved quantitative estimates of the hydrographic parameters (volumetric exchange rate, net exchange rate, compartment volume, mean compartment depth, coastline length, diffusion rate, suspended sediment load, and sedimentation rate) used by the Environment Agency's initial radiological assessment tool and by PC-CREAM. Parameters are given for over 80 local compartments around the England and Wales coast. These locations are primarily those associated with the discharges of radioactive wastes from the non-nuclear sectors, such as educational establishments and hospitals. Guidance on how to use these values has been provided by the Environment Agency, together with a comparison with the values currently used in PC-CREAM.

For the majority of sites, sufficient data were available to calculate the hydrographic parameters. However, occasionally insufficient data were available to determine a particular parameter value, and in this situation a 'best-estimate' has been provided based on knowledge of similar compartments and/or the nearest available data. These values should be used with care, and, depending on the nature of the assessment being undertaken, further effort may be warranted to better determine the level of uncertainty in these estimates and provide a revised parameter value.

Acknowledgements

Contents

1 Introduction

Under the Environmental Permitting Regulations 2010 (EPR 2010) the disposal or discharge of radioactive waste to the environment requires prior authorisation. In England and Wales, the Environment Agency is responsible for determining whether such an authorisation should be granted, subject to appropriate limits and conditions. The Environment Agency must be satisfied that the waste discharged will not give rise to a radiation dose to members of the public above the UK dose limit of 1 mSv (millisievert, a measure of the effective dose). In addition to this limit, the Environment Agency must have regard to constraints on the dose from individual sites and sources..

The Environment Agency uses various systems to calculate concentrations of radionuclides in sediment, water and biota arising from discharges of radioactivity to the environment. These concentrations are used to assess doses to the public. One of the systems is an initial radiological assessment system which allows a relatively simple and cautious assessment to be made of discharges to the coastal marine environment. A second system called PC-CREAM allows a more comprehensive assessment using detailed input data. These systems use mathematical models to simplify the complex processes that occur in the environment. The models may be conservative in nature, in order to demonstrate regulatory compliance - that is, even in the most restrictive situation, the exposure of members of the public will not exceed the specified dose limits and/or constraints. The level of detail required to run different models varies considerably, and consequently so does the effort required in determining realistic input parameters.

The initial radiological assessment system developed by the Environment Agency (2006) provides a tiered approach to dose calculations. At each stage the user assesses if enough information is available for a regulatory decision to be made or whether further information is required. The first stage uses conservative generic assumptions, the second requires some site specific data, and the third recommends detailed modelling.

One of the scenarios considered is the impact of releases of radioactivity to estuarine or coastal waters on a generic (hypothetical) fisherman family. This family are assumed to be exposed to radionuclides deposited in shoreline sediments and by consuming fish and shellfish that have incorporated radionuclides from the surrounding water. If the potential exposure of the fisherman family exceeds the screening level at the first stage of assessment, parameter values specific to the estuary or coastal water body receiving the radioactive discharge (the "local compartment" in the model) are required.

This report provides quantitative estimates of the hydrographic parameters used in the Environment Agency's initial radiological assessment system (Environment Agency, 2006) for 80 locations around the coast of England and Wales. Additional data have been presented that can be used with PC-CREAM for defining dispersion for marine assessments. Appendix 3 of this report provides guidance on how to use the estimated parameter values within the Environment Agency's initial radiological assessment system. Appendix 4 compares the results of this work with other published values, to assess the effect that using this report may have on dose assessments.

2 Hydrographic parameters

The purpose of this report is to present recommended tidal, bathymetric and sediment parameter values for approximately 80 locations around the coast of England and Wales. The locations were primarily those associated with the discharges of radioactive wastes from the non-nuclear sector, such as educational establishments and hospitals, and the nuclear sector.

These values have been derived from a number of datasets such as Admiralty Charts and Tide Tables, nautical almanacs, and technical reports. The methods used to calculate the parameters are described in Section 4. They have been manipulated as appropriate to output dimensions (units) which are consistent with the Environment Agency's initial radiological assessment methodology.

The hydrographic parameters calculated are

V_{ex} – volumetric exchange rate; $m^3 \, s^{-1}$

V_n – net exchange rate (based on generic assumptions); $m^3 \, s^{-1}$

V – compartment volume; cubic metres, m^3

D – mean compartment depth; metres, m

L_c – coastline length; kilometres, km

K_x – diffusion rate; square metres per second, $m^2 \, s^{-1}$

S_L – suspended sediment load; milligrams per litre, $mg \, l^{-1}$

S_R – sedimentation rate; kilograms per square metre per year, $kg \, m^{-2} \, y^{-1}$

The key parameter for use in the initial radiological assessment system is net exchange rate. During development of the system a limited sensitivity analysis of the parameters used for marine dispersion modelling was completed. Volumetric exchange rate was found to have the biggest effect on the dose to the fisherman family. A larger volumetric exchange rate means that more dilution occurs, and therefore the concentration will be lower and the exposure to the fisherman family will be less.

There is an uncertainty and variability associated with each of the parameters presented, and as such the values given are not expected to apply at all times or at all points within the location specified. For instance, a 10 kilometre square compartment may contain a range of bathymetric data from, say, 2 to 20 metres with an average value of 10 metres. In this case a mean depth of 10 metres would be recommended for this compartment, even though relatively few points in the compartment actually have such a depth.

Specifying one recommended value for parameters which are inherently dynamic implies that the given number will represent a spatial and temporal mean. Therefore, where possible, the data that have been collated for this report have been drawn from a number of sources.

For the majority of sites, sufficient data were available to calculate the hydrographic parameters. However, occasionally insufficient data were available to determine a particular parameter value, and in this situation a 'best-estimate' has been provided based on knowledge of similar compartments and/or the nearest available data. These values should be used with care, and the significance of their use considered when interpreting results. Depending on the nature of the assessment being undertaken,

further effort may be warranted to better determine the level of uncertainty in these estimates and provide a revised parameter value.

A table of the derived parameter values is presented in Appendix 1.

3 Definition of a local compartment

The locations around the coast of England and Wales for which tidal, physical and sediment parameters have been established are described in Appendix 2. The geographical location of each compartment is illustrated in Figures A2.1 – A2.5.

This section describes the rationale used in determining what was considered a 'local' compartment. The local compartment is the body of water which receives the initial discharge: dispersion occurs within this compartment and exchange occurs with a larger regional compartment.

In defining a local compartment it is necessary to ensure that tidal, bathymetric and sedimentary conditions remain broadly homogeneous across such compartments (and hence the derived parameter values are applicable to the compartment as a whole).

Coastal locations are typically 'open' – they are not (locally) constrained by other coastlines or riverbanks. Coastal compartments have thus been limited to a horizontal extent of 10 kilometres by 10 kilometres square, giving a fixed surface area of 100 square kilometres.

Estuarine locations are constrained by the local geography – the riverbanks – and the tidal regimes present in the estuary. Larger estuaries have been divided into two or more discrete sections in order that the available data can be better applied to the region to which it pertains.

In addition to these regions, we have also parameterised a number of semi-enclosed bays, for which the extent of the local compartment is well defined by the geographical situation.

4   Calculation methods

This section describes the method of aggregation of available data for the various parameters, and briefly discusses their inherent uncertainties.

Representative numerical values have been obtained for parameters associated with the tidal regime in the local area, the physical extent of each compartment, and characteristic sediment loads and sedimentation properties. A description of each parameter and the underlying data that have been used to derive a numerical value is given below. Where appropriate, a comment on the uncertainty associated with each parameter is given, together with an indication of the potential effect of this uncertainty on the transport and dispersion of radioactive wastes.

To enable the parameter values given in this report to be altered when new tidal or physical information become available, the basic method of calculation of some of the quantities is described and an example given. These examples consider the middle section of the Severn estuary. Four tidal stations were found to be located in this compartment, at Portishead, Avonmouth, Sudbrook and Beachley. Admiralty Tide Tables (UKHO, 2009) refer tidal heights to a primary port, which in this case is Avonmouth (Port of Bristol). The information provided in the Tide Tables is summarised in Table 4.1.

Table 4.1   Tidal heights at stations in the Severn (mid) compartment

Tidal station	Primary port				Differences to primary port			
	MHWS	MHWN	MLWN	MLWS	MHWS	MHWN	MLWN	MLWS
Avonmouth	13.2	9.8	3.8	1.0	-	-	-	-
Portishead	"	"	"	"	-0.4	-0.2	0.2	0.0
Beachley	"	"	"	"	-0.4	-0.2	0.2	0.0
Sudbrook	"	"	"	"	0.2	0.1	-0.1	0.1

Notes: MHWS = mean high water springs
MHWN = mean high water neaps
MLWN = mean low water neaps
MLWS = mean low water springs

Table 4.1 gives the mean high and low water heights above the level of Chart Datum (CD) for a primary port, and the differences from this primary port for secondary ports. It is thus simply calculated that mean high water springs at Portishead is 12.8 m above CD (13.2 + (-0.4) = 12.8), whilst mean low water neaps at Beachley is 4.0 m above CD (3.8 + 0.2 = 4.0).

In this way, the mean high and low water heights above CD can be calculated for springs and neaps at each tidal station of interest.

4.1   Tidal height (m)

The tidal height is the height of water above a given reference level. Admiralty Charts and Tide Tables refer tidal heights to Chart Datum (CD), which is the Lowest Astronomical Tide (LAT, the lowest water level expected as a result of tidal forces).

The mean tidal height is assumed to be the mean of the high and low water heights. This is averaged across spring and neap tides and over all tidal stations in the local compartment. The tidal heights have not been weighted to account for the proportion of the compartment that one tidal station may represent. An example calculation is given below.

Complex tidal regimes in some regions, such as the double high tide along parts of the south coast, may cause the true mean tidal height to differ from that calculated in this report. Detailed tidal curves, showing the evolution of mean tidal heights over a tidal cycle, are available in Reeds (2009) for selected ports, and, if required, these can be used to refine this parameter by calculating the mean of the hourly tidal height predictions.

Where a tidal height is listed as having no data, the nearest available data have been substituted. Where a tidal height is listed as drying out at low tide, the height has been reduced to CD. This will have the effect of decreasing the mean tidal height, and consequently the compartment volume (see Section 4.5), but increasing the tidal range and, in most cases, the volumetric exchange rate. Figure 4.1 shows a stylised cross-sectional area of a compartment, with various tidal heights and mean water levels.

Calculating the mean tidal height

The mean tidal height has been defined as the mean of the water heights at high and low tides above a reference level, which in the case of Admiralty Charts is LAT. Using the data in Table 4.1, we can calculate the mean high water (MHW) height at Avonmouth as

$$(MHWS + MHWN)/2 = (13.2 + 9.8)/2 = 11.5 \text{ m},$$

and the mean low water (MLW) height as

$$(MLWS + MLWN)/2 = (1.0 + 3.8)/2 = 2.4 \text{ m}.$$

These heights are represented in Figure 4.1 as h_2 and h_1 respectively. The mean of these values then gives the mean tidal height at Avonmouth to be 6.95 m. Similarly, the mean tidal height can be calculated at the other tidal stations in Table 4.1 (6.85 m at Portishead, 6.85 m at Beachley and 7.025 m at Sudbrook). We define the mean tidal height for the Severn (mid) compartment as the mean of the tidal heights at the four stations in the compartment. In this case, the mean tidal height for the Severn (mid) compartment is

$$(6.95 + 6.85 + 6.85 + 7.025) / 4 = 6.9 \text{ m, to two significant figures.}$$
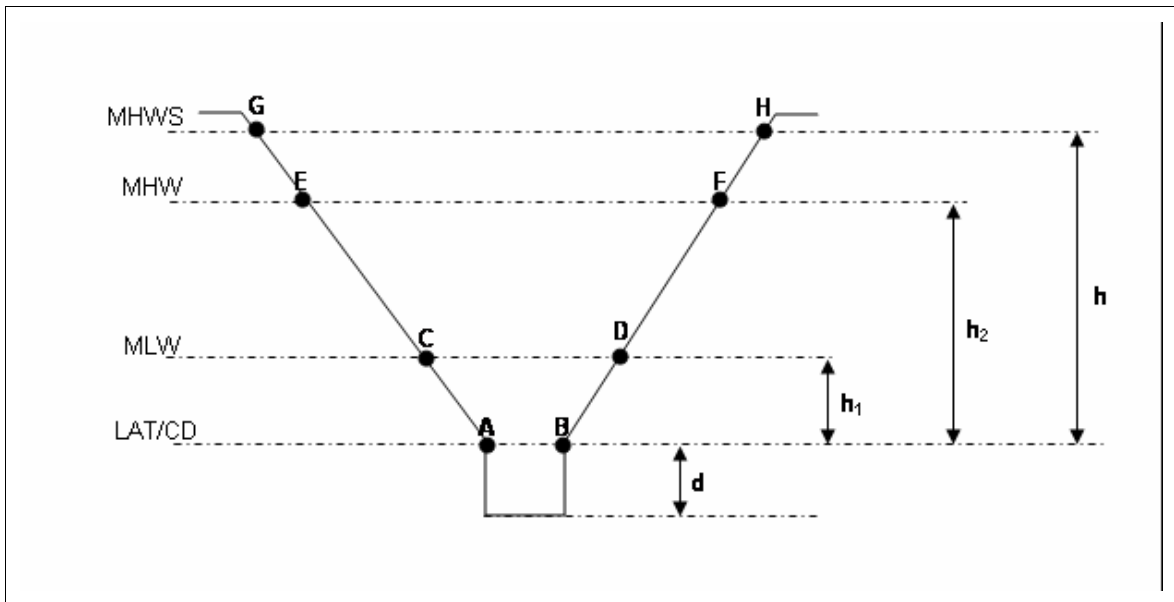
Figure 4.1 Vertical cross section of a compartment, illustrating various water levels and tidal heights. Mean high water (MHW) is the mean of high water heights at spring and neap tides; mean low water (MLW) is the mean of low water heights at spring and neap tides.

4.2 Tidal range (m)

The tidal range is the difference in water level from high to low tide and vice versa. During spring tides, the tidal range will be at its local maximum, and at neap tides it will be at its local minimum. The tidal range varies considerably around the UK, being particularly large in the Severn estuary.

To derive a representative tidal range for each location of interest, the mean high and low water heights from spring and neap tides were taken from stations within the local compartment. These data can be obtained from Admiralty Tide Tables (UKHO, 2009) and nautical almanacs such as Reeds (2009). The mean spring tide range is thus defined as the difference between the mean high water spring tide and the mean low water spring tide. An example calculation is given below.

The mean of the spring and neap tidal ranges at each station were then averaged to give an overall mean tidal range for the compartment. No attempt has been made to weight the tidal ranges from individual stations according to what proportion of the local compartment they are thought to represent.

The tidal range is used, in conjunction with information concerning the physical extent of the region of interest, to estimate the net volume of water which flows into and out of the local compartment. A smaller tidal range would therefore imply a lower net flow rate through the compartment, all else being equal. Stations within the same local compartment will generally return similar mean tidal ranges, suggesting a degree of confidence in the overall mean range.

Calculating the mean tidal range

The tidal range is defined as the difference between the height of high and low tides. At Avonmouth (Table 4.1), the tidal range on spring tides is 12.2 m (MHWS – MLWS) and on neap tides is 6.0 m (MHWN – MLWN). The mean of these tidal ranges gives the mean tidal range at Avonmouth, 9.1 m ((12.2 + 6.0)/2 = 9.1).

Similarly, the mean tidal ranges at Portishead, Beachley and Sudbrook can be calculated as 8.7 m, 8.7 m and 9.25 m respectively. The mean tidal range across these four stations is then

$$T_r = (9.1 + 8.7 + 8.7 + 9.25)/4 = 8.9375 \text{ m;}$$

this has been rounded to 8.9 m in Table A1.4. The mean tidal range is equivalent to the difference between MHW and MLW, or from Figure 4.1,

$$T_r = h_2 - h_1.$$

4.3   Mean surface area (km^2)

For coastal compartments, as defined in Section 3, the surface area is assumed to remain constant over a tidal cycle. For estuaries and, to a lesser extent, bays, the surface area of the water body will change from a minimum at low tide to a maximum at high tide. To determine the volume of water flowing into and out of the compartment over a tidal cycle, and the mean compartment volume, it is necessary to quantify this change in surface area.

Admiralty Charts generally depict the state of an estuary at LAT (see Figure 4.2). By studying the relevant charts it is possible to estimate the surface area of the water body at this tidal state. Drying areas are also depicted, indicating the regions which will become inundated as the tide reaches its highest point. By assuming a linear relationship between the surface area of the water body and the tidal height, it is possible to derive a value for the surface area at MLW and at MHW. For instance, in Figure 4.1 the channel widths denoted by the lines CD and EF would be multiplied by the streamwise extent of the compartment to find the surface area of the water body at MLW and MHW respectively. The average of these two values gives a mean surface area for the water body. Where drying areas are indicated in a bay, a similar calculation has been performed.

The mean surface area is used to derive a value for the compartment volume (see Section 4.5). This may be used to indicate the initial dilution of a substance discharged into the compartment, and so smaller values of the mean surface area will tend to produce more conservative estimates of radionuclide concentrations.

The linear relationship between tide height and surface area represents a considerable uncertainty. The dynamic nature of sediment and mud flats in an estuary makes it extremely difficult to predict what portion of the total surface area of the estuary will be covered by water at any time.
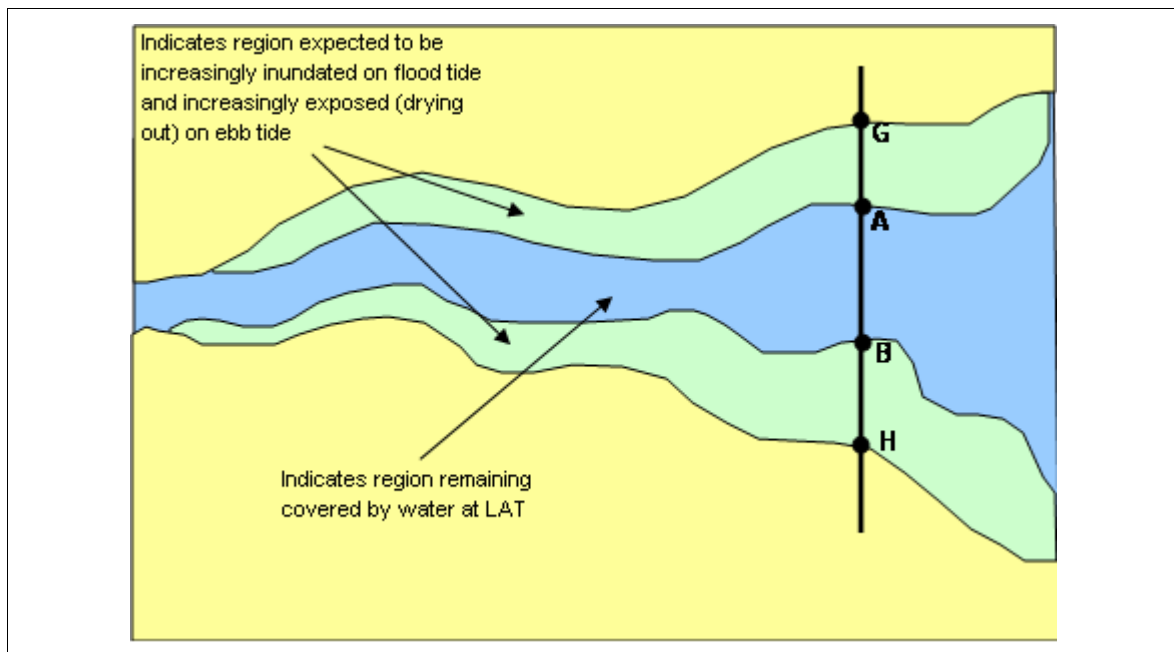
Figure 4.2 Plan view of an estuary, showing the area covered by water at LAT (blue) and drying areas (green). The line GABH refers to the cross section in Figure 4.1.

Calculating the mean surface area

It is assumed that the surface area (SA) of some of the compartments considered in this report will increase with the rising tide, and this is particularly true of estuarine compartments, which contain significant areas of mud flats at low tide. For the compartment shown in cross-section in Figure 4.1, the mean surface area would be calculated as follows:

> i) the surface area at LAT is the channel width (AB) multiplied by the streamwise extent of the compartment (say, E_S). The tidal height at this point is 0.

> ii) the surface area at mean spring high tide is the channel width at this tidal state (GH) multiplied by E_S. The tidal height at this point is h.

> iii) compartment surface areas for all tidal states between LAT and MHWS will therefore range from (AB x E_S) to (GH x E_S).

> iv) as we are assuming that surface area increases linearly with tidal height, the equation

$$SA = (AB \times E_S) + (GH \times E_S - AB \times E_S) \times (H / h)$$

> will give the surface area at tidal height H.

> v) in the case of Figure 4.1, H = h_1 will give the surface area at MLW and H = h_2 will give the surface area at MHW.

This procedure can be generalised to compartments of non-uniform width, as long as the assumption that surface area increases in proportion to tidal height is maintained.

For example, the Severn (mid) compartment is defined geographically in Appendix 2 as the region from Portishead /Newport to the northern Severn road bridge. An inspection of Admiralty Charts of this region suggests that this compartment is approximately 18 km in the streamwise direction, with a mean width of approximately 6 km at high

(spring) tide. This gives a surface area of 108 km^2. Some two-thirds of this area may dry at LAT, giving a minimum surface area of 36 km^2.

Using the data in Table 4.1, and the assumption that the surface area of the region increases linearly with tidal height, it is possible to calculate the surface area of the Severn (mid) compartment at MLW as:

$$SA_{MLW} = 36 + (108 - 36) \times MLW / MHWS$$

and MHW as:

$$SA_{MHW} = 36 + (108 - 36) \times MHW / MHWS.$$

Thus, the tidal data from Table 4.1 for Avonmouth suggest a surface area at mean low water of

$$36 + (108 - 36) \times 2.4 / 13.2 = 49.1 \text{ km}^2$$

and a surface area of

$$36 + (108 - 36) \times 11.5 / 13.2 = 98.7 \text{ km}^2$$

at mean high water. This procedure is repeated using the data from each of the tidal stations in Table 4.1 to provide a range of estimated surface areas according to the different tidal conditions across the compartment. We define the mean surface area of the compartment as the mean of each of these quantities. Thus, at Avonmouth the mean surface area suggested by the calculations above is 73.9 km^2. Similar calculations at Portishead, Beachley and Sudbrook yield surface areas of 74.5 km^2, 74.5 km^2 and 73.7 km^2 respectively, giving a mean surface area for the Severn (mid) compartment of 74.2 km^2.

4.4 Mean depth (m)

The mean depth of a compartment is defined as the mean of all bathymetric data, adjusted to represent mean tidal height. This adjustment is necessary as the bathymetric data displayed on Admiralty Charts is reduced to CD – that is, the depth given at any point is that expected to occur at LAT (see depth d in Figure 4.1). The mean tidal heights above LAT (see Section 4.1) have therefore been added to the mean of the bathymetric data in each local compartment. Bathymetric data have been obtained from Admiralty Charts (UKHO, various years), using a GIS application to collate and analyse the data points relevant to each compartment.

Bathymetric data also include drying heights, which are given as negative values of the depth at LAT. For example, if the estuary in Figure 4.1 was surveyed whilst the tidal height was at MHW, then the depth above the point C would be ($h_2 - h_1$). This would be reduced to a depth at LAT by subtracting h_2 (the tidal height during the survey), leaving a reported depth at this point of $-h_1$. Bathymetric data taken between the points G and A, or between points B and H (see Figures 4.1 and 4.2) will thus be recorded as a negative depth value. Data taken between points A and B will give positive depth values, as this area is assumed to remain covered by water at LAT.

The inclusion of all drying heights in calculations of mean depth will decrease the recommended value of the mean depth, as it is likely that at least some of the bathymetric data will be from areas that remain dry at the mean water level. This will provide a conservative value of depth and, consequently, compartment volume.

As the depth data are discrete and represent the combined data from many surveys, they are often clustered in particular areas of interest. Where this is especially evident

and will have affected the calculation of mean depth in a compartment, a note to this effect is made beneath the relevant Table in Appendix 1.

Calculating the mean depth

The mean depth of the Severn (mid) compartment, based on bathymetric data contained in relevant Admiralty Charts, is 2.2 m. This is the mean of all bathymetry data points inside this compartment at LAT. The mean tidal height above LAT, as calculated in Section 4.1, is 6.9 m. Hence, we can calculate the mean water depth in this compartment to be 2.2 + 6.9 = 9.1 m. This has been rounded to 9 m in Table A1.4.

4.5   Compartment volume (m^3)

The compartment volume is calculated as the product of the mean surface area and the mean depth of a compartment, and as such is expected to represent the volume at mid-tide. The volume of compartments whose surface area has been assumed to increase linearly with tidal height (estuarine compartments and bays – see Section 4.3) will increase in proportion to the square of the increase in water depth. Consequently, the volume calculated for such compartments will be less than the 'mean' of the minimum and maximum compartment volumes, and will be closer to a temporal median.

The compartment volume can be used to indicate the initial dilution of a substance discharged into it, and therefore this definition of compartment volume will typically provide a more conservative assessment.

In some cases, the bathymetric data available have been insufficient to calculate the compartment volume, as the calculated mean depth lies above the mean water level. For these locations an alternative method of calculation has been used, based on an assumed minimum mean depth of the water body at CD. An example calculation is shown below.

Calculating the compartment volume

The volume of the Severn (mid) compartment is calculated as the product of its mean surface area (74.2 km^2; see Section 4.3) and its mean depth (9.1 m; see Section 4.4), to give

$$(74.2 \times 10^6) \times 9.1 = 6.75 \times 10^8 \text{ m}^3.$$

Modified method of calculating compartment volume

Compartments in which the addition of the mean tidal height to the mean depth at CD is not sufficient to give a positive (or reasonably representative) water depth require different treatment in order to derive a value for the compartment volume. In these cases a nominal and arbitrary water depth of 0.5 m is given to the area of the water body at CD ($d = 0.5$ in Figure 4.3), and the (assumed) linear relationship between tidal height and surface area is used to estimate the volume of water that enters the compartment by mid-tide.

For example, in the Lune estuary compartment the mean of the bathymetric data is 7.3 m above the water level at CD. The mean tidal height, based on tidal data from

Glasson Dock and Lancaster, is only 2.8 m. The surface area of this estuary has been estimated as 2 km^2 at CD (represented by the rectangle ABCD in Figure 4.3) and a nominal water depth of 0.5 m across this area gives an initial volume of 1×10^6 m^3. The surface area at mean tidal height, calculated using the method detailed in Section 4.3, is 4.9 km^2 (rectangle EFGH in Figure A2.3). The volume of the prism depicted in Figure 4.3 is the product of its height, h, and the mean area of the rectangles ABCD and EFGH. In this example, the mean surface area between CD and mean tidal height is

$$(2 + 4.9) / 2 = 3.45 \text{ km}^2.$$

Multiplying this surface area (in square metres) by the mean tidal height, h, gives

$$(3.45 \times 10^6) \times 2.8 = 9.7 \times 10^6 \text{ m}^3,$$

and the addition of the assumed volume of water in the compartment at CD leads to a final estimated compartment volume of

$$(9.7 \times 10^6) + (1 \times 10^6) = 1.07 \times 10^7 \text{ m}^3.$$

This method of calculation does not utilise any bathymetric data, and should therefore only be used when the available depth data is deemed insufficient.
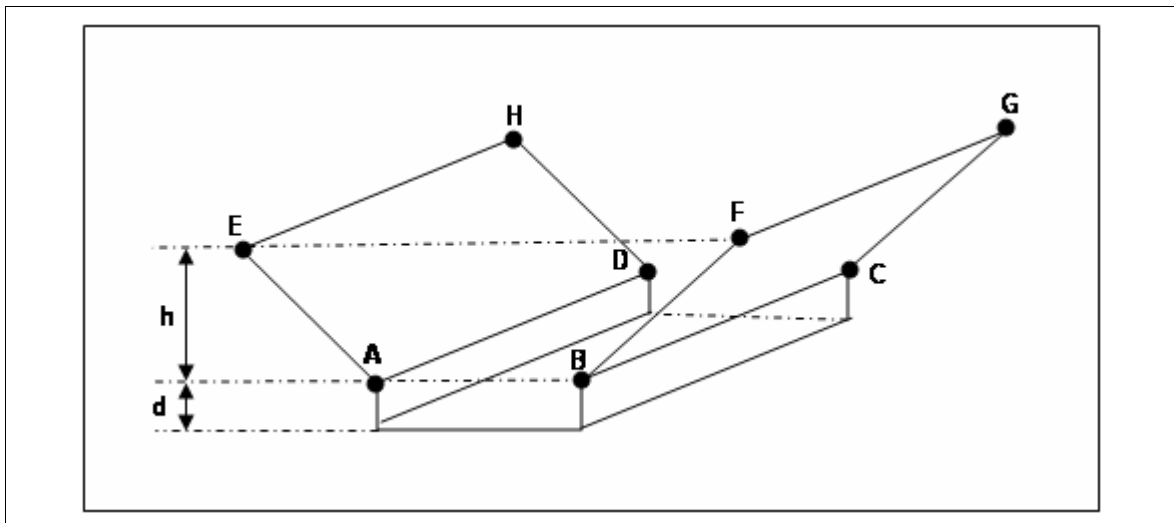
Figure 4.3 Representative estuarine compartment for volume calculation using the modified method discussed in Section 4.5

4.6   Exchange volume (m^3)

The exchange volume is the volume of water which flows into or out of a compartment with the changing tide. It is calculated as the product of the mean surface area and the mean tidal range of the local compartment. It can be visualised as the area of the trapezium CDFE in Figure 4.1 multiplied by the streamwise extent of the compartment.

The exchange volume can be divided by the mean compartment volume to give the proportion of the water in the local compartment that is exchanged with adjoining compartments between high and low tides. This is sometimes referred to as the fraction of exchange, and is used in simple dilution models to represent the amount of 'fresh' water available for further diffusion of the contaminant of interest.

Calculating the exchange volume and the fraction of exchange

The exchange volume of the Severn (mid) compartment is calculated as

$$(74.2 \times 10^6) \times 8.9 = 6.6 \times 10^8 \text{ m}^3,$$

and this is divided by the compartment volume as calculated in Section 4.5 to find the fraction of exchange:

$$(6.6 \times 10^8) / (6.75 \times 10^8) = 0.98.$$

4.7 Volumetric exchange rate ($m^3 s^{-1}$)

The volumetric exchange rate is a measure of the flux of water across the boundaries of the local compartment, and is calculated by referring the exchange volume to a time period to give the exchange as a mean flow rate. From high to low tide, this will be a net outflow of water from the compartment, whilst from low to high tide this will be a net inflow. A smaller volumetric exchange rate means that less dilution occurs, and this will tend to give a more conservative assessment.

Any given volumetric exchange rate will be highly dependent on the local tidal dynamics, which will determine what proportion of the (contaminated) water expelled from a compartment on the ebb tide will return on the next flood tide. In the absence of detailed hydrodynamic models of flow rates across each of the compartment boundaries, and following the methodology of Environment Agency (2006), it has been assumed that none of the exchange volume returns to the local compartment. The values given for the volumetric exchange rate in Tables A1.1 – A1.5 reflect this. This implies that the inflowing water on a flood tide is uncontaminated, an assumption that will overestimate the volumetric exchange rate for compartments where a significant proportion of the exchange volume returns to the local compartment on subsequent tides.

The time period to which the exchange volume is referred must also be considered. The net flux across a compartment's boundaries over a full tidal period will, by definition, be close to zero (that is, the volume of water flowing out of a compartment on an ebb tide will be similar to the volume that flows in on the subsequent flood tide). However, we are essentially assuming that the principal inflow and outflow occurs across different boundaries and so it is reasonable to refer the exchange volume to a tidal period, giving the mean volumetric exchange rate across the boundary of interest. The tidal period for UK coastal waters is slightly over twelve hours (~43,200 s), and the period from high to low tide is approximately six hours (~21,600 s).

There are uncertainties associated with this method of calculating volumetric exchange rates – firstly the assumption that none of the exchange volume returns to a compartment, and secondly the averaging of the flow rate over the whole tidal period. These are briefly discussed below, in order that the values given for the exchange rate in Tables A1.1 – A1.5 may be modified if judged necessary.

Calculating the tidal exchange rate

The volumetric exchange rate parameter values in this report have been calculated based on a reference time of one complete tidal period, which around the UK is ~12 hours, or 43,200 seconds. Thus, for the Severn (mid) compartment, we have

$$(6.6 \times 10^8) / 43200 = 1.53 \times 10^4 \text{ m}^3 \text{ s}^{-1}$$

as our calculated volumetric exchange rate. This is the value listed in Table A1.4.

The mean volumetric exchange rate over the six-hour period from high to low tide (net outflow) or from low to high tide (net inflow) is simply

$$(6.6 \times 10^8) / 21600 = 3.06 \times 10^4 \text{ m}^3 \text{ s}^{-1}.$$

To obtain the mean volumetric exchange rate for a six hour period, the exchange rates in Tables A1.1 – A1.5 should be multiplied by 2.

4.8   Net tidal exchange rate ($m^3 s^{-1}$)

If hydrodynamic information suggests that a significant proportion of water is being recycled from tide to tide (that is, contaminated water expelled from a compartment on an ebb tide is being returned to the same compartment on the flood tide) then the volumetric exchange rate can be modified to produce a net tidal exchange rate. This will provide a more conservative dose assessment as it will be smaller than the volumetric exchange rate.

To derive a net tidal exchange rate, some knowledge of the proportion of water returning to the local compartment is required. The simplest method for estimating this proportion is to examine local tidal velocities to derive a residual velocity over a tidal period. Sources of information on tidal velocities include current meters, drifter studies and numerical models, each of which have considerable uncertainties associated, particularly in the near-shore area. Round (1998) and Aldridge (2006) suggest that residual velocities of 0.01 – 0.05 m s^{-1} are appropriate for UK coastal waters.

An alternative modification of the volumetric exchange rate is to shorten the reference time period to six hours, effectively giving the mean inflow and outflow rates during a flood and ebb tide respectively. This may be useful to study the initial dilution of a discrete release, but is unsuitable for longer time periods. It will double the exchange rates given in Tables A1.1 – A1.5, and is not recommended for general use.

Calculating the net exchange rate

The exchange rates in Tables A1.1 – A1.5 can also be used to estimate the net tidal exchange rate, using the streamwise extent of the compartment and available information on the local residual velocity.

For example, the Severn (mid) compartment has a length of 18 km (see Section 4.3), and for illustration a residual velocity of 0.03 m s^{-1} is assumed. Then, over a full tidal period, the net displacement downstream is

$$0.03 \times 43200 = 1296 \text{ m}$$

which implies that some

$$1296 / 18000 = 0.072 = 7.2\%$$

of the exchange volume in the local compartment has been replaced by 'fresh' water from an adjoining compartment. As only a small proportion of the exchange volume has actually been exchanged in this situation, it is modified accordingly and divided by the tidal period, giving a net tidal exchange rate of

$$(6.6 \times 10^8) \times 0.072 / 43200 = 1100 \text{ m}^3 \text{ s}^{-1}.$$

In general terms, the relationship between the volumetric exchange rates, V_{ex}, given in Tables A1.1 – A1.5 and the net exchange rate, V_n, can be written as

$$V_{ex} \times (R_v \times 43200) / L_c = V_n$$

where R_v is the residual velocity and L_c is the streamwise extent of the compartment. Compartment coastline lengths, as given in Tables A1.1 – A1.5, are in most cases appropriate for the streamwise extent of estuarine and coastal compartments. This parameter is less well defined for semi-enclosed bays, where it may be difficult to determine the appropriate reference length.

As discussed, values for residual velocity are calculated from field studies (e.g. current meters, drifter studies) or numerical models. It is unlikely that these data will be readily available; therefore costs would be incurred in obtaining them. Values for residual velocity can be derived from tidal diamond information in Admiralty charts (e.g in Allison & Grzechnik 2003). For the purposes of this report, these residual velocity values are not considered suitable to use in calculating net exchange rates, because the tidal diamond measurements could have been affected by the influence of local wind conditions at the time, and because they may not adequately describe the residual movement of water below the wind-affected surface layer.

Where suitable residual velocity values are unavailable, an assumption that ~10% of the exchange volume is lost to adjacent compartments over a tidal period is considered reasonable. However, conceptually this proportion could vary from almost <1% (no water exchanged) in a really small enclosed bay to nearly 100% (all water exchanged) for an estuary with large tidal range. As a general rule, over a tidal period coastal sites in the English Channel and on the west coast, and estuaries, may lose more than 10% of the exchange volume; coastal sites on the east coast about 10% of the exchange volume; and small enclosed bays less than 10%.

Most of the net exchange rates in Tables A1.1 – A1.5 have been calculated based on these generic assumptions, that is, assuming that 90% of the exchange volume is returned to the compartment over a full tidal period. The Pagham Harbour and Lulworth Cove compartments are small enclosed bays, so for these compartments it is assumed that 100% of the exchange volume is returned. It is not possible to calculate a net exchange rate for the Cardiff Basin compartment because at this site, the exchange is determined by the river input and is controlled by the mechanical locks of the Cardiff Bay Barrage.

4.9 Diffusion rate ($m^2 s^{-1}$)

The diffusion rate is an aggregated parameter to represent the many turbulent parameters acting on the water body that cannot be individually modelled. Diffusion acts to increase the area occupied by a contaminant, and when referred to a characteristic timescale gives the diffusion rate. This parameter is difficult to measure accurately, and can vary by two or three orders of magnitude in a short space of time. A higher diffusion rate would tend to decrease the concentration of a contaminant.

Diffusion rates for each compartment have been determined by reference to the most appropriate data in Talbot (1976), which documents a number of experimental measurements of diffusion rate in UK waters. A summary of these parameter values for UK waters is provided in Table 4.2.

The rapid fluctuations in the diffusion rate observed by Talbot (1976) make the selection of a single value for this parameter difficult. In general, a value of 10 – 15 appears to be appropriate for most locations, but there are significant data gaps, particularly for the Severn estuary. Slightly higher observed diffusion rates for the Blackwater estuary and the River Crouch suggest that a value of 20 may be more appropriate for estuaries. Given the variability of this parameter and the relative

scarcity of experimental data, values for the diffusion rate should be regarded as a source of uncertainty.

Table 4.2   Diffusion rates (m^2 s^{-1}) around the UK coast

Location	Diffusion rate (range)
North Sea – Southern Bight	3 – 20
North Sea – Yorkshire coast	12 – 20
North Sea – Sizewell	7 – 15
North Sea – German Bight	3 – 40
North Sea – Lowestoft	6 – 140
Blackwater estuary	13 – 30
River Crouch, Essex	12 – 70
Solent	2 – 100
Cornish coast – St Austell/Veryan Bays	7 – 20
River Fal – Cornwall	1 – 4
Irish Sea – Liverpool Bay	3 - 55

4.10   Coastline length (km)

The coastline length of a compartment can be used to determine the overall shape of the compartment. For the majority of coastal compartments both the coastal length and the offshore length are 10 kilometres. For estuaries the coastline length given relates to the linear distance from one end of the compartment to the other, and should therefore be doubled for an (approximate) total coastline length. The complexity of some of these areas means that it may not be possible to infer the mean width of an estuary as the total area will include inlets and mud flats. The coastline length of harbours and bays has been calculated as the total length of coastline in the particular compartment.

4.11   Suspended sediment load (mg l^{-1})

The suspended sediment load refers to the mass of solids suspended in the water column per unit volume of water. Both sediment and suspended particulate matter are included in this description, as they would both be expected to adsorb radionuclides. A database of experimental sediment load determinations, from coastal and offshore locations around the UK, has been interrogated to find all data from within each local compartment. Where few sample results are available for a given compartment, the range was extended by 10 kilometres in each direction.

The mean of the individual sample results from each compartment are given in Tables A1.1 – A1.5. Sediment loads range up to ~500 mg l^{-1} around the compartments, with the highest values being found in estuaries such as the Humber and the Severn.

4.12   Sedimentation rate (kg m^{-2} y^{-1})

The sedimentation rate is the mass of sediment that drops out of the water column per unit area per unit time. Measurements of this quantity are sparse and the level of uncertainty associated with this parameter is very high. In estuaries, particularly, sedimentation can be highly erratic.

Brownless et al. (2001) stated that sedimentation rates around the UK ranged from 0 – 10 kg m^{-2} y^{-1}. Using this range, and noting that sedimentation rate is likely to be proportional to sediment load, values for this parameter have been calculated for each local compartment according to the relation

$$S_R = 10 \times (S_L/500)$$

where S_R is sedimentation rate and S_L is the suspended sediment load in the compartment. In this way, a sediment load of around 500 mg l^{-1} will give a sedimentation rate at the upper end of the suggested range. The uncertainty of this parameter is considered to be uniformly high.

4.13   Sediment density (kg m^{-3})

The density of wet sediment at the base of a local compartment (e.g. on the seabed) varies according to the porosity of the mixture, the density of the materials composing the mixture, and how well-packed the sediment has become (Soulsby, 1997). Indicative ranges for this parameter are presented in Table 4.3 for differing sediment grain densities. The density of quartz-based sediment is typically 2650 kg m^{-3}.

As seawater is denser than freshwater, the resulting mixture of sediment and seawater will be denser than that of sediment and freshwater. The density increases according to how well-packed the sediment is – in dynamic estuarine environments, the mixture may not have the opportunity to become as densely packed as that in a coastal box or sheltered bay.

Values in Table 4.3 are based on the porosity of averagely-mixed sediments (Soulsby, 1997). A well-mixed/well-sorted sediment would have a lower/higher density than the values given, although the variation is small.

Table 4.3   Modelled wet sediment densities (kg m^{-3})

	Loosely packed		Average		Densely packed	
Sediment grain density (kg m^{-3})	2000	3000	2000	3000	2000	3000
Seawater[1]	1580	2150	1610	2210	1640	2270
Freshwater[2]	1570	2140	1600	2200	1630	2260

[1] Seawater density: 1027 kg m^{-3}
[2] Freshwater density: 1000 kg m^{-3}

5   Conclusions

Site-specific parameters have been calculated for 80 coastal sites which may receive the discharges of radioactive wastes from the non-nuclear sectors, such as educational establishments and hospitals, or the nuclear sector. These hydrographic parameters include:

V_{ex} – volumetric exchange rate; $m^3 s^{-1}$

V_n – net exchange rate (based on generic assumptions); $m^3 s^{-1}$

V – compartment volume; cubic metres, m^3

D – mean compartment depth; metres, m

L_c – coastline length; kilometres, km

K_x – diffusion rate; square metres per second, $m^2 s^{-1}$

S_L – suspended sediment load; milligrams per litre, $mg\ l^{-1}$

S_R – sedimentation rate; kilograms per square metre per year, $kg\ m^{-2}\ y^{-1}$

Site-specific values are provided in Tables A1.1-A1.5 in Appendix 1. Descriptions of each site are provided in Appendix 2.

Guidance regarding use of the parameters has been provided by the Environment Agency in Appendix 3, together with a comparison of the parameters with those currently used in other methods as Appendix 4.

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Appendix 1 – Parameter values

Tables A1.1 – A1.5 contain values for the principal parameters of interest, divided into regional groups and ordered clockwise from the northeast coast of England to the Solway Firth.

The parameter values presented in Tables A1.1 – A1.5 have been rounded to a suitable accuracy, so as not to convey an impression of undue precision. Intermediate values used in the calculation of these parameters have not been rounded.

The parameters quantified in this section and their dimensions are as follows:

T_r – mean tidal range; metres, m

V_{ex} – volumetric exchange rate; cubic metres per second, $m^3 \, s^{-1}$

V_n – net exchange rate (based on generic assumptions); $m^3 \, s^{-1}$

V – compartment volume; cubic metres, m^3

D – mean compartment depth; metres, m

L_c – coastline length; kilometres, km

K_x – diffusion rate; square metres per second, $m^2 \, s^{-1}$

S_L – suspended sediment load; milligrams per litre, $mg \, l^{-1}$

S_R – sedimentation rate; kilograms per square metre per year, $kg \, m^{-2} \, y^{-1}$

Parameter values considered to be particularly uncertain, as a result of poor underlying data, are denoted in ***bold italics*** in the Tables. Diffusion rates are drawn from a limited and highly variable dataset, and accordingly are denoted in ***bold italics*** throughout. They are generally grouped according to region and water body type.

Guidance regarding use of the parameters has been provided by the Environment Agency in Appendix 3.

Table A1.1 Northeast England

Location	Subsection	T_r	V_{ex}	V_n	V	D	L_c	K_x	S_L	S_R
Northumberland coast	north	3.3	7.5 E+03	750	1.7 E+09	17	10	*15*	6.5	0.1
	south	3.1	7.2 E+03	720	1.3 E+09	13	10	*15*	1.5	0.1
Blyth coast		3.2	7.4 E+03	740	2.2 E+09	22	10	*15*	*2.8[a]*	0.1
Tyne estuary		3.2	320	32	2.6 E+07	6.0	17	*20*	4.5	0.1
Sunderland coast		3.3	7.6 E+03	760	1.2 E+09	12	10	*15*	3.2	0.1
Tees estuary		3.5	510	51	2.8 E+07	4.4	12	*20*	8.7	0.2
Scarborough coast		3.6	8.2 E+03	820	1.2 E+09	12	10	*15*	*11[a]*	0.2
Bridlington coast		3.7	8.6 E+03	860	1.1 E+09	11	10	*15*	*16[a]*	0.3
Humber estuary	outer	4.6	1.2 E+04	1.2 E+03	*4.9 E+08[b]*	*4.3[b]*	12	*15*	110	2.2
	mid	4.9	8.0 E+03	800	6.9 E+08	9.7	20	*20*	330	6.6
	inner	5.2	6.3 E+03	630	3.6 E+08	6.9	26	*20*	560	11
Mablethorpe coast		4.4	1.0 E+04	1.0 E+03	8.0 E+08	8.0	10	*15*	63	1.3
The Wash		4.8	5.1 E+04	5.1 E+03	2.9 E+09	6.2	75	*10*	24	0.5

[a] Fewer than 20 sediment samples available in immediate compartment; values given are drawn from results within 20 km of a central coastline point.
[b] Bathymetric data for the outer Humber are predominantly clustered around Grimsby. Mean depth and compartment volume may be affected.

Table A1.2 East Anglia and southeast England

Location	Subsection	T_r	V_{ex}	V_n	V	D	L_c	K_x	S_L	S_R
Great Yarmouth coast		1.5	3.5 E+03	350	1.1 E+09	11	10	*15*	19	0.4
Lowestoft coast		1.6	3.9 E+03	390	1.0 E+09	10	10	*15*	40	0.8
Aldeburgh coast		1.9	4.3 E+03	430	2.0 E+09	20	10	*10*	36	0.7
Harwich coast		3.0	1.9 E+03	190	*7.7 E+07[b]*	*2.8[b]*	20	*10*	45	0.9
Orwell estuary		3.1	780	78	3.5 E+07	3.1	18	*15*	*58[a]*	1.2
Stour estuary		3.1	1.8 E+03	180	9.1 E+07	3.6	18	*15*	*58[a]*	1.2
Blackwater estuary		3.8	2.3 E+03	230	1.0 E+08	4.0	14	*15*	38	0.8
Thames estuary	outer	4.6	8.1 E+03	810	6.6 E+08	8.7	25	*15*	30	0.6
	mid	5.2	2.3 E+03	230	1.7 E+08	8.7	29	*15*	100	2.1
	inner (lower)	5.5	670	67	3.1 E+07	6.0	18	*20*	75	1.5
	inner (upper)	5.1	470	47	1.2 E+07	3.1	28	*20*	65	1.3
Medway		4.3	5.4 E+03	540	3.0 E+08	5.5	*20[c]*	*15*	24	0.5
Whitstable coast		4.0	9.1 E+03	910	3.8 E+08	3.8	10	*15*	46	0.9
Margate coast		3.4	7.8 E+03	780	7.8 E+08	7.8	10	*5*	44	0.9
Pegwell Bay		3.2	220	22	6.2 E+06	2.0	5	*15*	59	1.2
Sandwich coast		3.9	9.0 E+03	900	9.5 E+08	9.5	10	*5*	38	0.8
Dover coast		4.6	1.1 E+04	1.1 E+03	1.8 E+09	18	10	*5*	*31[a]*	0.6
Hythe coast		5.1	1.2 E+04	1.2 E+03	1.4 E+09	14	10	*5*	*12[a]*	0.2
Dungeness coast		5.2	1.2 E+04	1.2 E+03	2.5 E+09	25	10	*5*	61	1.2
Eastbourne coast		5.0	1.2 E+04	1.2 E+03	1.5 E+09	15	10	*5*	*17[a]*	0.3

[a] Fewer than 20 sediment samples available in immediate compartment; values given are drawn from results within 20 km of a central point.
[b] Bathymetry data for Harwich coast do not appear to include points in the Harwich deep water channel, and is therefore likely to underestimate the mean water depth. Compartment volume will be similarly affected.
[c] Due to the complex geography of the Medway estuary, the coastline length given should be treated as uncertain and modified dependent on which part of the estuary is of interest.

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Table A1.3 South coast of England

Location	Subsection	T_r	V_{ex}	V_n	V	D	L_c	K_x	S_L	S_R
Brighton coast		4.3	9.9 E+03	990	8.6 E+08	8.6	10	*5*	*21[a]*	0.4
Worthing coast		4.2	9.6 E+03	960	7.4 E+08	7.4	10	*5*	*7.1[a]*	0.1
Pagham Harbour		3.8	200	2	*5.8 E+05[b]*	*0.3[b]*	5	*5*	*8.4[a]*	0.2
Chichester Harbour	Main Harbour	3.1	350	35	1.6 E+07	3.3	7	*5*	8.2	0.2
	Chichester Channel	3.2	200	20	2.9 E+06	1.1	10	*5*	8.2	0.2
	Bosham Channel	3.2	100	10	1.9 E+06	1.4	8	*5*	8.2	0.2
	Thorney Channel	3.1	440	44	1.3 E+07	2.1	8	*5*	8.2	0.2
	Emsworth Channel	3.2	360	36	6.7 E+06	1.3	14	*5*	8.2	0.2
Langstone Harbour		3.0	690	69	1.8 E+07	1.8	15	*5*	7.9	0.2
Portsmouth coast		2.9	4.7 E+03	470	7.0 E+08	10	10	*10*	9.5	0.2
Solent	east	2.7	3.6 E+03	360	6.1 E+08	11	12	*15*	14	0.3
	west	2.0	4.2 E+03	420	6.1 E+08	6.7	24	*15*	16	0.3
Southampton Water	outer	2.8	1.2 E+03	120	8.1 E+07	4.3	10	*10*	20	0.4
	inner	3.0	340	34	1.5 E+07	3.1	7	*10*	31	0.6
Christchurch Bay		1.0	420	42	7.1 E+07	3.7	14	*10*	*11[a]*	0.2
Poole Bay		1.1	1.6 E+03	160	4.2 E+08	6.5	22	*10*	9.3	0.2
Lulworth Cove		1.3	3.1	0.03	3.3 E+05	3.0	1.5	*2*	*7.6[a]*	0.2
Weymouth Bay		1.3	260	26	5.1 E+07	6.0	8	*5*	4.0	0.1
Exmouth and Torbay	Exmouth coast	2.8	6.4 E+03	640	1.0 E+09	11	10	*10*	*40[a]*	0.8
	Exe estuary	2.8	530	53	2.2 E+07	2.7	7	*15*	*36[a]*	0.7
	Babbacombe Bay	2.7	6.3 E+03	630	9.8 E+08	9.8	10	*10*	43	0.9
	Tor Bay	3.0	1.6 E+03	160	2.0 E+08	8.3	14	*5*	31	0.6
Dart estuary		2.7	410	41	3.6 E+07	5.3	17	*10*	12	0.2
Plymouth Sound		3.3	1.3 E+03	130	1.7 E+08	10	5	*10*	4.4	0.1
Plym estuary		3.4	210	21	9.5 E+06	3.5	7	*10*	4.6	0.1

Location	Subsection	T_r	V_{ex}	V_n	V	D	L_c	K_x	S_L	S_R
Tamar estuary (Hamoaze)		3.4	400	40	5.0 E+07	10	6	*10*	4.6	0.1
St Austell Bay		3.4	1.3 E+03	130	9.7 E+07	5.6	12	*10*	7.5	0.2
Falmouth Bay		3.5	3.6 E+03	360	4.1 E+08	8.9	- [c]	*3*	5.0	0.1

[a] Fewer than 20 sediment samples available in immediate compartment; values given are drawn from results within 20 km of a central point.
[b] Parameter values are based on one available bathymetric data point in Pagham Harbour. Mean depth and compartment volume are therefore highly uncertain.
[c] Due to the complex geography of Falmouth Bay, no coastline length is given as the value required will be highly dependent on which part of the bay is of interest.

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Table A1.4 Land's End to Milford Haven

Location	Subsection	T_r	V_{ex}	V_n	V	D	L_c	K_x	S_L	S_R
St Ives Bay		4.2	1.3 E+03	130	1.3 E+08	9.9	10	*10*	*1.1[a]*	0.1
Barnstaple Bay		5.5	1.9 E+04	1.9 E+03	1.6 E+09	11	35	*10*	26	0.5
Torridge estuary		5.1	140	14	*2.1 E+06[b]*	*1.8[b]*	6	*15*	*25[a]*	0.5
Taw estuary		4.4	710	71	*8.9 E+06[b]*	*1.3[b]*	12	*15*	25	0.5
Parrett estuary		*8.3[c]*	*460[c]*	*46[c]*	*5.8 E+06[d]*	*2.4[d]*	10	*15*	97	1.9
Severn estuary	outer	8.6	5.0 E+04	5.0 E+03	2.9 E+09	11	20	*20*	210	4.3
	middle	8.9	1.5 E+04	1.5 E+03	6.8 E+08	9.2	18	*25*	450	9.1
	inner	7.6	5.7 E+03	570	1.3 E+08	4.0	24	*25*	690	14
Avon estuary		8.9	230	23	3.2 E+06	2.9	12	*15*	430	8.5
Usk estuary		8.8	275	27.5	4.0 E+06	2.9	9	*15*	270	5.4
Cardiff Bay		8.4	5.3 E+03	530	1.9 E+08	7.0	15	*20*	180	3.6
Cardiff Basin		-	-	-	*9.0 E+06[e]*	*4.5[e]*	10	*5*	*180[a]*	3.6
Porthcawl Bay		6.6	680	68	1.3 E+07	2.9	7	*10*	*32[a]*	0.6
Swansea Bay		6.8	9.4 E+03	940	3.5 E+08	5.9	20	*10*	13	0.3
Loughor estuary		5.2	2.9 E+03	290	6.0 E+07	2.5	10	*15*	61	1.2
Milford Haven	outer	4.5	1.5 E+03	150	1.8 E+08	13	8	*15*	*7.9[a]*	0.2
	inner	4.5	1.8 E+03	180	1.4 E+08	8.6	10	*20*	10	0.2

[a] Fewer than 20 sediment samples available in immediate compartment; values given are drawn from results within 20 km of a central point.
[b] Bathymetry data for Taw/Torridge estuaries are likely to underestimate mean depth and compartment volume.
[c] Tidal station used for Parrett estuary is outside the estuary, in the Bristol Channel.
[d] Few bathymetric data available in the Parrett estuary.
[e] Cardiff Basin water level controlled by locks (Cardiff Bay Barrage); depth maintained to 4.5 m dependent on dredging regime, although this is likely to apply only in the main basin area. Consequently the mean depth and compartment volume are likely to be overestimated.

Table A1.5 Mid-Wales coast to Solway Firth

Location	Subsection	T_r	V_{ex}	V_n	V	D	L_c	K_x	S_L	S_R
Aberystwyth coast		2.5	5.7 E+03	570	1.1 E+09	11	10	*15*	10	0.2
Tremadog Bay		3.1	1.2 E+04	1.2 E+03	1.5 E+09	8.6	40	*15*	*13[a]*	0.3
Traeth Bach		3.2	490	49	7.0 E+06	1.0	7	*20*	13	0.3
Caernarfon Bay		3.0	2.1 E+04	2.1 E+03	4.5 E+09	15	50	*15*	9.0	0.2
Menai Strait	southwest	3.3	980	98	6.3 E+07	4.8	16	*20*	7.8	0.2
	northeast	5.1	940	94	4.3 E+07	5.4	6	*20*	9.3	0.2
Holyhead Harbour		3.7	950	95	7.7 E+07	6.8	6	*20*	*5.4[a]*	0.1
Cemaes coast		4.3	1.0 E+04	1.0 E+03	2.7 E+09	27	- [g]	*15*	*4.9[a]*	0.1
Conwy estuary		5.2	920	92	2.0 E+07	2.6	14	*20*	*7.3[a]*	0.1
Rhyl coast		5.5	1.3 E+04	1.3 E+03	9.6 E+08	9.6	10	*15*	11	0.2
Dee estuary		5.1	4.1 E+03	410	1.1 E+08	*3.2[b]*	20	*25*	17	0.3
Mersey estuary	outer	6.6	6.3 E+03	630	3.3 E+08	8.0	18	*25*	78	1.6
	inner	4.5	1.6 E+03	160	*3.2 E+07[c]*	*-[d]*	14	*25*	150	2.9
Ribble estuary	outer	6.1	4.5 E+03	450	*1.1 E+08[c]*	*-[d]*	13	*25*	94	1.9
	inner	4.2	490	49	5.3 E+06	*1.1[e]*	10	*25*	130	2.6
Wyre estuary		6.2	970	97	1.4 E+07	2.1	9	*20*	68	1.4
Lune estuary		3.4	400	40	*1.1 E+07[c]*	*-[d]*	13	*20*	79	1.6
Morecambe Bay		6.4	2.6 E+04	2.6 E+03	8.2 E+08	*4.6[f]*	40	*10*	81	1.6
Walney Channel/Barrow Harbour		6.2	1.7 E+03	170	1.5 E+07	1.3	6	*15*	64	1.3
Workington/Whitehaven coast		5.6	1.3 E+04	1.3 E+03	1.1 E+09	11	10	*15*	31	0.6
Solway Firth	outer	5.8	6.3 E+04	6.3 E+03	4.1 E+09	8.5	25	*20*	27	0.5
	inner	5.0	2.3 E+04	2.3 E+03	7.0 E+08	3.6	34	*25*	180	3.7

[a] Fewer than 20 sediment samples available in immediate compartment; values given are drawn from results within 20 km of a central point.
[b] Bathymetry data for Dee estuary are located across the mouth of the estuary; large areas of mud flats further up the estuary indicate that this may be an overestimate of true mean depth.

Evidence Report – Parameter values for coastal dispersion modelling

[c] Compartment volumes estimated using modified method described in Appendix 2.

[d] Bathymetry data predominantly from drying areas, and should not be used to calculate mean depth at these locations.

[e] Bathymetry data very sparse beyond Warton Bank.

[f] Bathymetry data predominantly from south-western corner of this compartment; large areas of mud flats indicate that this may be an overestimate of true mean depth.

[g] Cemaes coastal box set outside Cemaes and Cemlyn bays and as such has no coastal boundary.

Appendix 2 – Description of locations and subsections

The compartments referred to in Tables A1.1 – A1.5 are defined geographically as follows:
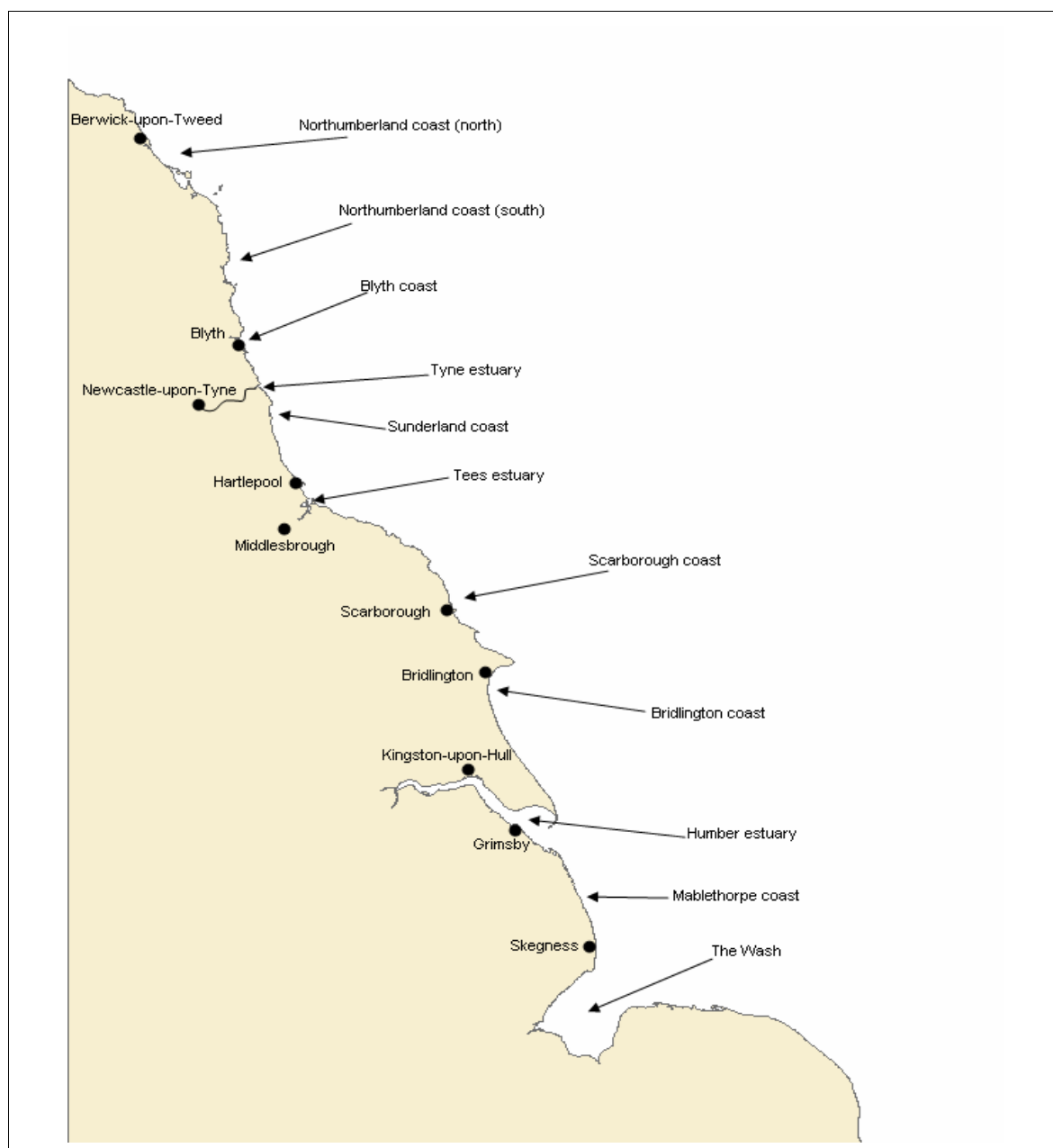
Northeast England

Figure A2.1 Compartments along the northeast coast of England

Northumberland coast north – 10km square coastal box, extending offshore between Berwick and Holy Island

Northumberland coast south – 10 km square coastal box, extending offshore between Boulmer and Amble

Blyth coast – 10km square box, coastal boundary centred on Blyth

Tyne estuary – River Tyne from Newcastle-upon-Tyne to the north and south piers at Tynemouth.

Sunderland cost – 10km square coastal box, coastal boundary centred on Sunderland

Tees estuary – River Tees from Middlesbrough to point where Tees Mouth meets Tees Bay

Scarborough coast - 10km square coastal box, coastal boundary centred on Scarborough

Bridlington coast – 10km square coastal box incorporating much of Bridlington Bay, coastal boundary running south from Bridlington

Humber estuary (outer) – large estuary basin partially enclosed by Spurn Head spit, inland to Grimsby

Humber estuary (mid) – River Humber from Grimsby to Kingston-upon-Hull

Humber estuary (inner) – River Humber from Kingston-upon-Hull to the confluence of the Trent and the Ouse

Mablethorpe coast – 10km square coastal box, coastal boundary centred on Mablethorpe

The Wash – Area enclosed by a line from Gibraltar Point to Hunstanton

East Anglia and southeast England

Great Yarmouth coast – 10km square coastal box, coastal boundary centred on Great Yarmouth

Lowestoft coast – 10 km square coastal box, coastal boundary centred on Lowestoft

Aldeburgh coast – 10km square coastal box, coastal boundary centred on Aldeburgh

Harwich coastal area – Area enclosed by Harwich, Landguard Point and The Naze, including Hamford Water (much of which dries at low tide)

Orwell estuary – River Orwell from Ipswich to Harwich

Stour estuary – River Stour from Manningtree to Harwich

Blackwater estuary – River Blackwater from eastern side of Northey Island to West Mersea

Thames estuary (outer) – River Thames from Tilbury to Southend-on-Sea/Isle of Grain

Thames estuary (mid) – River Thames from Thames tidal barrier (Woolwich) to Tilbury
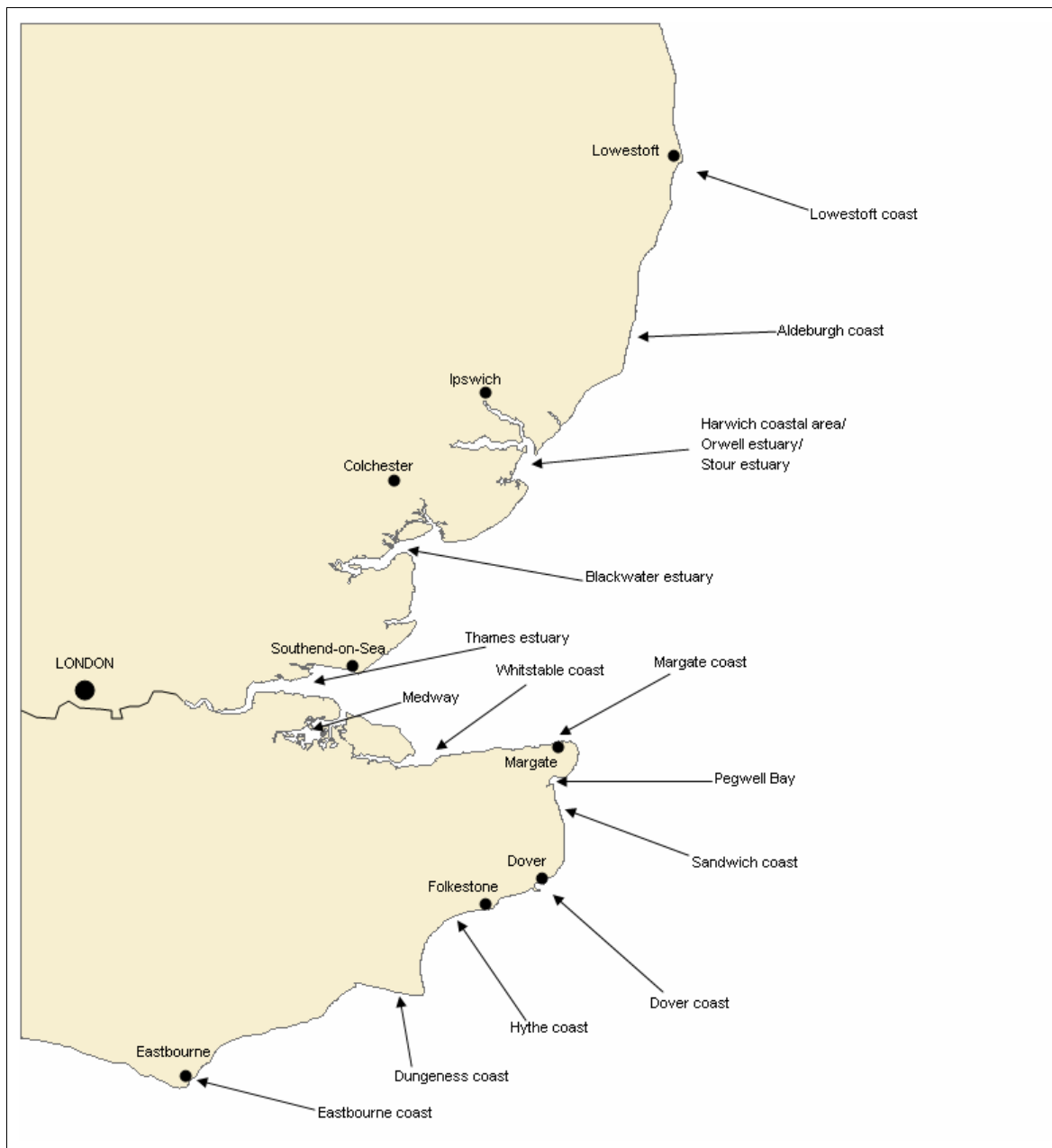
Figure A2.2 Compartments in East Anglia and the southeast of England

Thames estuary (inner – lower) – River Thames from Westminster Bridge to Thames tidal barrier

Thames estuary (inner – upper) River Thames from Teddington (Richmond) lock to Westminster Bridge

Medway – River Medway from Rochester to Sheerness/Isle of Grain

Whitstable coast – 10km square coastal box, coastal boundary centred on Whitstable

Margate coast – 10km square coastal box, coastal boundary centred on Margate

Pegwell Bay – small bay south of Ramsgate, north of Sandwich Flats

Sandwich coast - 10km square coastal box, coastal boundary running south from Sandwich Flats to Deal

Dover coast - 10km square coastal box, coastal boundary centred on Dover

Hythe coast - 10km square coastal box, coastal boundary centred on Hythe

Dungeness - 10km square coastal box, coastal boundary running west from Dungeness

Eastbourne coast - 10km square coastal box, coastal boundary running from Pevensey Bay to Beachy Head
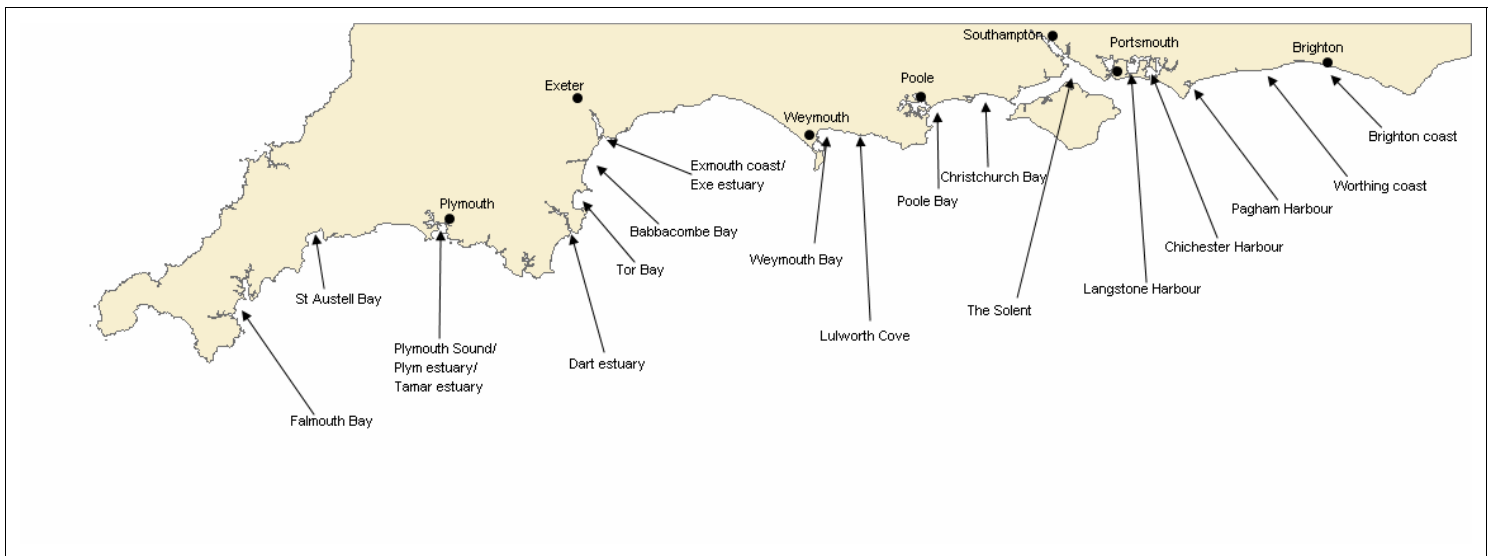

South coast of England

Figure A2.3 Compartments along the south coast of England

Brighton coast - 10km square coastal box, coastal boundary centred on Brighton

Worthing coast - 10km square coastal box, coastal boundary centred on Worthing

Pagham harbour – small natural harbour southwest of Pagham

Chichester Harbour (main) – southern end of Chichester harbour, from its entrance to the southern point of Thorney Island

Chichester harbour (Chichester Channel) – easternmost channel, from West Itchenor

Chichester Harbour (Bosham Channel) – small channel running north from West Itchenor

Chichester Harbour (Thorney Channel) – channel to the east of Thorney Island

Chichester Harbour (Emsworth Channel) – channel to the west of Thorney Island, and the area at the northern end of Hayling Island as far west as the road bridge

Langstone Harbour – natural harbour, from entrance to Hayling Island road bridge

Portsmouth coast – coastal box, coastal boundary running between Langstone harbour entrance and Gilkicker Point, extending south 10km until constrained by the Isle of Wight

The Solent (east) – area enclosed by Gilkicker Point, Ryde, Cowes, Calshot and Lee-on-Solent

The Solent (west) – area enclosed by Calshot, Cowes, Totland and Hurst Point

Southampton Water (outer) – Calshot/Lee-on-Solent inland to the confluence of the River Itchen and the River Test

Southampton Water (inner) – River Test from confluence with River Itchen inland to Totton bypass road bridge

Christchurch Bay – Bay enclosed by a line from Milford on Sea to Hengistbury Head

Poole Bay – Bay enclosed by a line from Hengistbury Head to The Foreland (Handfast Point)

Lulworth Cove – very small bay ~ 20km east of Weymouth

Weymouth Bay – Bay enclosed by a line from Osmington Mills to Weymouth

Exmouth coast – 10km coastal box, coastal boundary running southwest from Budleigh Salterton

Exe estuary – River Exe from Exmouth to Topsham

Babbacombe Bay – 10km coastal box, coastal boundary centred on Teignmouth

Tor Bay – natural bay enclosed by a line running due north from Berry Head

Dart estuary – River Dart from Totnes to open sea 2 km south of Kingswear

Plymouth Sound – area north of Renney Point/Penlee Point, as far as the Narrows in the northwest and Mountbatten Point in the northeast

Plym estuary – River Plym from A38 road bridge to Mountbatten Point

Tamar estuary (Hamoaze) – River Tamar from A38 road bridge to the Narrows (Cremyll), including St John's Lake

St Austell Bay – bay enclosed by a line from Gribbin Head to Black Head

Falmouth Bay – area enclosed by a line from St Anthony Head to Porthoustock, including Carrick Roads water to the north and Helford River to the west

Land's End to Milford Haven

St Ives Bay – Bay enclosed by a line from St Ives to Navax Point headland

Barnstaple Bay – large bay enclosed by a line from Hartland Point to Croyde Bay/Baggy Point

Torridge estuary – River Torridge from Bideford to Appledore

Taw estuary – River Taw from Barnstaple to Appledore

Parrett estuary – River Parrett from Stert Flats/Burnham-on-Sea, inland to Dunball ~4 km north of Bridgwater

Severn estuary (outer) – the Mouth of the Severn, from Weston-super-Mare/Cardiff to Portishead/Newport, excluding Cardiff Bay

Severn estuary (mid) – Portishead/Newport inland to the northern (M48) Severn Bridge at Beachley
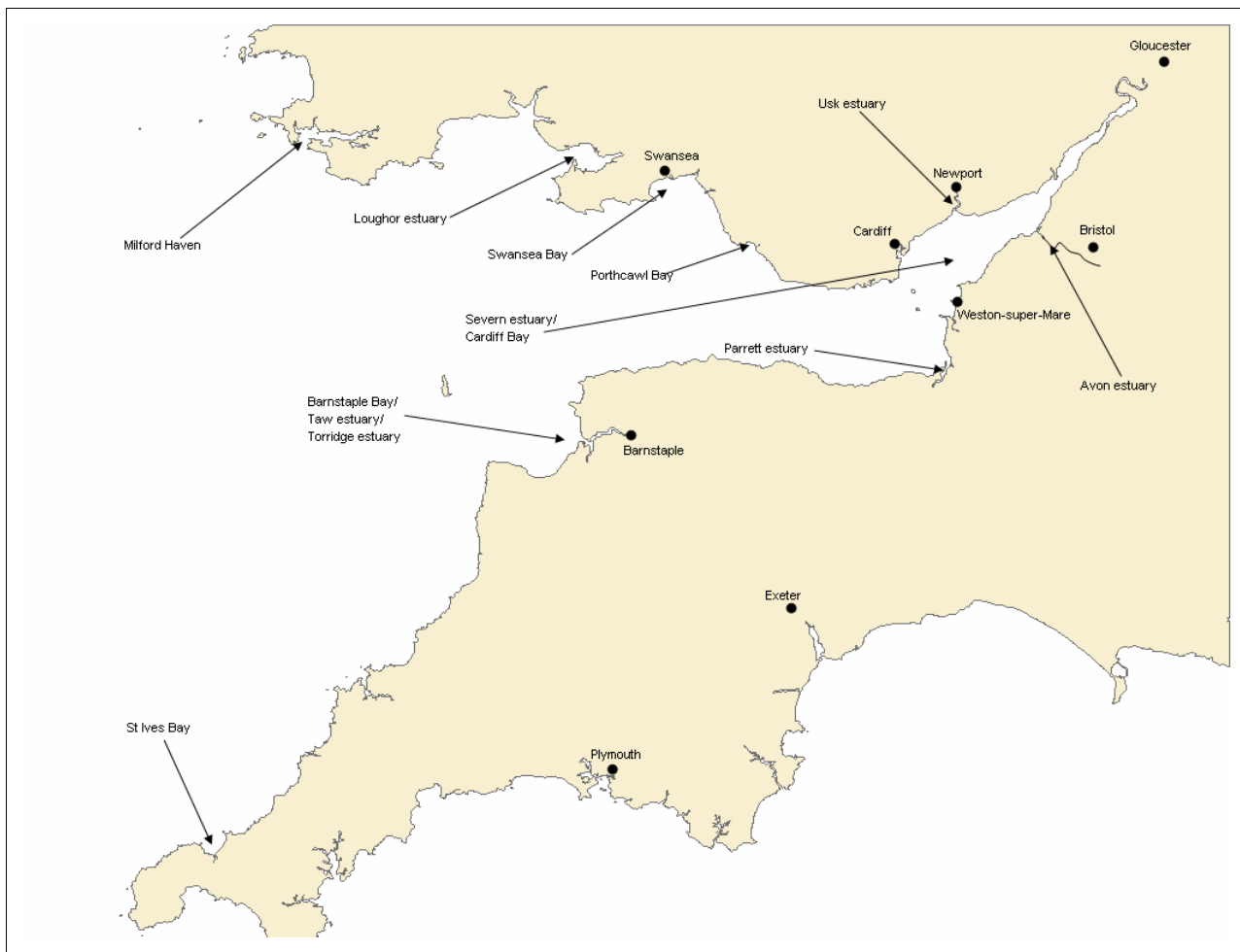
Figure A2.4 Compartments from Land's End to Milford Haven

Severn estuary (inner) – Northern Severn Bridge inland to The Noose (where the Severn narrows significantly)

Avon estuary – River Avon from Avonmouth to the Brunel Way road bridge (A370)

Usk estuary – River Usk from Uskmouth/confluence with the Severn inland to the M4 road bridge

Cardiff Bay – bay enclosed by a line from Petertone Wentlooge to Lavernock Point, excluding the area enclosed by the Cardiff Bay barrage

Cardiff Basin – area enclosed by the Cardiff Bay barrage and the A4232 and A4055 road bridges

Porthcawl Bay – small bay enclosed by a line from Ogmore-by-Sea to Porthcawl

Swansea Bay – bay enclosed by a line from Port Talbot harbour to Mumbles Head

Loughor estuary – estuary from Whiteford Point/Burry Port inland to Loughor

Milford Haven (outer) – outer haven, from St Ann's Head to Milford Haven/Angle (excluding Angle Bay)

Milford Haven (inner) – inner haven, from Milford Haven/Angle inland to Neyland, including Angle Bay

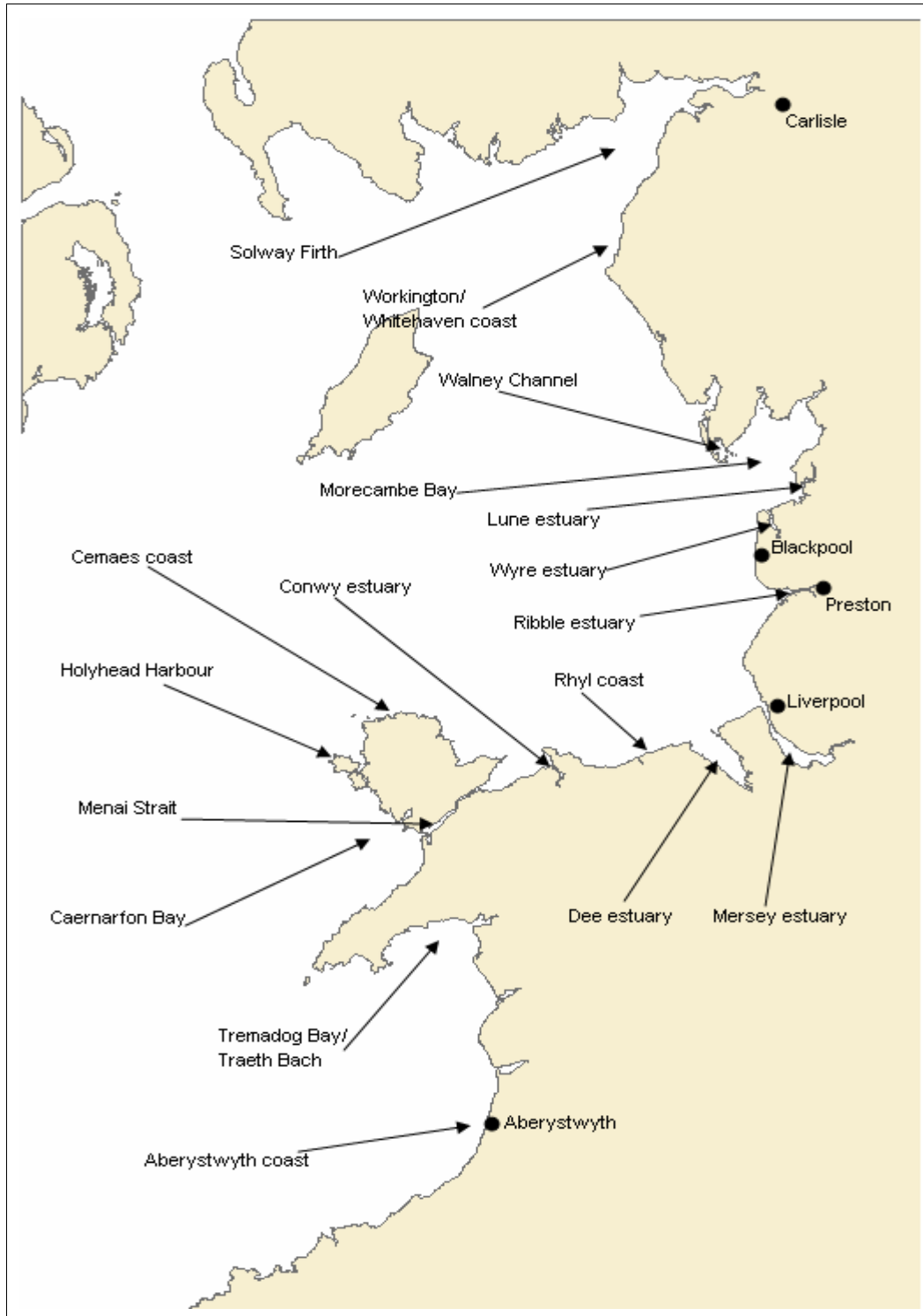# Mid-Wales coast to Solway Firth

Figure A2.5 Compartments from mid-Wales to the Solway Firth

Aberystwyth coast – 10km coastal box, coastal boundary centred on Aberystwyth

Tremadog Bay – large bay enclosed by a line running due west from the headland west of Llanbedr

Traeth Bach – estuary from Harlech Point at the entrance to Tremadog Bay inland to the toll bridge south of Penrhyndeudraeth

Caernarfon Bay – very large bay, enclosed by a line running due north from Morfa Nefyn to the southern tip of Holy Island

Menai Strait (southwest) – from Abermenai Point on Caernarfon Bay to the western Menai Bridge

Menai Strait (northeast) – from the western Menai Bridge to a line running southeast from Beaumaris to the Welsh mainland

Holyhead Harbour – the area southeast of the harbour wall as far as the A5 road bridge

Cemaes coast – a 10km square coastal box, coastal boundary centred on the mouth of Cemaes Bay and running across the mouth of Cemlyn Bay

Conwy estuary – River Conwy from a line running due south from Great Ormes Head, including Conwy Sands, and inland to Tal-y-Cafn

Rhyl coast – 10km coastal box, coastal boundary centred on Rhyl

Dee estuary – River Dee, from Point of Ayr/West Kirby inland to Connah's Quay

Mersey estuary (outer) – River Mersey from Bootle to Ellesmere Port

Mersey estuary (inner) – River Mersey from Ellesmere Port to Widnes/Runcorn

Ribble estuary (outer) – River Ribble from Southport/Lytham St Annes inland to Warton Bank

Ribble estuary (inner) – River Ribble from Warton Bank to Preston

Wyre estuary – River Wyre from Fleetwood ~8 km inland to the A588 road bridge, and channel north of Fleetwood through North Wharf and Bernard Wharf mud flats

Lune estuary – River Lune from Sunderland Point to Lancaster, and channel west of Sunderland Point through Bernard Wharf and Sunderland Bank mud flats

Morecambe Bay – large bay, enclosed by a line from Heysham to Hilpsford Point at the southern end of Walney Island, excluding Barrow Harbour

Walney Channel/Barrow Harbour – area northwest of a line from Hilpsford Point to Roa Island, a far as the road bridge linking the Walney Island to the English mainland

Workington/Whitehaven coast – 10km square coastal box, coastal boundary running between Workington and Whitehaven

Solway Firth (outer) – very large estuary compartment, running from Workington/Abbey Head inland to Southerness/Dubmill Point

Solway Firth (inner) – Solway from Southerness/Dubmill Point inland to Gretna, including Blackshaw Bank mud flats

Appendix 3 – How to use the parameters in this report

In this Appendix, the Environment Agency provides guidance on how to use the parameters in this report.

In the coastal / estuarine scenario of our initial radiological assessment system, volumetric exchange is the parameter used to make an assessment site-specific at Stage 2. In this report we have presented two values for volumetric exchange, one for overall exchange 'volumetric exchange rate' and a second which has been modified to allow for recycling of water 'net exchange rate'. We recommend that the net exchange rates presented in this report are used in the initial radiological assessment system.

As described in detail in Section 4.8, the values for net exchange rate have been calculated based on the generic assumption that 10% of the exchange volume is lost to an adjacent compartment over a tidal cycle (or 1% for the small enclosed bays of Pagham Harbour and Lulworth Cove). For radiological assessments, smaller values for the proportion of exchange water lost to adjacent compartments will tend to result in higher environmental concentrations being maintained for longer. Adoption of 10% for an initial assessment is considered to be a reasonable first approximation.

If you have reason to think that this is an inappropriate assumption for your site, then site specific values for residual velocity should be obtained.

If the outcome of your assessment is a dose >20 μSv/y then a site specific assessment may be required using PC-CREAM and a review of the value for volumetric exchange should be made at this point. This review should consider the release environment, in particular if the release occurs to a relatively enclosed bay.

Appendix 4 – Comparison with other published values

In this Appendix the Environment Agency has compared the results of this work with other published values, to assess the effect that using this report may have on dose assessments.

The initial radiological assessment methodology (Environment Agency, 2006) contains typical volumetric exchange rates for estuary/coastal water. The majority of these values are equivalent to those given in the Health Protection Agency's PC-CREAM methodology report (HPA report, Smith and Simmonds 2009), with the exception of the values for the Cumbrian coast and inner tidal Thames compartments. The HPA report contains hydrographic parameters for nuclear sites in Europe, and includes volumetric exchange rate, compartment volume, depth, suspended sediment load and sedimentation rate. The report does not explain how the values were calculated or where they were sourced from.

Table A4.1 compares the results of this report with the values in the HPA report, using the nearest relevant compartment. The geographical extent of the compartments in the HPA report is not described. Comparing the values for surface area can indicate whether the compartments are similar in size. The open coastal compartments (e.g. Dungeness) tend to be more similar than the estuaries and bays (e.g. Hartlepool/Tees estuary). Almost all the compartments in the HPA report have depths of either 10m or 20m – presumably a generic value for a 'shallow' or 'deep' coastal compartment.

Estuaries

The volumetric exchange rates for estuaries in the HPA report appear to be generic. Seven estuaries have a volume of 2×10^8 m^3 and a volumetric exchange rate of 127 m^3/s, and two estuaries have a volume of 5×10^9 m^3 and a volumetric exchange rate of 3,170 m^3/s. While these volumetric exchange rates are within an order of magnitude of those in this report, further comparison is probably not worthwhile given the generic versus site specific nature of the values.

Bays

The volumetric exchange rates for bays are more than an order of magnitude different. This is most likely to be due to differences in the geographical definition of these compartments.

Weymouth Bay is a relatively small compartment, with a mean surface area of approximately 8.5km^2 and a mean depth of 6m. This has been compared to the Winfrith compartment from the HPA report. The Winfrith compartment has a surface area of 1.0×10^8 m^2, which is the same as the open coastal compartments and probably defined as a 10km x 10km compartment. The depth parameter associated with this larger compartment is understandably greater than for the relatively shallow bay. As the overall volume of the Weymouth Bay compartment is smaller than the Winfrith compartment, it follows that less water will be exchanged with neighbouring compartments to bring about the local change in tidal height.

The surface area of the Morecambe Bay compartment is an order of magnitude larger than the Heysham compartment, so the geographical definition of the compartments

must be significantly different. As the Morecambe Bay compartment is much larger, it follows that more water will be required to effect the observed change in tidal height, and hence more will be exchanged with neighbouring compartments.

Open coast

The coastal compartments in this report were defined as a 10km x 10km box, and this appears to also be the case for the majority of those in the HPA report. While the volumetric exchange rates for the Dungeness, Aldeburgh and Cemaes compartments are relatively similar to the compartments in the HPA report (approximately within a factor of 2), Dungeness and Cemaes both have larger compartment volume than the respective HPA compartment yet a lower volumetric exchange rate.

The volumetric exchange rate for the Whitehaven / Workington coast compartment (Cumbrian coast) is an order of magnitude lower than that of the Sellafield compartment from the HPA report. The compartment volumes are similar, so it is unclear why the volumetric exchange rates are so different.

Implications for dose assessments using the initial radiological assessment methodology (Environment Agency, 2006)

One of the scenarios considered by the initial radiological assessment methodology is the impact of releases of radioactivity to estuarine or coastal waters on a generic fisherman family. The methodology is based on dose per unit release (DPUR) data. The DPUR values can be scaled to take account of site specific conditions, and in the case of the estuary/coastal scenario this is done by using volumetric exchange rates. Using the site specific volumetric exchange rates from this report compared to those from the HPA report would lead to:

- significantly more conservative dose assessments for Cumbrian coast and Weymouth Bay

- conservative assessments for Thames inner lower & upper, Solway Firth inner, Tamar estuary, Dungeness coast, Tees estuary, Ribble estuary inner, Traeth Bach and Cemaes coast

- less conservative assessments for Barrow Harbour, Severn estuary outer and inner, Aldeburgh coast, and Ribble estuary outer

- significantly less conservative assessments for Morecambe Bay.

Table A4.1 – Comparison of results with HPA-RPD-058

HPA-RPD-058	Surface area (m²)	Depth (m)	Volume (m³)	Volumetric exchange rate (m³/s)	This report	Surface area (m²)	Depth (m)	Volume (m³)	Net exchange rate (m³/s)
Aldermaston / Amersham	2.0E+07	10	2.0E+08	127	Thames inner (lower)	5.2E+06	6	3.1E+07	66
					Thames inner (upper)	4.0E+06	3	1.2E+07	46
Barrow	2.0E+07	10	2.0E+08	127	Walney Island / Barrow Harbour	1.2E+07	1	1.5E+07	170
Cardiff	2.5E+08	20	5.0E+09	3170	Severn estuary outer	2.5E+08	11	2.9E+09	5020
Chapelcross	2.5E+08	20	5.0E+09	3170	Solway Firth (inner)	2.0E+08	4	7.0E+08	2270
Devonport	2.5E+08	20	2.0E+08	127	Tamar estuary (Hamoaze)	5.0E+06	10	5.0E+07	40
Dungeness	1.0E+08	20	2.0E+09	2540	Dungeness coast	1.0E+08	25	2.5E+09	1190
Hartlepool	2.0E+09	10	2.0E+08	127	Tees estuary	6.3E+06	4	2.8E+07	51
Heysham	1.0E+07	10	1.0E+08	254	Morecambe Bay	1.8E+08	5	8.2E+08	2600
Oldbury / Berkeley	2.0E+07	10	2.0E+08	127	Severn estuary inner	3.2E+07	4	1.3E+08	570
Sellafield / Calder Hall	1.0E+08	20	2.0E+09	15800	Workington / Whitehaven coast	1.0E+08	11	1.1E+09	1300
Sizewell	3.0E+07	10	3.0E+08	349	Aldeburgh coast	1.0E+08	20	2.0E+09	430
Springfields	2.0E+07	10	2.0E+08	127	Ribble estuary (outer)	3.2E+07	0	1.1E+08	450
					Ribble estuary (inner)	5.0E+06	1	5.3E+06	49
Trawsfynydd	2.0E+07	10	2.0E+08	127	Traeth Bach	6.7E+06	1	7.0E+06	49
Winfrith	1.0E+08	20	2.0E+09	1270	Weymouth Bay	8.5E+06	6	5.1E+07	26
Wylfa	1.0E+08	20	2.0E+09	1270	Cemaes coast	1.0E+08	27	2.7E+09	995

Estuary	Bay	Coastal

Volume = compartment volume

List of abbreviations

CD   Chart Datum

LAT   Lowest Astronomical Tide

MHW   Mean High Water

MHWN   Mean High Water Neaps

MHWS   Mean High Water Springs

MLW   Mean Low Water

MLWN   Mean Low Water Neaps

MLWS   Mean Low Water Springs

Glossary

Bathymetry	Data concerning the underwater depth and topography of the seabed.
Chart Datum	The level of water from which depths and heights are measured from on hydrographic charts. The UK Hydrographic Office use Lowest Astronomical Tide as chart datum for their Admiralty Charts.
Drying area	An intertidal area of shoreline or riverbank which is exposed at low tidal states and becomes progressively inundated with the rising tide. Drying areas in estuaries are often referred to as mud flats.
Ebb Tide	The period from high to low tide, when the tidal height reduces to its local minimum.
Flood Tide	The period from low to high tide, when the tidal height increases to its local maximum.
Lowest Astronomical Tide	The lowest theoretical tide due to gravitational effects.
Mean High Water	The average height above Chart Datum of the high tide. In this report, Mean High Water is defined as the mean of the high water heights at spring and neap tides.
Mean Low Water	The average height above Chart Datum of the low tide. In this report, Mean Low Water is defined as the mean of the low water heights at spring and neap tides.
Neap Tide	Neap tides are characterised by a smaller than average tidal range, and lower/higher water level than average at high/low tide. This is principally due to the relative positions of the sun and the moon.
Residual velocity	The net water velocity over a tidal period. For example, a patch of water may move 10 km along the coast from high to low tide, only to return 9 km as the tide comes in, giving a net movement of 1 km in the tidal period. The residual velocity would therefore be $1/12$ km h^{-1} or 0.023 m s^{-1}.
Spring Tide	Spring tides are characterised by a larger than average tidal range, and higher/lower water level than average at high/low tide. This is principally due to the relative positions of the sun and the moon.

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