Statement of use

This document provides information for Defra and Environment Agency staff, researchers and consultants about the research project Development of Estuary Morphological Models and constitutes an R&D output from the joint Defra / Environment Agency Flood and Coastal Erosion R&D Programme, Modelling and Risk Theme.

Outputs from FD2107 comprise morphological model developments, some predictions from these models for the form of eight UK estuaries in 2050, an extended database of UK estuary characteristics, and an assessment of effects of changed morphology on flooding risk and habitats. It is expected that models and data will be used in predictions of future estuary form, flood risk and habitat; in order to underpin policy, inform estuary management and assess impact of schemes; by consultancies acting for Defra, the Environment Agency and local authorities. The work in this project owes much to its initiator, David Prandle.

This report is a contribution to research, and it would be imprudent for third parties to rely on it in specific applications without first checking its suitability. Various sections of this report use data supplied by or drawn from third party sources. The research team (POL, HR Wallingford, ABPmer and University of Plymouth) accepts no liability for loss or damage suffered by the client or third parties as a result of errors or inaccuracies in such third party data.

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This project FD2107 addressed mainly (iii), developing Hybrid models for (50-year) morphological prediction (combining advantages of T-D and B-U approaches). Several models were applied for different intervention and climate change scenarios to identify the impacts on the levels and form of eight varied UK estuaries.

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- ABP Marine Environmental Research
- HR Wallingford
- Delft hydraulics
- Technical University of Delft
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A. ASMITA Background Understanding

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1. **Introduction**

**Definition:** Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast (ASMITA).

This manual has been written as a guide to using the Matlab ASMITA model and illustrates the concepts and methodology used in long-term morphological modelling.

1.1 **Background Information**

As part of the Estuaries Research Program Phase 2 (ERP2), funded by the Environment Agency and Department for Environment, Food and Rural Affairs (Defra), a long-term morphological prediction tool ASMITA has been developed. The contributions from the following project partners are gratefully acknowledged (Figure 1).

- ABP Marine Environmental Research Ltd (ABPmer);
- HR Wallingford;
- Delft Hydraulics; and
- Delft Technical University.

![Figure 1. Splash screen acknowledging the project partners who have contributed to the ASMITA program](image)

1.2 **What is ASMITA and when should it be applied?**

The idea behind ASMITA (Figure 2) is that a tidal basin, or any characteristic area (element) evolves towards an equilibrium volume relative to tidal forcing. For example, under conditions of an unchanging water level, an element is in static equilibrium and the accommodation space is zero (no net change in the change in the transport of sediment); with increased mean sea level, the estuary is no longer in equilibrium, the accommodation space becomes positive and sediment may be
imported. The opposite is true when sea level falls. The key concepts of the ASMITA model are:

- The estuary is schematized into a number of geomorphologic elements;
- The state of each element is described by its volume (water or sediment);
- Integrated parameters of hydrodynamics (tidal prism, or tidal range) are used;
- Empirical relationships define the morphological equilibrium for each element;
- Deviation from the morphological equilibrium causes sediment demand; and
- A gradient in sediment demand drives sediment transport, and thereby morphological change.

Appendix A describes the theory and concepts used within the ASMITA model.

Figure 2. A schematised representation of the concept of ASMITA

Due to the highly complex nature of estuaries, process based numerical models struggle to describe the large number of variables needed to fully predict the long-term morphological response to changing environmental conditions. Often for such models the required information is poorly understood, computational times are long and sensitivity testing is very difficult to undertake.

ASMITA however, can be quickly applied to most systems and is capable of providing rapid answers following an ensemble of test conditions. ASMITA can be applied to investigate the long-term changes in morphology following some perturbation to the system, such as the inclusion of realignment areas, climate change and so on. As a general rule, ASMITA should be applied to support a range of studies either as a stand alone or in combination with other assessment tools to provide a greater degree of confidence in the long-term morphological predictions.
1.3 About ASMITA Software

The ASMITA software has been written using the Matlab software language by Mathworks, version R2008a (Figure 3). The software utilises only the functions present within Matlab and does not require additional toolboxes. Distributed alongside this manual is a document that details the relationships between the various routines that make up the ASMITA program (Appendix A).

![Figure 3](image.jpg) The ASMITA program has been developed using the software Matlab R2007a from Mathworks

1.4 Opening ASMITA

Within Matlab navigate to the folder containing the Matlab ASMITA scripts. From the command line, type `asmui`; (Figure 4) this command will invoke the installation and setup of the ASMITA graphical user interface (GUI).
Figure 4. To load and run ASMITA type ‘asmui;’ within the command window

Figure 5. The Matlab environment after calling the ASMITA program

The information entered into the ASMITA model (type, properties, flow, diffusion rates and so on) are contained within global variables stored within the Matlab environment. This information is used throughout the various routines and stored in memory throughout the lifetime of the application. The user can view this information either through the graphical interfaces provided in the software (Section 9) or by opening these global variables from the workspace window (Figure 5).

Note: Within Matlab, information is stored as numbers, cell arrays and structured arrays.
The user is able to control all aspects of the ASMITA model through the ASMITA interface (Figure 6), there is no requirement for the user to access this data through the Matlab command window. 

*Note:* Users have full access to the code that will enable them to make fine adjustments to the controlling algorithms. For example, additional driving forces may be needed that are not described in the current setup. Having full access to the software code allows the user to add additional functionality.

![ASMITA interface diagram](image)
2. File Operations

From within the ASMITA interface (Figure 6) there are a number of menu options. The menu item **FILE** allows the user to perform a number of file operations such as open or create a new instance of ASMITA, exit the program or save the current model setup. The following section explains the options available to the user for each of these items under the FILE menu.

2.1 New (Create a New Model Setup)

After selecting **New** from the File menu option a series of popup windows will appear. The user is asked a number of questions regarding the project name and scenario (Figure 7). This information will be displayed in the ASMITA interface (Figure 6).

![Figure 7. A dialog window appears after selecting the New menu item](image)

2.2 Open (Open an Existing Model)

Information regarding existing ASMITA models can be stored within a Matlab work file (*.mat). The *.mat file contains the information regarding the complete model setup including element and system defined properties.

![Figure 8. Shows the dialog window that appears after selecting the Open menu item, only *.mat files should be selected](image)
Select an existing ASMITA model setup file from the common dialog box. By default the *.mat file extension is visible (Figure 8). An example *.mat project is provided along with the model scripts.

2.3 Save and Save As

The user can save the current setup of the ASMITA model by selecting Save or Save As from the File menu item. If the user selects Save without first specifying a name then the program will, by default, request a name from the user.

2.4 Exit

The user can exit the ASMITA program at any point by going to the Exit menu item in the File drop down list.

3. Tools

Within the ASMITA model software there are a number of tools designed to assist in the building and visualisation of the model elements. Also included are a number of tools that allow the user to clear unwanted figures or clear the whole ASMITA model setup. These tools are described in more detail below.

3.1 Load Image

In order to understand the complexity of the system an image can be loaded as a background map, showing the areas of intertidal, channel, delta and so on (Figure 9). This can help the user visualise the schematised approach.

![Figure 9. The dialog box that appears after selecting the Load Image option from the Tools file menu](image-url)
The user is able to select from the following image types:

<table>
<thead>
<tr>
<th>ID</th>
<th>Num</th>
<th>File Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>JPEG File Interchange Format (*.jpg, *.jpeg)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Tag Image File Format (*.tif)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Windows Bitmap (*.bmp)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Portable Network Graphics (*.png)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Hierarchical Data Format (*.hdf)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>PC Paintbrush (*.pcx)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>X Window Dump (*.xwd)</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2 Refresh

The **Refresh** function updates the screen image, if an image appears incorrectly then use the **Refresh** function to redraw the screen image.

### 3.3 Clear Model/Figures

The **Tools → Clear → Clear Model** function (Figure 10) resets all parameters in ASMITA, allowing the user to start the process of setting up an ASMITA model without the need to close the whole application.

**Tools → Clear → Clear Figures** function will delete any open plot windows (results from. Under the **Plot** menu item (Section 9) the user can plot selected information in numerous windows. To simply close all figure windows click the **Clear Figures** function from the drop down menu list (Figure 10).

![ASMITA model definition - Version: 1.3; Date: Feb 2008](image)

**Figure 10.** Clear model/figures can be accessed via the main interface
4. **Element Setup**

As discussed previously, the concept of ASMITA is a schematisation of the various parts of the environment under investigation. To define the individual environment elements the user must first know the following properties:

- Type;
- Name;
- Initial Volume;
- Initial Area;
- Tidal Range;
- Bed Slope;
- Element Length;
- Import Density;
- Bulk Bed Density;
- Transport Coefficient;
- Vertical Exchange;
- Regime coefficients (Vp, Sp);
- Exclude element (no volume/area change).

![ASMITA GUI](image)

**Figure 11.** ASMITA GUI that allows the user to enter element specific information

Since many of the items for the specified element maybe unknown, tool tips are provided that give the user additional information such as typical default values for a tidal flat, channel, delta or coast. Figure 11 shows the tool tip provided for element name.

4.1 **Elements Units**

Element definitions and units are defined in the element specification GUI (Figure 11), this information is presented in Table 1.
Table 1. Element unit definitions and associated default values where appropriate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Flat, Delta, Channel</td>
</tr>
<tr>
<td>Initial Volume</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Initial Area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Tidal Range</td>
<td>m</td>
</tr>
<tr>
<td>Bed Slope</td>
<td>n/a</td>
</tr>
<tr>
<td>Element Length</td>
<td>m</td>
</tr>
<tr>
<td>Import Density</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Bulk Bed Density</td>
<td>kg/m$^3$ (default value 1350)</td>
</tr>
<tr>
<td>Transport Coefficient</td>
<td>no units (default value 2)</td>
</tr>
<tr>
<td>Vertical Exchange</td>
<td>m/s</td>
</tr>
<tr>
<td>Coefficient k (Vp)</td>
<td>no units</td>
</tr>
<tr>
<td>Coefficient k (Vp)</td>
<td>no units</td>
</tr>
</tbody>
</table>

Note: A number of sensitivity runs should be performed by the user to determine how sensitive the system is to the information specified in the element and system specifications.

4.2 Defining Elements

As discussed previously, elements within the environment under investigation can be schematised into various parts depending on the individual characteristics, for example an element defined as a channel may have distinct properties compared with an element defined as intertidal and so on. To define an element the user must select the **Setup → Element → Define** item from the drop down menu item (Figure 12).

After selecting the **Setup → Element → Define** function, using the mouse draw a rectangle on the ASMITA interface. To draw (define) the element, select the position of the top right hand corner. Whilst holding down the left mouse button, drag the mouse until you have reached the desired size for the element (rectangle). (Figures 12 and 13) illustrate this concept.

Note: The size of the rectangle drawn plays no part in the calculation, the rectangle only represents the schematisation of the environment under investigation.
Figure 12. Step one: define element position within the ASMITA interface

Figure 13. Step two: new defined element within the ASMITA interface
No overlapping of elements is allowed, and no more than 20 elements can be specified in the current version (Version 1.3). It is recommended that the user define at least two elements and that the user allow for a suitable gap between elements, this ensures easier selecting of elements.

Note: The order of the elements specified by the user determines the order in which they are stored within the Matlab data structure.

4.3 Element Properties

After defining a new element the user is asked to provide the information specific to this element type (Table 1). Where possible, default information is provided; this information is displayed as tool tips (Figure 11) when the user hovers over the specific element property.

Note: Default information is not element specific.

To select the element property the user can right click on the specific element, and then select Properties. The selected element will be highlighted in red as shown in Figure 14. Alternatively, the user can select Setup → Element → Properties from the drop down menu list. The last element selected will be chosen, if no elements have been selected in that session, then no element properties will be highlighted.

Note: The right click method is the recommended approach.

Figure 14. Element specification GUI
4.3.1 Equilibrium Volume and Area coefficients

The tidal flat and channel equilibrium conditions are specified by linear equations as a function of tidal prism of the form:

\[ Ve = kv \times Vp \text{ and } Se = ks \times Sp, \]

Where:

\[ Sp = \frac{Vp}{tr} \]

\( Ve \) and \( Se \) are the equilibrium values, 
\( kv \) and \( ks \) are the scaling coefficients, 
\( Vp \) is the tidal prism and \( tr \) is the tidal range.

A unique value of \( kv \) and \( ks \) can be specified for each element using the input boxes ‘Coefficient k (Vp)’ and ‘Coefficient k (Sp)’. When a delta element is included, the delta equations are also multiplied by \( kv \) and \( ks \), so they can be used to re-scale the delta equilibrium equations.

If the values of ‘Coefficient k (Vp)’ are left at the default value of 1 for ALL elements, the model defaults to calculating the values of \( kv \) and \( ks \) internally. This is done using the initial values of element volume and tidal prism for \( kv \) and element surface area and prism area, \( Sp \), for \( ks \).

If the values of ‘Coefficient k (Vp)’ and set to 0 in ALL elements the code uses the hypsometry routine to calculate \( Ve \) and \( Se \) (see Appendix A for details).

If any of the values of ‘Coefficient k (Vp)’ differ from 1 or 0 the code uses the user-defined values in the linear equations noted above.

4.4 Deleting Specific Elements

To delete an element from the ASMITA interface the user should right click on the element to be deleted. From the menu items, select Delete. A popup window will appear asking the user to confirm this action, click yes to permanently delete this element.
4.5 Defining Flow and Diffusion

One of the main drivers within the ASMITA model is the flow and diffusion of sediment into and out of the specified elements, either from one element to another, or to and from the surrounding environment.

Summary of defined Flow pathways:

- Element to Element Flow;
- Environment to Element Flow; and
- Element to Environment Flow.

In order to specify the flow from **Element to Element** the user should right click on the specified element in which they want the flow to originate, and select **Flow** from the popup menu. A window will appear showing the specified element flow arrangement (Figure 15), the user should then click on the element in which they wish the flow to enter. After specifying the second element a textbox will appear on the flow specification window, the user should define the rate here.

To specify flow from **Element to Environment**, the user should follow the method stated above, however, rather than selecting a second element the user should click outside any elements within the ASMITA interface (Outside environment).

To select the **Environment to Element** the user has to access the **Flow** method from the main menu drop down list. The user should select **Setup → Element → Flow**, using the mouse click onto the **Outside Environment**. The user can then select the element in which flow will enter from the outside world.

![ASMITA Interface or Outside Environment](image)

**Figure 15.** Definition of the flow/diffusion through the various pathways
The process is similar for defining the diffusion between elements. However, diffusion is non-directional and so one can either select an element and select **Diffusion** from the popup window, or access the same utility using **Setup → Element → Diffusion**. Popup windows guide the user to select elements and enter diffusion rates. The order in which elements or the Outside Environment are selected does not matter.

### 4.6 Defining Change

Changes can be defined as one or more adjustments to the volume and/or area of individual elements to represent alterations to the system. The user can specify specific periods where a known change in an element may have occurred, for example a capital dredge or some engineering works, or a repeating cycle such as may be needed to represent maintenance dredging.

To specify a change in the element the user should select **Setup → System → Change** (Figure 16). The user is provided with 3 options **New, Edit and Load**, each menu item refers to a excel sheet that can be generated from within the ASMITA interface by selecting **New**.

#### 4.6.1 New

After selecting **New** (Figure 16), a spreadsheet (‘Change.xls’) will be generated. All previous information stored in the ‘Change.xls’ file will be lost, a warning dialog will appear to remind user of this. A separate sheet will be generated for each element that has been defined by the user. Each worksheet (numbered 1 to n) will have the following header information:

<table>
<thead>
<tr>
<th>Ri.fl-flat</th>
<th>Year</th>
<th>Volume</th>
<th>Area</th>
</tr>
</thead>
</table>

The user then selects a year (within the specified simulation period) and the change in area and volume associated with that year. The user must enter the year of change in ascending order e.g. 2000, 2004, 2005 and so on. The user can specify the change to either all elements or a selection of elements.

**Note:**  _The change specified is specific to the number of elements and period of the model. The generation of the ‘Change.xls’ may take several minutes._

#### 4.6.2 Edit/Load

The user can load or edit an existing ‘Change.xls’ file by selecting **Setup → System → Change → Edit/Load**. After selecting either **Edit** or **Load** the ‘Change.xls’ file will open and the user will be able to amend this. The user must then close Excel before moving on to other operations within the ASMITA program. Matlab will determine when the ‘Change.xls’ file has been closed and prompt the user to update the global variables. Selecting yes will update the system change variables within the global defined variables.
5. System Setup

5.1 Properties

System properties are not element dependent, that is to say the information defined within the system properties represents the whole environment. The system properties include:

- Tidal Range;
- Global Sediment Equilibrium Concentration;
- Water Density;
- Sediment Density;
- Sea Level Rise (SLR);
- Cyclic information:
  - Number of cycles;
  - Phase;
  - Amplitude;
  - Period;
- Project Details:
  - Name;
  - Scenario;
  - Date;
  - Tidal amplitude factor (LW/HW)

The user can access the system properties by selecting **Setup → System → Properties** from the menu drop down list (Figure 17). Again, tool tips are provide for system properties information to help assign default values and provide additional background information.
6. Configure Time Step

The number of time steps represents the length of time the simulation will be run. For example, (Figure 18) shows 1120 time steps at an interval of 0.5yrs starting from year 1500. In this example, the model will run for the period 1500 to 2060 and will calculate the change in element areas and volumes at an interval of 0.5 years. The fixed surface check box is used to calculate the volume and areas based on a fixed surface area (defined as the starting level). Leaving this box unchecked means that the surface area varies with time, as well as the volume, in response to the applied conditions.

Summary of time step configuration parameters:

- Size of time step (years);
- Number of time steps (years);
- Start year (year); and
- Fixed surface calculation (optional).
- Equilibrium includes flow (optional)
- Include user defined changes (optional)

To access the time step configuration window select Setup → Time Step from the main menu drop down list (Figure 18).
6.1 Use Fixed Surface Areas (Optional)

When this box is checked, the initial area of each element is treated as a constant. This reproduces the original ASMITA model that only considers changes in volume.

6.2 Equilibrium Includes Flow (Optional)

When a flow through the channel elements (and delta) is specified, this can be considered as a perturbation to the equilibrium condition, or implicit in it. For the former this flag is left unchecked. Where initial values are used to define the equilibrium coefficients (see Section 4.1 and Appendix) it is implicit that the initial condition is being defined as an equilibrium state. By checking this flag, a correction is applied such that, at equilibrium, the rate of change is zero, including the flow.

6.3 Include User Defined Changes (Optional)

Changes to the system imposed by the user for defined years (section 4.6) in the ‘Change.xls' file will be included in the ASMITA equations.
7. Running ASMITA

7.1 Check Input

After defining the individual elements and assigning the element and system properties the user has the option to check the input data and run the ASMITA model. The **Check Input** function checks all data entered to ensure consistency. The diagnostic information is reported back to the Matlab command window (Figure 19), a dialog box will also appear if all values specified with ASMITA are correct. Note the **Check Input** function is called when the user chooses the **Run Model** option. However, it might be more convenient to establish the model setup without actually running ASMITA, in this circumstance the user should select the **Check Input** function. Missing or inconsistent values will be reported to the user who will then be able to address these errors.

To access the **Check Input** function the user should select **Run – Check Input** from the main menu drop down items (Figure 20).

![Diagnostic information](image)

**Figure 19.** The Matlab command window where the diagnostic information is reported back to the user

7.2 Run Model

To run the ASMITA model the user should select **Run → Run Model** from the main menu drop down list (Figure 20).
Figure 20. The Check Input and Run Model menu items

After selecting the Run Model option the ASMITA program will evaluate the data entered by the user. Before the model is initiated the ASMITA program asks for a file name (Figure 21) with NO extension. After running ASMITA there will be two output files. One will be a text file with the setup information and a second spreadsheet file. The spreadsheet will contain results from the model simulation as well as the setup information. The name of both the text and spreadsheet files are identical, except for the file extension.

Figure 21. Dialog box asking for user defined name

8. Results

The results that can be obtained from ASMITA to inform the user of the consequences of an engineering project, dredge, and climate change and so on are the following:
Volumes/Areas:
- Moving Surface Volume/Area (values relative to any changed water level);
- Equilibrium Volume/Area (values that determine the equilibrium condition); and
- Fixed Surface Volume/Area (values relative to a fixed (initial) water level).

9. Plotting Routines

In order to visualise the results generated by the ASMITA model a plotting routine has been developed (Figure 22). To access the plotting routine select **Plot → Plot Results** from the drop down menu item.

There are no limits to the number of plot windows, the user can clear individual windows by clicking on the cross in the top right hand corner. The user can clear all plot windows by selecting the **Tools → Clear → Clear Model** function (Section 3.3). The plotting routines will not allow identical parameters for the same element to be plotted on the same figure. By design, selected parameters will be added to the last active figure.

![Plot Element Specifications](image)

**Figure 22.** Plot specification window, allows the visualisation of ASMITA results

A typical example of the output from ASMITA is displayed in Figure 23. The user can access this data either through Matlab or from the stored data in the spreadsheet.
The output parameters from the ASMITA model are:

**Moving Surface Volume**
The volume below a water level that may rise and fall over the simulation period depending on the input parameters e.g. climate change, nodal cycle and so on\(^1\). The moving surface volume describes the combined morphological and water level change in the element.

**Equilibrium Volume**
This depends on the formulation used to define the equilibrium condition (see Appendix) but is typically some function of the tidal prism. The equilibrium volume describes the volume that the element will try to adjust towards at any given point in time\(^1\).

**Fixed Surface Volume**
The volume below a fixed water level defined by the water level at the start of the simulation\(^1\). The change in volume represents the morphological change in the element.

**Moving Surface Area**
This is the plan area of the element at the water level at each time interval. Like the moving surface volume it reflects both morphological and water level changes.

**Equilibrium Surface Area**
This depends on the formulation used to define the equilibrium condition (see Appendix) but is typically some function of the tidal prism. The equilibrium

\(^1\) This will be a wet/water volume if the transport coefficient for the element is positive, otherwise it will be a dry/sediment volume
surface area describes the area that the element will try to adjust towards at any given point in time.

**Fixed Surface Area** → The surface area at a fixed water level defined by the water level at the start of the simulation. The change in surface area describes the morphological change in the element.

The output parameters from the ASMITA model can be used to inform the following:

- How elements change over time, responding to perturbations (e.g. dredging and reclamations) or ongoing changes (e.g. sea level rise and changes in tidal range).
- The response in a moving frame of reference (moving surface) and fixed frame of reference (fixed surface).
- The morphological phase lag and damping, based on the differences between the moving and equilibrium values.

Volumes, comparisons of the various volumes help the user define the effect of changes to the element. In particular, differences between the fixed and moving surface may inform the user of the effects (import/export of sediment by subtracting the moving from the fixed values) of sea level rise within the specified element.

### 10. Program Structure

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Appendix A

ASMITA Background Understanding
Area and volume changes in an estuary

Introduction

ASMITA (Aggregated Scale Morphological Interaction between a Tidal Basin and the Adjacent coast, Stive et al. 1998) is an approach developed for the study of estuary response to sea level rise. The model is based on an aggregated model that considers the estuary as a box (or set of boxes) that fills and empties under tidal action. The methodology was developed to look at the combined response of tidal delta, channel and tidal flats and has been applied to the impact of sea level rise on tidal inlets (van Goor et al. 2003) and the response of an estuary to the nodal tidal cycle (Jeuken et al. 2003).

This note summarizes the basis of the ASMITA model, combining multiple elements with marine and fluvial sources. In addition the existing ASMITA, which only considers variations in estuary volume, is extended to represent time varying surface area. This allows perturbations to be introduced in the form of changes to the volumes and areas due to interventions such as dredging and reclamation, as well as sea level rise and cyclic variations in the tidal range. The basis of the empirical relationship used to define the equilibrium relationships is also given some further consideration.

Single element volume model

For a single element model, comprising just an estuary channel, the equilibrium state is derived from the equilibrium relationship assumed between the channel volume and the tidal prism:

\[ V_{ce} = f(P) \]  

(1)

Where \( V_{ce} \) is the equilibrium volume of the channel and \( P \) is the tidal prism (Eysink, 1990).

The other assumption made is that the ratio of the actual flow velocity to the equilibrium condition is proportional to the ratio of the equilibrium volume and actual volume. The local equilibrium concentration can therefore be written in terms of the actual volume, \( V \), and the equilibrium volume, \( V_{ce} \):

\[ c_{ce} = c_E \left( \frac{V_{ce}}{V} \right)^n \]  

(2)

Here \( c_{ce} \) is the local equilibrium concentration, \( n \) is the concentration transport exponent and \( c_E \) is the equilibrium concentration for the system as a whole (usually taken as the open boundary value). The difference between the actual concentration and the local equilibrium value induces morphological change governed by the exchange between the water column and the bed:

\[ \frac{dV}{dt} = wS(c_{ce} - c) \]  

(3)

Where \( w \) is the vertical exchange coefficient, \( S \) is the surface or plan area of the channel and \( c \) is the actual concentration. If we now consider a sediment balance where the (long-term residual) sediment transport between elements is assumed to be simply diffusive (in this case the channel and the external environment):

\[ wS(c_{ce} - c) = \delta_{eo}(c - c_E) \]  

(4)
The parameter $\delta$ is the horizontal exchange coefficient and the r.h.s. of equation (4) represents the exchange with the external environment.

Combining equations (2)-(4) and adopting a simple linear relationship for equation (1) of the form $V_e = \alpha P$, where $\alpha$ is an empirical coefficient, the moving surface volume, $V_m$, is given by:

$$\frac{dV_m}{dt} = \frac{w\delta c_E S}{\delta + wS} \left[ \left( \frac{V_e(t)}{V_m(t)} \right)^n - 1 \right] + \frac{d\zeta}{dt} S + i\omega \frac{\eta}{2} e^{i\omega t} \cdot S$$

(5)

Which includes the variation in volume due to sea level rise and the some cyclic variation in tidal range, such as the nodal tidal cycle.

In this form, the equilibrium volume, $V_e$, and the fixed surface volume, $V_f$ can be written:

$$V_e(t) = \alpha \cdot P = V_o + \alpha \cdot \Delta P$$

$$\Delta P = \eta \cdot e^{i\omega t} \cdot S$$

$$V_f(t) = V_m(t) - \frac{d\zeta}{dt} S \cdot t - \frac{\eta}{2} e^{i\omega t} \cdot S$$

(6)

Where the variables are defined as follows:

- $V_e$ – equilibrium volume
- $V_o$ – initial volume at time $t=0$
- $V_m$ – moving surface volume
- $V_f$ – fixed surface volume
- $P$ – tidal prism
- $\zeta$ – vertical sea level movement
- $\omega$ – angular frequency of nodal tide
- $\eta$ – amplitude of nodal tide
- $S$ – surface area of basin
- $n$ – sediment transport exponent, usually taken as ~2.
- $w$ – vertical exchange rate
- $\delta$ – horizontal exchange rate
- $c_E$ – global equilibrium concentration

In this simple model the plan area is treated as constant. On the basis that $V_e \sim f_n(P)$ any hydraulic changes that result in a change in tidal prism are represented in $V_e$ but those that change the volume of the system (such as sea level rise, dredging or reclamation) are represented in $V_m$.

The variation in equilibrium, moving and fixed estuary volumes, due to a linear rise in sea level and the nodal tidal cycle, are illustrated in Figure 1. The lag and damping of the response, relative to the equilibrium volume, is due to the dynamics associated with the morphological response time of the estuary (Jeuken et al. 2003).

The reduction of the volume relative to a fixed surface, shown in Figure 1, reflects the infilling of the basin that takes place, in order for the morphology to warp up vertically to keep pace with sea level rise (and the superimposed nodal cycle). Thus, vertical translation of the system is incorporated in this model. If, however, we wish to include the possibility of horizontal translation, as well as the vertical response, it is necessary to adjust the plan area rather than treat it as constant.

In this formulation, the morphological timescale is determined by $n$ and $c_E$. In addition, the horizontal exchange is related to the vertical exchange as a function of hydraulic depth and velocity. This means that by defining the vertical exchange, $w$, and the sediment transport exponent, $n$, based on the sediment characteristics of the estuary, and the global equilibrium concentration, $c_E$, to give the correct morphological time scale, the horizontal exchange coefficient is scaled by some factor, $\varepsilon$, to calibrate the model (see Wang et al. 2007 for further details).
Multi-element volume model

The basic concept of the multi-element model is to subdivide the estuary into a number of elements and define the exchanges between elements and the equilibrium conditions for each element. As already noted, this has been presented in the literature as the ASMITA model (Aggregated Scale Morphological Interaction between a Tidal basin the Adjacent coast) and was introduced by Stive et al (1998; see also van Goor et al. 2003; and Kragtwijk et al. 2004). The system can be schematised into any number of discrete elements, which might be sections along the channel as used in ESTMORF (Wang et al. 1998), or geomorphological components, such as the channel and tidal flats as typically used in ASMITA. This is illustrated in Figure 2, which shows the linkage between tidal flat, channel and tidal delta through to the open sea, referred to as the outside world. For each component the volume can be defined in terms of the sediment or water volume. In the derivation presented here, only water volumes are used and the equations presented reflect this (for the more general case see the papers noted above). So, for example, the scheme shown in Figure 2 would be represented by:

Tidal delta - total water volume over delta (where the delta has a volume relative to undisturbed coastal bed)
Channel - total water volume below MLW
Tidal flats - total water volume between MLW and MHW over flats (i.e. not including the prism over the channel)

The variation in these volumes depends on the transport of sediment in and out of the elements and any changes to the water volume itself. The latter may be due to sea level rise, subsidence of the bed, or any form of progressive change in the basin volume. Hence, over the long-term (time scales much longer than a tidal cycle) the rate of change of the element volume depends on the residual flux, the change in sea level as follows and any change in tidal range:

\[
\frac{dV_j}{dt} = \sum_i J_{i,j} + S_i \frac{d\zeta_j}{dt} + S_j \frac{d(\text{tr})}{dt}
\]

where \( J \) is the sediment volume flux between elements \( i \) and \( j \), \( S \) is the plan area of the element and \( \zeta \) is the elevation of mean sea level. The residual sediment flux between two elements is assumed to have advective and diffusive components:

\[
J_{i,j} = q_{i,j} \cdot c_i - q_{j,i} \cdot c_j + D_{i,j} A_{i,j} \frac{\partial c}{\partial x}
\]

where \( q \) (m³·s⁻¹) is the residual discharge rate (\( q_{i,j} \neq q_{j,i} \)), \( D \) (m²·s⁻¹) is the diffusion coefficient between the two elements, \( A \) (m²) is the vertical area of the interface between the two elements and the sign convention reflects the change to the water volume. This can be written in a form similar to the r.h.s. of equation (4):

\[
J_{i,j} = q_{i,j} \cdot c_i - q_{j,i} \cdot c_j + \delta_{i,j} (c_i - c_j)
\]

In equations (8) and (9) the subscripts \( i \) and \( j \) refer to the elements the transport is from and to respectively. The advective component assumes that the concentration of the flux is that of the element supplying the sediment, which is important for external inputs such as from the rivers. In contrast the diffusive component simply uses the gradient between the elements.
The equations presented for the single element model can be conveniently written in matrix form to represent a multi-element model. Here we follow the naming convention of Kragtwijk et al (2004) for volumes and add some additional terms to make the model more general with respect to diffusion, advection and the sources of perturbations in the volume.

Vectors are defined for a number of the variables as follows:

- \( V \): element volumes
- \( \gamma \): volume ratios \((V_{ke}/V_{k})^n\)
- \( S \): element surface areas
- \( \sigma \): surface area ratios \((S_{ke}/S_{k})^{abs(n)}\)
- \( c_e \): local equilibrium concentrations
- \( \delta_E \): horizontal exchange coefficients with environment
- \( \epsilon \): element concentrations
- \( n \): concentration transport exponent, positive for wet volumes and negative for sediment volumes
- \( c_{ext} \): concentrations for fluxes into the system from the environment

In addition use is made of the following diagonal matrices:

- \( W \): vertical exchange coefficient \( w \);
- \( S \): surface areas;
- \( I \): unit or identity matrix;
- \( M \): unit matrix with sign of \( n \).

The matrix \( D \) reflects the structure of the horizontal exchange between elements and with the outside world. For an \( n \)-element system with all elements linked and exchanging sediment with external environments, this would take the following form:

\[
D = \begin{pmatrix}
\sum \delta_{1,n} + \delta_{1,E} & -\delta_{1,2} & \ldots & -\delta_{1,n} \\
-\delta_{2,1} & \sum \delta_{2,n} + \delta_{2,E} & \ldots & -\delta_{2,n} \\
\vdots & \vdots & \ddots & \vdots \\
-\delta_{n,1} & -\delta_{n,2} & \ldots & \sum \delta_{n,n} + \delta_{n,E}
\end{pmatrix}
\]

(10)

For a 3-element system in which only element 3 is connected to the external environment (e.g. a tidal flat, channel and delta) this would take the form:

\[
D = \begin{pmatrix}
\delta_{1,2} & -\delta_{1,2} & 0 \\
-\delta_{2,1} & \delta_{2,1} + \delta_{2,3} & -\delta_{2,3} \\
0 & -\delta_{3,2} & \delta_{3,2} + \delta_{3,E}
\end{pmatrix}
\]

(11)

For diffusion the matrix is symmetric because \( \delta_{ij} = \delta_{ji} \) and the direction of transport depends on the concentration gradient. However, for residual discharge the transport has a specified direction and as already noted we adopt the convention of transport from element \( i \) to element \( j \). The matrix for an \( n \)-element system is then given by:
\[
Q = \left( \begin{array}{cccc}
\sum q_{1,n} + q_{1,E} & -q_{1,2} & \cdots & -q_{1,n} \\
-q_{2,1} & \sum q_{2,n} + q_{2,E} & \cdots & -q_{2,n} \\
\vdots & \vdots & \ddots & \vdots \\
-q_{n,1} & -q_{n,2} & \cdots & \sum q_{n,n} + q_{n,E}
\end{array} \right)
\]

(12)

Where \(q_{n,E}\) all relate to fluxes out of the system. In order to ensure continuity of water mass we also require that, for each element, the sum of the discharges in and out of the element is zero, i.e. \(\Sigma q_i = 0\).\(^1\)

The basic equations can now be written:

\[
\frac{dV}{dt} = \text{MWS}(c_e - \bar{c})
\]

\[
(D + Q^T)c = \text{WS}(c_e - \bar{c}) + c_E(\delta_{ext} + k_{c_e} \cdot q_{ext})
\]

(13)

From which the following expression can be derived for the rate of change of volume (note the vector \(\bar{d}\) has the opposite sign to that given in equation (17) of the paper by Kragtwijk et al):

\[
\frac{dV}{dt} = B\bar{r} - d + S \frac{dc_e}{dt} + S \times \text{trs} \frac{d(\bar{r})}{dt} + \Delta V
\]

where

\[
B = c_E \text{MWS}(I - (D + Q^T + WS)^{-1} WS)
\]

\[
d = c_E \text{MWS}(D + Q^T + WS)^{-1}(\delta_{ext} + k_{c_e} \cdot q_{ext})
\]

(14)

Here \(\bar{r}\) refers to the tidal range and the expression \(\times \text{trs}\) refers to element by element multiplication by \(\frac{1}{2}\) with a sign that reflects whether the element is influenced by high or low water. The term \(\Delta V\) refers to any other changes in volume, introduced at any given time, within each element, e.g. due to reclamation or dredging.

Equilibrium and fixed volumes then have a similar form to equation (6), where \(\delta r\) is the variation in the tidal range from its mean value:

\[
V_e = \alpha \cdot P = V_o + \alpha \cdot \Delta P
\]

\[
V_f = V_o - \bar{S} \cdot \zeta - \bar{S} \times \text{trs} \cdot \delta r
\]

(15)

The relationship between estuary volume and surface area

As estuaries vary throughout their length, the change in depth is generally much smaller than the change in width. This obvious statement induces a corollary that the tidal, wave, fluvial and geotechnical effects that define an estuary geometry induce much larger changes to the width of a cross-section than to the depth. In addition, the downstream part of an estuary, which is predominantly tidal, tends to experience less proportional change in depth with distance than the head

\(^1\) However, provision is made for the sediment concentrations associated with these discharges to vary.
of an estuary which is much more affected by fluvial discharges. Since the volume and surface area within an estuary tend to be dominated by the much wider and deeper downstream reaches, where cross-section area correlates highly with width, estuary volume also tends to correlate highly with surface area.

Figure 3 indicates how in simple terms a change ($\delta A$) in channel cross-section area can be related to the change in width ($\delta W$), i.e. $\delta A = h \cdot \delta W$. Because of the above arguments it is possible to extend this idea to surface area ($S$) and volume ($V$), i.e. $\delta V = h \cdot \delta S$. Moreover the same argument can be made for change in tidal flat volume and surface area.

**Variable Surface Area**

For a single element (such as a channel) linked to the open sea, the above arguments lead to the following expression (in the absence of sea level rise and tidal node variation):

$$\frac{dS}{dt} = \frac{1}{h} \cdot \frac{dV_m}{dt} = \frac{1}{h} \cdot \frac{w \cdot \delta c_x S}{\delta + wS} \left(\frac{V_m(t)}{V_m(t)}\right)^n - 1 = \frac{\hat{w} \cdot \delta c_x S}{\delta + \hat{w}S} \left(\frac{S_m(t)}{S_m(t)}\right)^n - 1$$

where:

$$\hat{q} = \frac{q}{h}; \quad \hat{\delta} = \frac{\delta}{h} \quad \text{and} \quad \hat{w} = \frac{w}{h}$$

The effect of sea level rise and nodal tide variation is included by considering the change in surface area that arises from a change in mean sea level and a change in tidal range. The non-linear equations (for the single element model) describing the variation in surface area are therefore similar to equation (5) and (6) for volumes, viz:

$$S_e(t) = \hat{\alpha} \cdot \frac{P}{\tau r} = S_o + \hat{\alpha} \cdot \frac{\Delta P}{\tau r}$$

$$\frac{dS_m}{dt} = \frac{\hat{w} \cdot \hat{\delta} c_x S}{\hat{\delta} + \hat{w}S} \left(\frac{S_e(t)}{S_m(t)}\right)^2 - 1 + \frac{dS}{dt} \cdot R + \frac{\eta}{2} e^{i\omega t} \cdot R$$

The parameter $R$ represents the change in area for a unit change in water level and is given by $R = k L m_b$, where $k$ is the number of bed surfaces in the element (generally 2 for the two sides of the estuary), $m_b$ is the transverse bed slope (i.e., slope is given by the ratio 1:$m_b$) and $L$ is the length of the element.

As for volumes, this can be applied to multiple elements, extended to include advective flow, and the rate of change for the surface area $S$, is given by:
\[
\frac{dS}{dt} = F \sigma - e + R \frac{d\zeta}{dt} + R \times trs \frac{d(tr)}{dt} + \Delta S
\]

where

\[
F = c_p M\hat{W}S(I - (\hat{D} + \hat{O}^\tau + \hat{W}S)^{-1}\hat{W}S)
\]

\[
e = c_p M\hat{W}S(\hat{D} + \hat{O}^\tau + \hat{W}S)^{-1} \cdot (\hat{\zeta}_{ext} + k_{\zeta} \hat{q}_{ext})
\]

\[
\sigma = \left( \frac{S_e}{S_m} \right)^{abs(n)}
\]

where \(\hat{D}, \hat{\zeta}_{ext}, \text{and} \hat{W}\) are derived from \(D, \delta_{ext}\) and \(W\) in accordance with equation (17).  The equilibrium and fixed surface areas then have a similar form to equation (15):

\[
S_e = \hat{\alpha} \cdot P = S_m + \hat{\alpha} \cdot \Delta P
\]

\[
S_f = S_m - R \cdot \zeta - R \times trs \cdot \delta tr
\]

**Tidal Prism Relationships**

Equation 1 postulates a link between the equilibrium volume and the tidal prism.  Similarly the value of the equilibrium surface area \(S_e\) in Equation 17 is likely to vary with the tidal prism.  Townend (2005) showed that the tidal prism exhibits a strong correlation with the plan area and volume of the estuary.  From a sample of 66 UK estuaries he found that the total surface area, total volume and tidal prism exhibited the following relationships:

\[
S_{mtl} = 0.42P^{0.96}, \quad R^2 = 0.92; \quad (21)
\]

\[
V_{mtl} = 0.073P^{1.13}, \quad R^2 = 0.92.
\]

The elements used within ASMITA comprise deltas, channels and tidal flats.  The UK estuaries database suggests that the channels and flats (when represented as a single element) can be adequately represented by simple linear relationships with exponents of one:

**Table 1 Linear form-prism ratios**

<table>
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<th>Volume</th>
<th>R²</th>
<th>Surface Area</th>
<th>R²</th>
</tr>
</thead>
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<tr>
<td>Channel</td>
<td>(V_c = 0.418P)</td>
<td>0.93</td>
<td>(S_c = 0.076P)</td>
<td>0.95</td>
</tr>
<tr>
<td>Tidal flats</td>
<td>(V_f = 0.163P)</td>
<td>0.74</td>
<td>(S_f = 0.077P)</td>
<td>0.47</td>
</tr>
</tbody>
</table>

However, individual estuaries can have values significantly different from the above.  The following are the average values for the Humber over the period 1851-2000 (based on 22 bathymetric data sets) with standard deviations indicating a small variation over time:

**Table 2 – Linear form-prism ratios for the Humber Estuary**

<table>
<thead>
<tr>
<th></th>
<th>Volume</th>
<th>St.dev</th>
<th>Surface Area</th>
<th>St.dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>(V_c = 0.738P)</td>
<td>0.021</td>
<td>(S_c = 0.130P)</td>
<td>0.003</td>
</tr>
<tr>
<td>Tidal flats</td>
<td>(V_f = 0.249P)</td>
<td>0.011</td>
<td>(S_f = 0.067P)</td>
<td>0.003</td>
</tr>
</tbody>
</table>
One of the strongest correlations revealed by the UK data is between the surface area at mean tide level, prism and tidal range, which takes the form:

\[ S_{\text{mtl}} = 1.07 \frac{P}{tr} \quad (R^2 = 0.996) \]  \hspace{1cm} (22)

This implies that the tidal prism is essentially the plan area at mean tide multiplied by the tidal range (particularly for the larger estuaries with \( P > 10^7 \text{m}^3 \)) and that the cross-shore shape of the intertidal is of secondary importance. Although the regression is strong it must be recognised that the error in predicting the plan area of an individual estuary can still be ±30% based on this data set, with most of the data points falling below this forced regression line (i.e. exponent=1 and intercept=0). The surface area at low water is also reasonably well represented by this form of relationship but the area of the tidal flats shows a poorer correlation, Table 3. The coefficients specific to the Humber are similar for the mean tide and channel (mlw) relationships but differs significantly for the tidal flats.

| Table 3 Linear form-prism ratios for surface area as a function of P/tr |
|------------------|----------------|----------------|
|                  | UK estuaries | Humber estuary |
| Channel          | \( S_c = 0.775P/tr \) | \( S_c = 0.733P/tr \) |
| Tidal flats      | \( S_f = 0.945P/tr \) | \( S_f = 0.386P/tr \) |
| Mean tide level  | \( S_{\text{mtl}} = 1.07P/tr \) | \( S_{\text{mtl}} = 0.96P/tr \) |

**Hypsometry Relationships**

An alternative approach is to use the equilibrium hypsometry relationships for channels (Cao & Knight, 1997) and tidal flats (Friedrichs & Aubrey, 1996) to define the form of the estuary cross-section. The resulting relationships can then be written in terms of volume and surface area by considering a representative length. Some trials for a number of estuaries suggest that this form description provides a reasonable characterisation of estuary cross-sections.

Friedrichs and Aubrey (1996) show that the lower intertidal width is a function of the equilibrium flow velocity and the angular tidal frequency: \( (w_o - w_{lw}) = \frac{u_{eq}}{\omega} \). This implies that the lower intertidal width reflects flow field, the erodibility of the sediments and the rate of convergence of the estuary. We therefore assume that the slope of the lower intertidal is a characteristic value, which in terms of surface area is given by:

\[ m_{eq} = \frac{S_{\phi} - S_{lv}}{2\eta} \]  \hspace{1cm} (23)

Using the initial estuary surface areas at mtl and lw, with the tidal range, the equilibrium slope can be calculated using equation (23). Similarly, the d-n ratio = \( (d-\eta)/(n+1) \) can be obtained as the ratio of the volume and area at low water. If the slope and d-n ratio are treated as being constant, equations (24) can be used to derive updated equilibrium volumes and areas for the channels and flats given a new value of the tidal prism.

\[ S_{lv} = \frac{1}{2\eta} \left( V_p - (1 + \pi) \cdot \eta^2 m_{eq} \right) \quad V_{lv} = \frac{d-\eta}{n+1} \cdot S_{lv} \]
\[ S_{\phi} = \left(1 + \frac{\pi}{2}\right) \cdot 2\eta \cdot m_{eq} \quad V_{\phi} = (1 + \pi)\eta^2 m_{eq} \]  \hspace{1cm} (24)

Fitting (24) to the UK estuaries database produces reasonable fits to the data. In particular, \( V_{lv} \) is well represented and the fit lines go through the centre of the data, whereas for \( V_{\phi} \), and \( S_{\phi} \) the fitted lines represent lower bounds.
Basis of equilibrium volumes and areas in ASMITA

The ASMITA model, as presented, makes use of the general nature of the results described above and provides the user a number of options.

(i) Equilibrium based on linear tidal prism functions
This method assumes that the governing equation for equilibrium volume is a linear function of the tidal prism and for surface area is a linear function of prism/tidal range. The user is able to set the values of the proportionality coefficients separately for each element. In the code the default values for these coefficients are 1 and if these are used, the routine calculates the coefficients from the initial values of volume, surface area, tidal prism and tidal range for each element. Thereafter, the coefficients are treated as constants. (NB: This uses the individual element volume or surface area as a proportion of the total upstream tidal prism.)

(ii) Equilibrium based on hypsometry functions
This method uses the initial values of volume, surface area, tidal prism and tidal range to calculate the equilibrium slope and the d-n ratio, as defined above. These values are then treated as constants and the equations for the equilibrium hypsometry (24) are used to compute volumes and areas for the channels and flats, taking account of change in tidal range and tidal prism. The method is activated by setting the volume equilibrium coefficients for every element to zero.

References


Figure 1 – Variation in estuary volume for rising sea level and nodal tidal cycle as predicted by the single element model.

Figure 2 – Schematic of elements for a tidal inlet as used in the ASMITA model.
Figure 3 – Sketch to illustrate relationship between changes in width and cross-sectional area

![Sketch of relationship between changes in width and cross-sectional area](image)

- $\delta W/2$
- $\delta A_{\text{flat}}$
- $\delta A_{\text{chan}}$
- $h$
- $h'$

Figure 4 – Tidal prism ratios for Cross-section area, Surface area and volume along the Humber estuary

![Graph of tidal prism ratios](image)

- Distance from mouth (km)
- Surface area
- Volume
- CSA
- $A-P$ ratio