Modelling transport of cohesive and non-cohesive sediments in the Mersey Estuary

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Abstract

The Mersey Estuary has been one of the most polluted estuaries in the world for decades. A project is now underway to attempt to restore water quality in the estuary. As part of this project a detailed water quality modelling project was undertaken. The models developed were used to simulate various materials in the estuary, including nutrients, sediments, heavy metals and persistent organic chemicals.

This paper describes work undertaken by the authors into developing a sediment transport model of the Mersey Estuary. Suspended sediments in the Mersey are composed of two main sources: sediments discharged into the estuary from outfalls etc. and resuspension of bed sediments. The bed sediments are contaminated with heavy metals and hence they are of particular interest. During mid-flood and mid-ebb tides strong tide-induced currents create high bed shear stress causing relatively large volumes of resuspended sediments. These sediments are transported about the estuary and, mostly, settle to the bed during periods of quiescent hydrodynamic activity. This is a complex system to model and highly important when performing the subsequent heavy metal simulation analyses. The authors outlined how the sediment modelling was executed and present typical modelling results.

Keywords: hydrodynamics, sediment transport, cohesive and non-cohesive sediments, Mersey Estuary.

1 Introduction

The Mersey Estuary, situated in northwest England, is one of the largest estuaries in the United Kingdom, with a catchment of some 5,000km^2, including the major cities of Liverpool and Manchester.

The estuary may be described physically in three separate sections. The Upper Estuary, between Warrington and Runcorn is a narrow meandering channel of approximately 15km in length. Below Runcorn, the estuary opens into a wide shallow basin to form the Inner Estuary, approximately 20km in length, with extensive inter-tidal banks and a large salt marsh on its southern edge. Downstream, the estuary converges to form The Narrows, a straight narrow channel up to 30m deep. Seaward of The Narrows the channel broadens to form the Outer Estuary, a large area of inter-tidal sand and mud banks, NRA [1].

The Mersey Estuary is a macro-tidal estuary with tidal ranges recorded at Gladstone Dock varying from 10.5m on extreme spring tides to 3.5m on extreme neap tides. Freshwater flow from the River Mersey into the estuary varies from approximately $10\text{m}^3/\text{s}$ to $500\text{m}^3/\text{s}$ at the extremes. These extreme values occur rarely, with more typical flows being in the range $20\text{-}60\text{m}^3/\text{s}$.

The numerical model developed by MarCon Computations International Ltd., includes the estuary from New Brighton at the seaward end to the tidal limit at Howley Weir. The numerical model simulated the hydrodynamic regime in the estuary along with the transport of nutrients, sediments, heavy metals, and persistent organics throughout the estuary. The estuary was represented in the numerical model by a mutually orthogonal horizontal grid. The grid spacing was set at 100m resulting in a model domain of 215 x 308 grid squares, or 66,220 computational grid points. Details of model development were described in the project Progress Reports No.'s 1 and 2.

2 Hydrodynamic model

The hydrodynamic model was calibrated by comparing model predictions against field measurements of water surface elevations and water currents for given environmental conditions. The empirical coefficients tuned to calibrate the model were:

momentum correction factor
bed roughness
eddy viscosity.

When executing the model, measured tidal elevations were specified at the northern open sea boundary and the 10-day average river flow from the River Mersey was specified as the eastern river boundary. Comparison between model predictions and recorded data were made at six locations through the estuary.

In comparing model results against field data, for the purpose of water elevation calibration, the following allowable error ranges were applied:

- Calibration of elevations to within 15% of Spring Tides or 20% of Neap Tides
- Timing of high water at the mouth to within ±15mins; ±20mins at the head.

The hydrodynamic dataset used for the calibration of the water surface levels in the hydrodynamic module of the numerical model was collected on 18th September 1989. The details of this recorded data set are tabulated below in Table 1.

Table 1: Water elevation calibration dataset.

Dataset	Details
Date	18/09/1989
Time	06:30-19:30
Tide	Spring
Tidal Range	9.36m
Mersey Flow (10 day average)	1,050x10^3 m^3/day

The values of the empirical coefficients used in the model calibration simulations, along with their associated recommended ranges, are presented in Table 2.

Table 2: Hydrodynamic calibration coefficients.

Empirical Coefficient	Calibrated Value(s)	Recommended Range
Momentum correction factor	1.016	1.016 – 1.200
Coefficient of eddy viscosity	1.0	0.15 – 100
Bed roughness length	Varying linearly from 100mm at open sea to 50mm at tidal limit	5– 200mm

The comparisons between model predicted water elevations and recorded elevations for model calibration at one location, Eastham, is presented in Figure 1. This represents typical calibration for the whole model domain.

In comparing model results against field data, for the purpose of water current calibration, the following allowable error ranges were applied:

- Calibration of current speeds to within ±10-20% of observed speeds
- Calibration of current directions to within ± 20 degrees of observed direction

As DIVAST is a two dimensional numerical model in the x and y plane, the water current velocity calculated in the water body is a depth averaged velocity, Falconer and Liu [2]. The recorded data used for calibration purposes was recorded at a number of depths through the water column. This recorded data was averaged over the depth of the water column prior to the model predicted depth averaged current velocity being calibrated against it. The hydrodynamic dataset used for the calibration of the water currents in the hydrodynamic module of the numerical model was collected on 22nd May 2000 at Eastham. Tabulated below are the details of this recorded data set.

The comparisons between model predicted water currents, (depth averaged), and recorded current, (depth averaged), for this date, are presented in Figure 2 for Eastham; similar correlations were obtained at other locations. The empirical coefficients were unchanged from those used in the calibration of the water surface elevations.

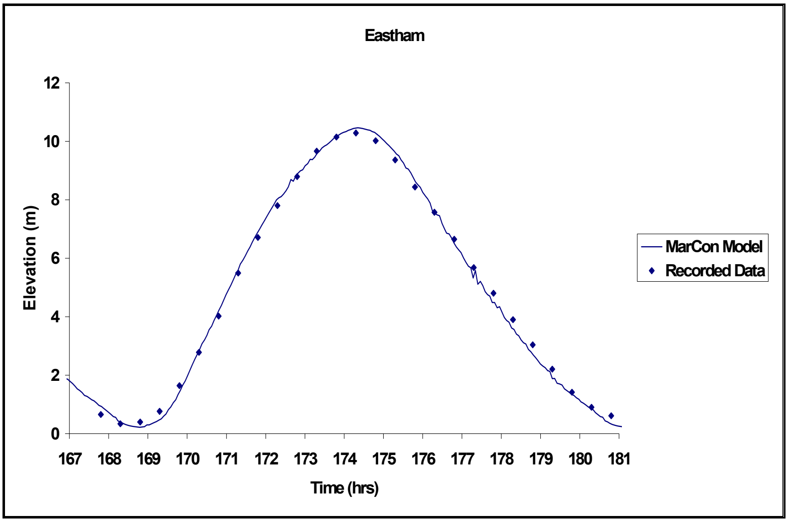

Figure 1: Water elevation calibration at Eastham.

Table 3: Velocity calibration dataset.

Dataset	Details
Date	22-23/05/2000
Time	13:30 – 02:11
Tide	Recorded
Tidal Range	5.7mm
Mersey Flow	Recorded

3 Sediment transport model

The sediment transport processes in the model DIVAST are divided into cohesive sediment transport and non-cohesive sediment transport. For cohesive sediment the two-dimensional depth-averaged equation is given as:-

$$\frac{\partial SH}{\partial t}+\frac{\partial SUH}{\partial x}+\frac{\partial SVH}{\partial y}-\frac{\partial}{\partial x}\left[HD_x\frac{\partial S}{\partial x}\right]-\frac{\partial}{\partial y}\left[HD_y\frac{\partial S}{\partial y}\right]=q_{ero}+q_{dep} \tag{1}$$

where S = depth-averaged cohesive sediment concentration; q_{dep}, q_{ero} = the deposition and erosion rates respectively, which calculated by the following equations:-

$$q_{dep} = \begin{cases} -w_s S_b \left(1 - \dfrac{\tau_b}{\tau_d} \right), & \tau_b < \tau_d \\ 0, & \tau_b \geq \tau_d \end{cases} \qquad (2)$$

$$q_{ero} = \begin{cases} E \left(\dfrac{\tau_b}{\tau_e} - 1 \right), & \tau_b > \tau_e \\ 0, & \tau_b \leq \tau_e \end{cases} \qquad (3)$$

where τ_b = the bed shear stress, τ_d = the critical shear stress beyond which there is no further deposition, τ_e = the critical shear stress for erosion, S_b = the near-bed cohesive sediment concentration, and E = the erosion constant ($kg\ m^{-2}\ s^{-1}$).

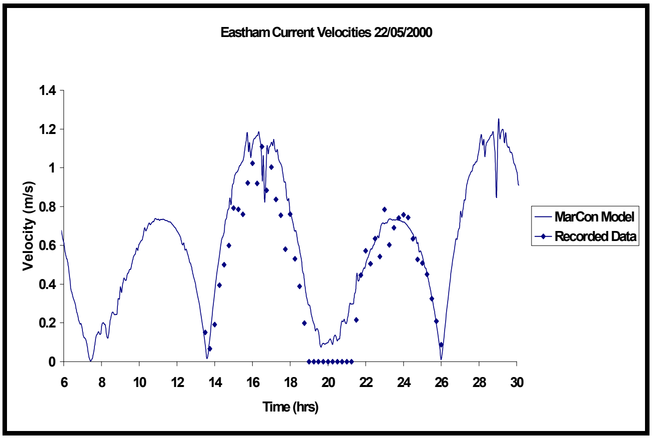

Figure 2: Current speed calibration at Eastham.

For the non-cohesive sediment transport, the depth-averaged equation is give as:-

$$\frac{\partial SH}{\partial t} + \frac{\partial SUH}{\partial x} + \frac{\partial SVH}{\partial y} - \frac{\partial}{\partial x}\left[HD_x \frac{\partial S}{\partial x} \right] - \frac{\partial}{\partial y}\left[HD_y \frac{\partial S}{\partial y} \right] = E_{ae} - w_s S \qquad (4)$$

where S = depth-averaged non-cohesive sediment concentration and w_s = settling velocity.

In modelling non-cohesive sediment transport, the sediment bed boundary is usually given at a small reference level above the bed, and then the reference concentration or gradient of the sediment concentration is prescribed by its equilibrium value at this reference level. A wide variety of relationships exist in the literature for predicting the near-bed reference concentration of suspended sediment, from which the entrainment rate of bed sediment flux into suspension can be obtained. The equilibrium reference sediment concentration expression used in this study was given by van Rijn (1984) and reads as:-

$$S_{ae} = 0.015 \frac{D_{50} T^{1.5}}{a D_*^{0.3}} \tag{5}$$

where S_{ae} = equilibrium reference sediment concentration; D_{50} = sediment diameter of which 50% of the bed material is finer; T = transport stage parameter; D_* = particle parameter.

The suspended sediment erosion, deposition, and transport in the numerical model were calibrated by comparing model predictions against field measurements of suspended sediment concentrations for given environmental conditions. To simulate sediment fluxes in the estuary both cohesive and non-cohesive sediments were considered. In the Upper Estuary, between Warrington and Runcorn, the sediment is considered as cohesive. The rest of the estuary is considered to contain non-cohesive sediment. The empirical coefficients tuned to calibrate the model were:

- empirical erosion constant
- critical shear stress for erosion
- critical shear stress for deposition.

The sediment size distribution used in the non-cohesive model was derived from up-to-date data supplied by the Environment Agency. Based on this data, the size distribution specified to the model was as follows: D_{16} = 10μmD_{50} = 50μm, D_{84} = 175μm and D_{90} = 205μm. The cohesive floc size was specified to the model as 64μm.

When running the model, tidal elevations were specified at the northern open sea boundary commensurate with measured tidal dynamics and the 10-day average river flow from the River Mersey was specified as the eastern river boundary. The suspended sediment transport aspect of the numerical model was calibrated by comparing suspended sediment concentrations as calculated by the model against field measurements. Comparison between model predictions and recorded data were made at six locations along the estuary. These locations are defined in Figure 3.

The dataset used for the calibration of the suspended sediment concentration levels in the numerical model was collected on 18th September 1989. The details of this recorded data set are tabulated above in Table 1. The values of the empirical coefficients used in the model calibration simulations are presented in Table 4.

The comparisons between model-predicted total sediment concentrations and recorded total sediment concentrations are presented in Figures 4-5. Comparisons between recorded and measured concentrations at other locations are similar.

Subsequent to model calibration, further data were used to validate model predictions; correlations between model predictions and data during the validation process are similar to the correlations shown in Figures 4 and 5.

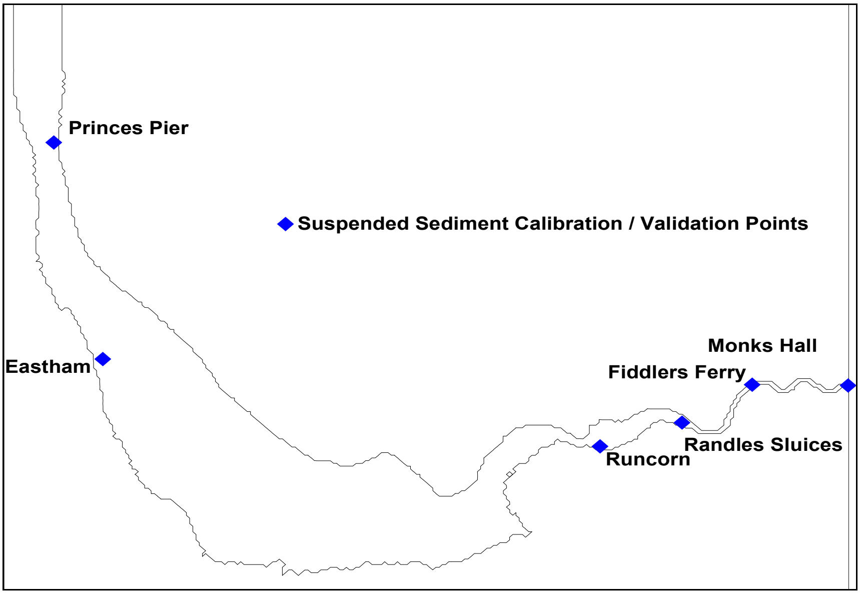

Figure 3: Locations for suspended sediment calibration.

Table 4: Sediment calibration coefficients.

Empirical Coefficient	Calibrated Value(s)
Empirical erosion constant	0.00004 kg/N/s
Critical shear stress for erosion	1.500 N/m^2
Critical shear stress for deposition	0.250 N/m^2

4 Conclusions

The developments outlined above illustrate that an accurate sediment transport model has been developed for the Mersey Estuary. The developments have shown that the model DIVAST can be used with good accuracy to predict resuspended bed sediments from macro-tidal estuaries such as the Mersey. This is extremely important, particularly with regards to the Mersey Estuary, as heavy metals have accumulated in the bed sediments during the course of the last century and more. In order to be able to model heavy with confidence it was vital to accurately model sediment transport in the first place. The authors have used the sediment transport model in conjunction with a model to simulate the transport and distribution of 6 heavy metals. Details of this work will be published in due course.

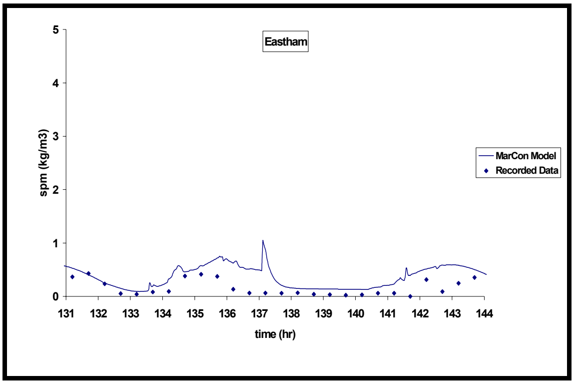

Figure 4: Suspended sediment calibration at Eastham.

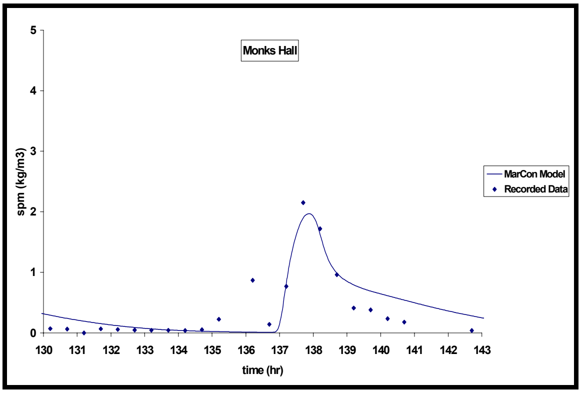

Figure 5: Suspended sediment calibration at Monks Hall.

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