

EstProc

**Implementation of Manning algorithm for settling velocity
to an estuarine numerical model**

Produced within Defra Project FD1905 (EstProc)

J Baugh

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Summary

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Implementation of Manning algorithm for settling velocity to an estuarine numerical model
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An important element within the EstProc studies was the implementation of the new or refined algorithms, produced under EstProc, into numerical models. The implementation stage was important as any extension in the understanding of estuarine processes from EstProc was required to be suitable for dissemination into the wider research community with a level of robustness for general applications demonstrated.

This report describes work done to implement one of the algorithmic outputs of the EstProc project into a 3D computational model of estuarine hydraulics and sediment transport (TELEMAC3D, developed by EDF-LNHE). The algorithm chosen as appropriate to the modelling requirements was the new formulation for settling velocity of mud (Manning, 2004).

For the purpose of implementing the Manning algorithm for settling velocity to an estuarine numerical model an existing model of a length of the Lower Thames estuary was chosen. This model was of interest because it had already been used for comparison of simulated sediment distribution with detailed sediment concentration measurements using the ADCP acoustic backscatter method Sediview, studies which included a number of model sensitivity tests.

The model results with the Manning algorithm included were compared to runs with (1) a constant settling velocity of 0.5 mm/s and (2) settling velocity based on a simple linear multiplier of concentration and with the above mentioned observations of suspended concentration.

The main conclusions of the implementation exercise were:

1. It is feasible to implement a complex relationship between settling velocity and concentration in a 3D computational model of estuarine hydraulics, without producing any significant increase in model run times or reducing model stability.
2. The use of the Manning algorithm greatly improved the reproduction of the observed distribution of suspended concentration both in the vertical and horizontal directions compared to the other simulations.

The application of the Manning algorithm to the Thames suggests that the algorithm is generally applicable to estuarine mud transport modelling. The large amount of data used in the algorithm establishment means that it represents the best presently available method for simulating settling velocity and should be routinely used.

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1. *Introduction*

An important element within the EstProc studies was the implementation of the new or refined algorithms, produced under EstProc, into numerical models. The implementation stage was important as any extension in the understanding of estuarine processes, gained under EstProc should be suitable for dissemination into the wider research community and demonstrated to be sufficiently robust for general application.

This report describes work done to implement one of the algorithmic outputs of the EstProc project into a 3D computational model of estuarine hydraulics and sediment transport (TELEMAC3D, developed by EDF-LNHE). The algorithm chosen as appropriate to the modelling requirements was the new formulation for settling velocity of mud (Manning, 2004).

For the purpose of implementing Manning algorithm for settling velocity to an estuarine numerical model an existing model of a length of the Lower Thames estuary was chosen. This model was of interest because it had already been used for comparison for sediment distribution with detailed sediment concentration measurements using the ADCP acoustic backscatter method Sediview including a number of model sensitivity tests.

As much of the material included in this report is fully described elsewhere. This report only briefly describes the observations, the model and the implementation of the Manning algorithm. The comparisons between the various model representations of settling velocity and the observations are then shown and conclusions drawn.

1.1 BRIEF DESCRIPTION OF OBSERVATIONS

The acoustic theory has been developed in a number of places, e.g. Thorne et al. (1991), Sheng and Hay (1988), Richards et al. (1996). Until relatively recently, the majority of successful applications have used relatively short-range, bed-mounted devices for detailed studies of near-bed sediment transport processes. The Sediview Method, used here, has been developed, using an approach provided to DRL by Thorne (1993), for vessel-mounted, longer-range applications (up to 100 metres or more).

The Port of London Authority commissioned HR Wallingford (HR) and Dredging Research Ltd (DRL) to undertake a demonstration Sediview survey in the Thames Estuary. The objective of the survey was to establish whether or not the Sediview Method of measuring suspended solids transport using Acoustic Doppler Current Profilers can be used as a tool to enhance the understanding of the sediment regime of the Thames estuary and contribute to possible future environmental studies. The survey was undertaken on 4 December 2001 and comprised 40 transects across the river at Coalhouse Point (Figure 1) to measure discharge and solids flux. The transects were sailed at regular intervals over a full tidal cycle. Calibration of the ADCP backscatter for sediment concentration was achieved by comparison with a large number of water samples, taken as part of the survey procedure.

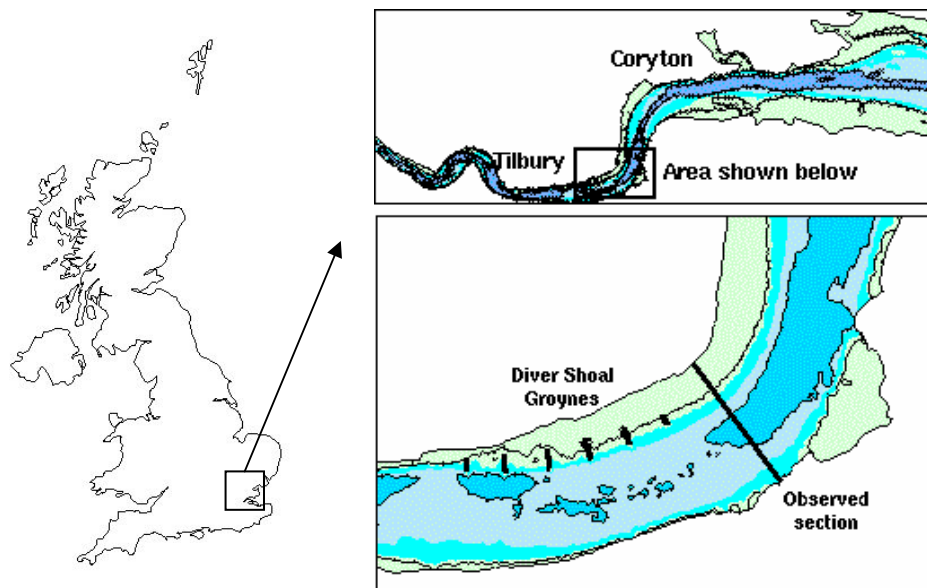


Figure 1 Location of survey transect

A full description of the survey procedure, the Sediview calibration and the results processing are shown in DRL and HR (2002).

Interestingly for the present work the data suggested that (at least) two sediment populations were present at various times during the survey. One was characterised by relatively low concentrations but with a highly variable siltmeter response, approximately proportional to the concentration of the samples. This population also appeared to have a sand content that increased rapidly with concentration. The second population appeared to be characterised by relatively high concentrations, a weak transmissometer response and only a slight rise in sand content with increasing concentration.

2. Numerical model

For the modelling studies TELEMAC3D, developed by EDF-LNHE was employed.

TELEMAC3D uses finite element solution methods to solve the Navier Stokes equations for fluid flow subject to the assumption assuming a free surface for flow and advection diffusion equations for the transport of salt, temperature, suspended solids and any other substances. The effect of the transported substances on the water density being taken into account using the Boussinesq approximation. For the present application as in most estuarine situations where the generality of the flow is in the horizontal direction TELEMAC3D was also able to employ the hydrostatic pressure assumption.

The equations are solved on an unstructured grid of triangles in the horizontal with a sigma transformation used to project the horizontal triangle cell into a series of prisms dividing up the vertical. For the present study an equal division of the vertical was used although this is not obligatory in TELEMAC3D. The various variables of the equations (bed elevation, water depth, free surface level and u and v velocity components) are

defined at the nodes (vertices of triangles) and linear variation of the water and bed elevation and of the velocity within the triangles is assumed.

The solution methods used in the hydrodynamic part of TELEMAC3D are described in Malcherek et al (1996) and in Janin et al (1992).

TELEMAC3D can also be run with the hydrodynamics coupled with the transport of suspended mud including the processes of deposition and erosion of mud on the riverbed. Details of the implementation of the mud processes in the model are as described in Le Normant (1998).

TELEMAC3D was applied to the Thames estuary between Crayfordness and Southend, a distance of approximately 40km. Experience of other estuarine applications has shown that adequate model mesh points to correctly define the estuary cross section are required. In general 10 or more model nodes across the river width has proved adequate to represent an estuary cross section, however in this case since the fine detail of the flows required simulation further resolution was used.

The mesh applied varied in grid size from 50m in the immediate area of the observations to 150m in the areas towards the imposed boundaries. This mesh resulted in approximately 30 model nodes across the river width at the observation site and a total of about 10,000 model nodes in the whole horizontal model domain. In the vertical direction a grid comprising 10 equally spaced layers was used.

2.1 BOUNDARY CONDITIONS

Hydrodynamic boundary conditions were required at the up and downstream model boundaries. For the downstream boundary the observed tide curve at Southend was applied. At the landward limit total discharge was imposed which was based on the calculated observed discharge from the ADCP observed cross section.

A schematic salinity boundary condition was imposed to provide an appropriate longitudinal salinity gradient. There is seldom significant salinity stratification in such a dynamic location as the Lower Thames Estuary. This was confirmed by the observations from the RDP deployed as part of the ADCP survey. The salinity boundary conditions were set to be of the current order as that observed during the HR fixed station survey of the Thames undertaken in September 1968 (HR Wallingford, 1969). The observed mean daily flow for the ADCP survey period and for the 1968 observations were both of the order of 90 m³/s (although the 1968 observation period was preceded by some much larger flows). The imposed salinity boundary conditions were defined to vary in line with the imposed tide curve with limits of 12-19ppt at the landward limit and 29-32 at the seaward extent of the model. As mentioned above the general small amount of stratification in the area meant no salinity variation was imposed in the vertical direction at the boundaries.

Boundary conditions for mud concentration were constant at the seaward end at 50 mg/l and time varying at the landward limit. The landward boundary condition was a synthesis of the concentrations observed by the HR 1968 survey and the observed total sediment flux the section.

2.2 MODEL PARAMETERS

The model parameters left unchanged for the testing of the model sensitivity to the formulation of the settling velocity were a constant horizontal diffusion coefficient of 1 m²/s with vertical turbulence treated with a mixing length model. The bed roughness was included via Chezy's law with a coefficient of 75. The critical stresses of erosion and depositions were 0.22 N/m² and 0.1 N/m², respectively.

Initial conditions

The initial conditions were set with salinity matching the initial boundary values and linearly varying between. The sediment concentrations were initially 30 mg/l at the seaward end with the muddier areas landward of the observed section starting at 550 mg/l. The initial condition included no initial deposition on the estuary bed or intertidal areas.

3. *Model tests*

3.1 BASELINE CASE– CONSTANT SETTLING VELOCITY

For the baseline run a constant settling velocity of 0.5 mm/s was used.

3.2 LINEAR SETTLING VELOCITY

Previous work on the Thames (Stevenson and Burt, 1985) suggested a power law relationship with concentration with an exponent factor of 1.37 – interestingly this value is close to the 4/3 predicted by Krone (1962) from theoretical considerations. However there is uncertainty in this relationship from the observation method (Owen tube) and from the evidence outlined above that the mud properties changed significantly during the observed tidal period. Therefore without specific in-situ information on floc sizes and settling velocity such as would be provided by an instrument such as INSSEV (Manning and Dyer, 2002) a initial linear law was thought of as adequate for the sensitivity test.

$$W_s = 0.002 * C \quad (1)$$

Where C is the concentration of suspended sediment.

The selling velocity would not be expected to continue increasing with ever increasing concentration as would result from this linear relationship. Observations taken from mud on the River Severn, for example, showed a peak settling velocity being reached before reducing at concentrations above 10,000 mg/l. At higher concentrations, processes such as hindered settling are known to reduce settling velocity (Whitehouse et al, 2000). For the simulation a maximal value of 10mm/s was used for the settling velocity. The reduction in W_s at very high concentrations was not included in the present simulations as such extremely high concentrations occurred rarely in the observations.

3.3 MANNING ALGORITHM

Manning's algorithm for settling velocity is an empirical formula, which though not presented in a dimensionless form, has the merit of being based on a large data set of accurate in situ settling velocity measurements from different estuaries and locations.

The algorithm is based on the concept of macroflocs – large aggregate floc structures – and microflocs – representing the constituent particles of the macroflocs. Equations are given for the settling velocity of macroflocs, for the settling velocity of microflocs, the ratio of macroflocs to microflocs in the floc population and the settling flux (Manning, 2004). The algorithm was initially implemented into the TELEMAC3D by HR Wallingford as part of Estproc and was applied to mud transport on tidal flats (HR Wallingford, 2004). The modular nature of the TELEMAC system allowed the subroutines developed for these studies to be directly inserted into the model of the Thames.

3.4 RESULTS

Cross sections of the model results were extracted at the survey section for times of peak ebb and flood tide and are presented as Figure 2 below. In the figures the view is presented looking downstream, with the inside of the bend at Coalhouse Point (north bank) on the left. This reach of the Thames is a very dynamic environment with peak mid-channel currents of 1.2-1.4 m/s during both the ebb and flood phases of a spring tide (depending on the detail of the tidal range). The tide range observed during the survey period was up to 6 m.

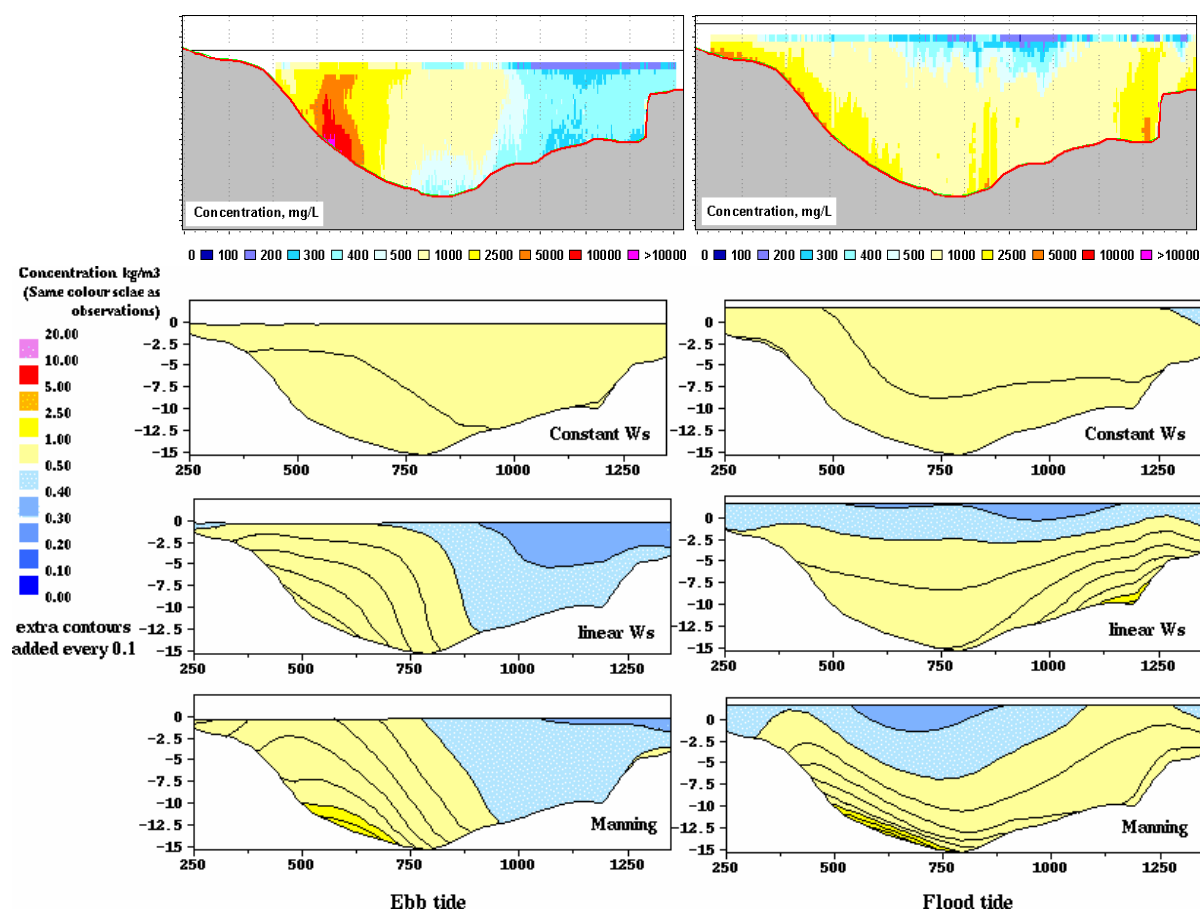


Figure 2 Comparison of observed sediment concentrations across the river section (top) and predicted sediment concentrations using different assumptions about the settling velocity

It can be seen that the use of a constant settling velocity did not result in the representation any of the observed structure of suspended concentrations. The use of a linear settling velocity was a great improvement, firstly in that it introduced an element of vertical variation in the predicted suspended concentration. The linear formulation also resulted in higher concentration occurring on the inside of the river bend during the ebb tide and on the outside of the bend on the flood tide as observed. The use of the Manning algorithm further improved the representation of the observed distribution by increasing the level of vertical variation in suspended concentration. The Manning algorithm also introduced an area of higher concentration on the inside of the bend during the flood tide, as was observed.

None of the improvements to the simulation of settling processes was able to help in the reproduction of the negative density gradient observed during the ebb tide. This feature is thought to be a result of the strong secondary currents in the area as the high current goes around the bend at Coalhouse Point. Such hydrodynamic effects are outside the scope of the present work but could be further investigated for example by the use of more near bed model layers or different turbulence schemes.

Note that while the implementation of the Manning algorithm does increase the simulated, near-bed suspended concentration on the left of the figure the simulation does not achieve the very high concentrations ($>5\text{kg/m}^3$) observed in that part of the cross-section. It is suggested that these concentrations are related to the groynes on Diver Shoal upstream of the observed section (see Figure 1) causing extra turbulence and suspension of material in this area during the ebb tide.

4. Conclusions

The Manning (2004) algorithm for settling velocity of mud in estuarine environments has been implemented into a 3D numerical model of the Lower Thames Estuary. The implementation was straight forward as the required subroutines had already been implemented into a TELEMAC3D model (HR Wallingford, 2004).

The model results with the Manning algorithm included were compared to runs with (1) a constant settling velocity of 0.5 mm/s and (2) settling velocity based on a simple linear multiplier of concentration and with acoustically derived and calibrated observations of suspended concentration.

The conclusions drawn from the modelling exercise relate not only to the direct comparisons with the data but with how the predicted behaviour changes with the different implementations of the concentration and settling velocity relationship. The main conclusions were as follows:

1. It is feasible to implement a complex relationship between settling velocity and concentration in a 3D computational model of estuarine hydraulics, without producing any significant increase in model run times or reducing model stability.
2. The use of a constant settling velocity did not represent any of the observed lateral or vertical variation in suspended solids concentration.

3. The use of a linear law improved the comparison with observations with more vertical variation and predicting high near bed concentrations in the correct locations.
4. The use of the Manning algorithm further increased the amount of vertical variation in the simulated suspended concentrations. It also better reproduced the lateral suspended concentration pattern observed during the flood tide.
5. The improvements to the representation of the vertical distribution of the suspended concentration did not improve the simulation of the negative density gradient observed on the inside of the observed section during the ebb tide. This phenomenon is thought to be linked to strong secondary currents at the bend in the estuary at Coalhouse Point. Such effects are outside the scope of the present work but could be investigated by the use of more near bed model layers or different turbulence schemes.
6. The application of the Manning algorithm to the Thames suggests that the algorithm is generally applicable to estuarine mud transport modelling. The large amount of data used in the algorithm establishment means that it represents the best presently available method for simulating settling velocity and should be routinely used. Exceptions would be in areas where the estuary behaviour differs greatly from those used for the observation on which the algorithm is based (e.g. highly stratified, dominant biological effects, etc).

5. *Acknowledgements*

The funding by the Port of London Authority of the Coalhouse Point Sediview survey is acknowledged.

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