Elsevier Editorial System(tm) for Estuarine, Coastal and Shelf Science
Manuscript Draft

Manuscript Number: ECSS-D-15-00780R3

Title: Two-phase flow modelling of sediment suspension in the Ems/Dollard estuary

Article Type: Research Paper

Keywords: Two-phase flow cohesive sediment flocculation suspension modelling

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Abstract: Understanding and quantifying mud suspension and sediment transport processes in estuaries are of great importance for effective exploitation and sustainable management of the estuarine environments. Event-based predictive models are widely used to identify the key interactions and mechanisms that govern the dynamics involved and to provide the essential parameterisations for assessing the long-term morphodynamic evolution of the estuaries. In this study, a one-dimensional-vertical (1DV) Reynolds averaged two-phase model is developed for cohesive sediments resuspension driven by tidal flows. To capture the time-dependent flocculation process more accurately, a new drag force closure which relates empirically settling velocity of mud flocs with suspended sediment concentration (SSC) is incorporated into the two-phase model. The model is then applied to simulate mud suspension at Ems/Dollard estuary during two periods (June and August 1996) of tidal forcing. Numerical predictions of bed shear stresses and sediment concentrations at different elevations above the bed are compared with measured variations. The results confirm the importance of including flocculation effects in calculating the settling velocity of mud flocs and demonstrates the sensitivity of prediction with the settling velocity in terms of flocs concentration. Although the two-phase modelling approach can in principle better capture the essential interactions between fluid and sediment phases, its practical advantages over the simpler single phase approach cannot be confirmed for the data periods simulated, partly because the overall suspended sediment concentration measured is rather low and the interaction between the two phases is weak and also because the uncertainties in the relationship between the settling velocity and flocs concentration.

Response to Reviewers: Referees' comments:
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Prof Mike Elliott

Editor of Estuarine, Coastal and Shelf Science

Inst. of Estuarine and Coastal Studies, University of Hull, Cottingham Road, Hull, HU6 7RX, UK

15 September 2015

Dear Prof Elliott

Submission of a manuscript

I and my co-author wish to submit a manuscript entitled "Two-phase flow modelling of sediment suspension in the EMS/ Dollard estuary" for review and potential publication in Estuarine, Coastal and Shelf Science. The paper investigates the sediment suspension in the EMS/Dollard estuary using a two-phase model. The two-phase model is first validated using experiments data from vertical settling tanks and then applied to simulate sedimentary processes and especially mud flocculation process in the estuary. We believe that the materials contained in the paper will be of interest to the wider readership of the journal and particularly those involved in studying the event-scale hydrodynamics, mud flocculation processes either in estuaries or in coastal seas.

The following people may be considered as the possible reviewers for the manuscript as they are all experts on the subject and currently active in research.

1. Prof Richard Whitehouse, HR Wallingford, Howbery Park, Wallingford OX10 8BA, Tel: +44(0)1491 835381. Fax: +44(0)1491 832233. Email: rjsw@hrwallingford.co.uk

2. Dr Shunqi Pan, Reader, School of Engineering, Cardiff University; Tel:+44 (0)29 2087 5694, Email: PanS2@cardiff.ac.uk

3. Prof Yakun Guo, School of Engineering, Bradford University, UK; Tel: 44 (0) 1274 233689
Email: Y.Guo16@Bradford.ac.uk

4. Prof Qiuhua Liang, Room 3.03, Cassie Building, School of Civil Eng and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK, Tel: +44 (0) 191 208 6413. Fax: 44 (0) 191 208 6502. Email: qiuhua.liang@ncl.ac.uk

Finally we would like to thank you for considering the manuscript for publication. I can be contacted by either phone or email should you have any queries.

Yours sincerely

Ping Dong

Professor of Coastal Engineering

School of Engineering, University of Dundee, Dundee DD1 4HN, UK

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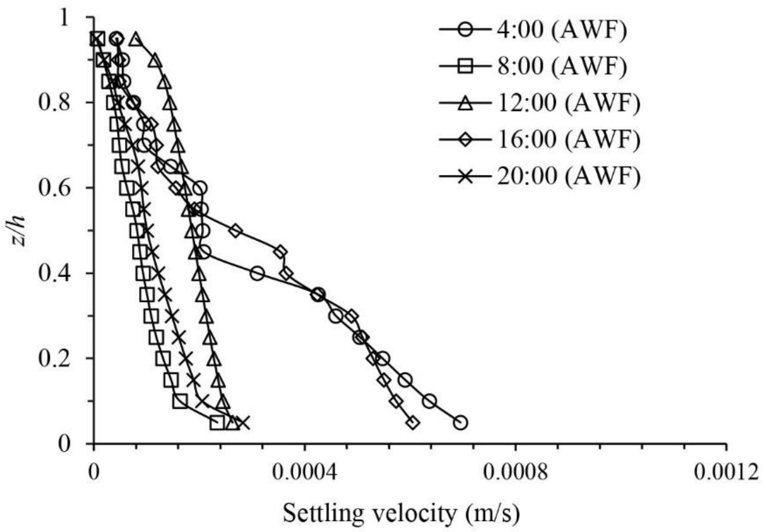

Fig. R1 Vertical profile of settling velocity predicted in AWF at different time

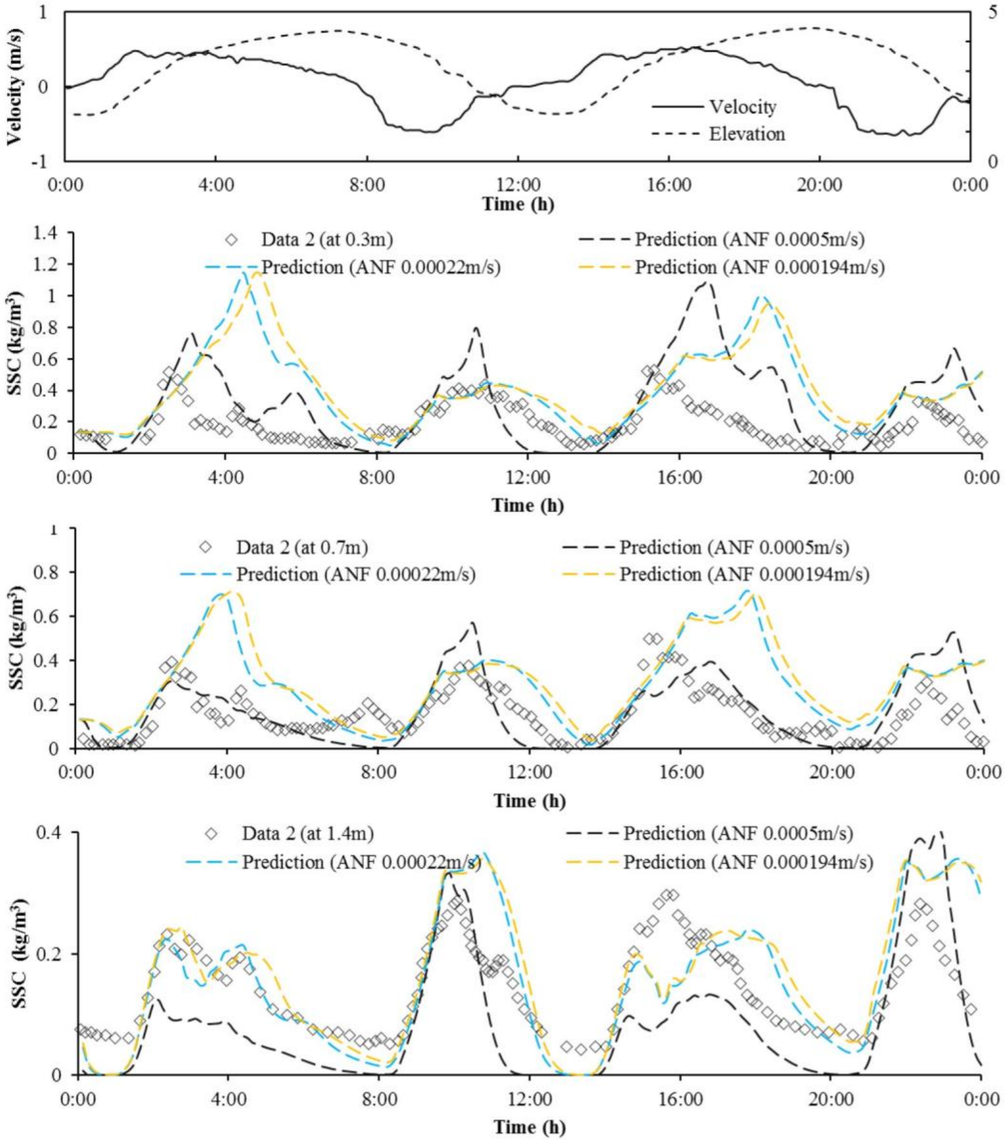

Fig. R2 The measured SSC by Van Der Ham et al. (2001) at 0.3 m (the second panel) 0.7 m (the third panel) and 1.4 m (the fourth panel) above the bed (diamonds) in August measuring period, numerical prediction from run JNF (black dashed curve 0.0005m/s, yellow dashed curve 0.000194m/s and blue dashed curve 0.00022m/s). The tidal elevation (dashed curve) and depth-averaged velocity (solid curve) are shown in the first panel.

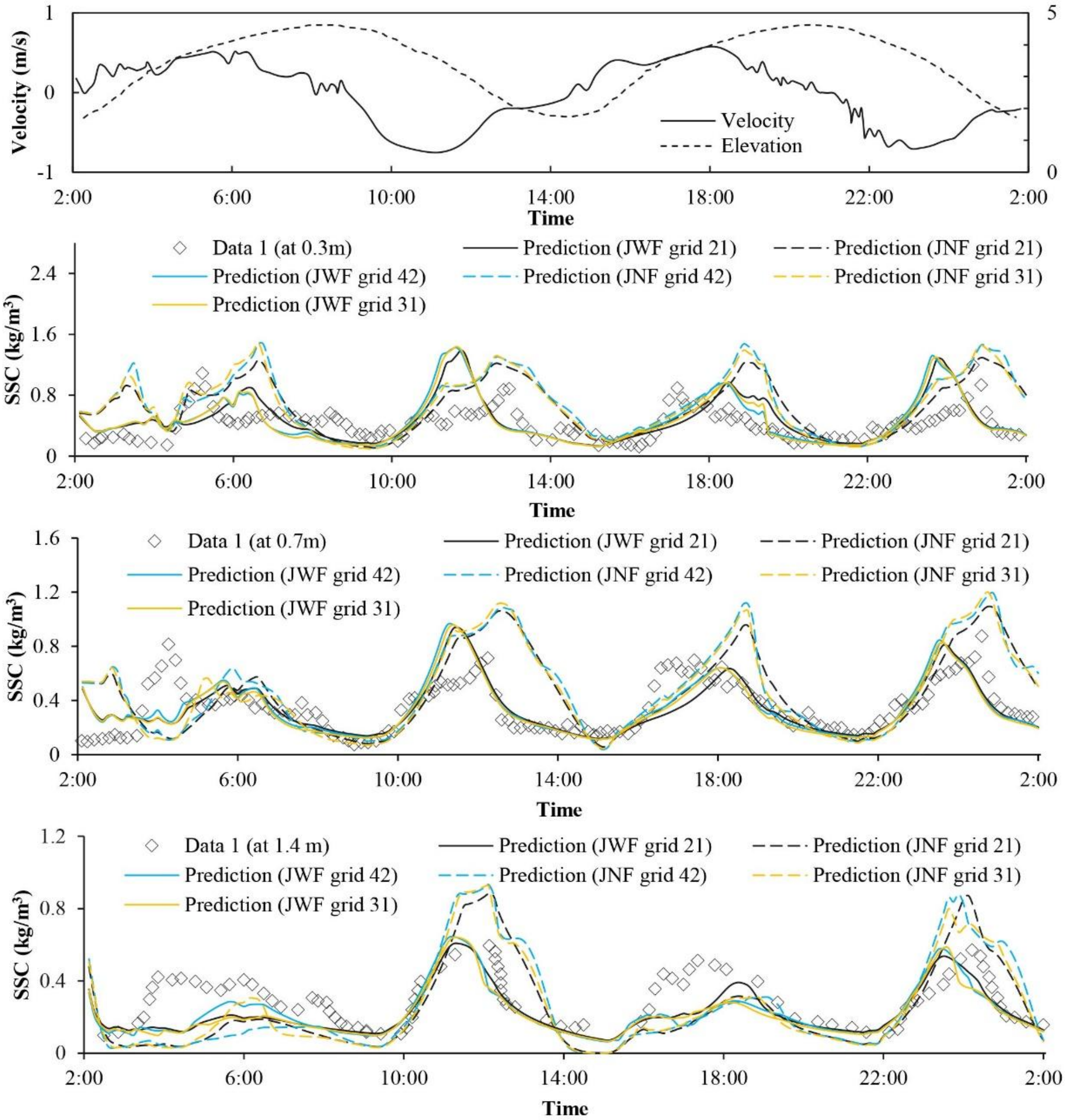

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Table R1

Root-mean-square errors between measured data and model results

Level above the seabed (m)	JWF (Data 1)			JNF (Data 1)			Son and Hsu (2011) (Data 1)
	grid 21	grid 31	grid 42	grid 21	grid 31	grid 42	
0.3	0.284	0.294	0.301	0.409	0.429	0.450	0.298
0.7	0.146	0.147	0.145	0.343	0.296	0.303	0.221
1.4	0.121	0.136	0.131	0.204	0.195	0.213	-

Two-phase flow modelling of sediment suspension in the Ems/Dollard estuary

Chunyang Xu[1] and Ping Dong[2,3*]

[1]College of Harbor Coastal and Offshore Engineering, Hohai University, Nanjing 210098, PR China

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[3] School of Engineering, University of Liverpool, Liverpool L69 3GH, United Kingdom

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Abstract

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[1] SSC: suspended sediment concentration

1996) of tidal forcing. Numerical predictions of bed shear stresses and sediment concentrations at different elevations above the bed are compared with measured variations. The results confirm the importance of including flocculation effects in calculating the settling velocity of mud flocs and demonstrates the sensitivity of prediction with the settling velocity in terms of flocs concentration. Although the two-phase modelling approach can in principle better capture the essential interactions between fluid and sediment phases, its practical advantages over the simpler single phase approach cannot be confirmed for the data periods simulated, partly because the overall suspended sediment concentration measured is rather low and the interaction between the two phases is weak and also because the uncertainties in the relationship between the settling velocity and flocs concentration.

Keywords: Two-phase flow; cohesive sediment; flocculation; suspension; modelling

1 Introduction

Cohesive sediment transport and the accompanying changes in the bed morphology play an essential role in the morphological evolution and dynamic equilibrium of muddy estuaries and coasts (Li et al., 2016; van der Ham and Winterwerp, 2001). Large amount of sediment from the upstream of rivers settles and accumulates at estuaries, which may cause complex sediment transport patterns, and large estuarine delta may form (Bian et al., 2013). Suspended cohesive sediment can also significantly affect the nutrients and pollutant cycles in the water column through sedimentation and re-suspension processes (Chen et al., 2015; Delandmeter et al., 2015; Percuoco et al., 2015). In water treatment industry, controlling the settling process of cohesive sediments is also one of the key technical challenges. Due to biological and chemical attraction, primary particles and small flocs are easily aggregated together and form larger flocs, known as flocculation process (van der Ham and Winterwerp, 2001). Consisting of a skeleton formed by solid primary mud particles and interstices filled with liquid , these mud flocs have dynamic characteristics completely different from that of primary clay particles, notably lower density, larger size, irregular shape and larger settling velocity (Maggi, 2013). The mud floc size is also time-dependent and controlled by various factors such as turbulence, concentration, salinity and biological effects. Any serious attempts to predict the cohesive sediment movements needs to account for the transient behaviour of the mud flocs throughout its life cycle of formation, evolution and settlement (Son and Hsu, 2011; Xu and Dong, 2016).

Ems/Dollard estuary is an ebb current dominated estuary (Dyer et al., 2000; Talke and de Swart, 2006; van der Ham and Winterwerp, 2001). Intra-tidal variations in suspended sediment concentration (SSC) are influenced by sediment availability, horizontal sediment transport and more importantly vertical mixing. Past observations have shown that there exist significant time lags between current velocity and SSC as the SSC tends to stop increasing before the maximum current velocity is reached, primarily due to the limited sediment availability (van der Ham and Winterwerp, 2001; Van der Lee, 2000). These studies have also found that flocculation process can significantly affect the settling velocities of cohesive sediments as well as the sediment transport rate in the Ems/Dollard estuary (Van der Lee, 2000; van Leussen, 1999, 2011).

To understand the sediment suspension behaviour, especially the effects of flocculation process on the distribution of SSC, a range of numerical models have been developed and applied to the Ems/Dollard Estuary. A single-phase 1DV model was applied by van der Ham and Winterwerp (2001) to calculate the suspended sediment concentration. In this model, separate empirical formulae or sub models were used to determine stratification effects, sediment availability and settling velocities. The settling velocities are related to SSC and calculated according to the level of turbulence and degrees of flocculation. During the flow deceleration period, the SSC decreases rapidly as the results of formation of large mud flocs and their rapid settling (van Leussen, 2011). Son and Hsu (2011) also applied a 1DV model to reanalyze the data used by van der Ham and Winterwerp (2001). The flocculation model incorporated in their 1DV model was an extension of Winterwerp (1998) by including the effects of variable fractal dimensions and yield stresses of mud flocs in the flocculation process. Despite the increased sophistication in theoretical formulation of flocculation processes, the calculated SSC from the model were no more accurate than that of van der Ham and Winterwerp (2001). In particular, the time lag between flow velocity and sediment concentration, which is known to be an important erosion/deposition feature in Ems, is not well predicted as the calculated SSC peaks always appear earlier than the measurements.

In the last two decades, two-phase flow modelling approach has been introduced to model sediment transport in coastal and estuarine areas(Chauchat et al., 2013; Dong and Zhang, 1999; Nguyen et al., 2012). In these models, the fluid phase and the solid phase are treated separately by solving the mass and momentum equations of each phase. Determination of closures for the two-phase flow model is one of the main tasks in implementing the technique to ensure the interactions between fluid and particle and between particles and particles to be adequately described. Until very recently, most of the two-phase models in coastal engineering are for non-cohesive sediment problems (Dong and Zhang, 1999; Hsu, 2004; Ono et al., 1996), in which the sediment (sand) size is taken as a known constant. This is clearly not the case for cohesive sediment because of flocculation, a process pertaining only to cohesive sediment dynamics. Recently a one dimensional vertical two-phase model has been developed by Chauchat et al. (2013) and was validated using settling tanks experiments. In this 1DV two-phase model, hindered settling and consolidation process are also considered whereas flocculation process is ignored.

In this paper, a one-dimensional-vertical (1DV) Reynolds averaged two-phase model for cohesive sediment resuspension driven by tidal flows is presented. To the best of the authors' knowledge, it is the first work to incorporate the mud particle flocculation process in the two-phase modelling framework. A notable new feature of the model is that the standard closure of drag force is modified to incorporate both flocculation and hindered settling effects. After validation against the data from settling tank experiments, the model is applied to simulate sediment dynamics in Ems/Dollard estuary over two periods during which tide currents are dominant and wave effects are negligible. The modelling results are presented and the effectiveness and limitations of the model are discussed.

2 Model formulation

2.1 Governing equations

The two-phase model is developed based largely on the work of Chauchat et al. (2013) and Dong and Zhang (1999). As cohesive sediment particles are much lighter than sands, the inertia effect is usually negligible. The flow and particle can be assumed to have the same mean horizontal velocity. Thus, the continuity and momentum equations for both phases can be derived as:

$$\frac{\partial U}{\partial t}+\frac{1}{\rho_{mix}}\frac{\partial P}{\partial x}=\frac{\partial}{\partial z}((\nu+\nu_T)\frac{\partial U}{\partial z}) \tag{1}$$

$$\frac{\partial \alpha_f \rho_f}{\partial t}+\frac{\partial \alpha_f \rho_f w_f}{\partial z}=\frac{\partial \rho_f}{\partial z}(-\Gamma_T\frac{\partial \alpha_k \rho_k}{\partial z}) \tag{2}$$

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$$\begin{aligned}\frac{\partial \alpha_s \rho_s w_s}{\partial t}+\frac{\partial \alpha_s \rho_s w_s w_s}{\partial z}&=-\alpha_s\frac{\partial p_f}{\partial z}-\frac{\partial \sigma_e}{\partial z}\\&+\alpha_s\frac{\partial \tau_v}{\partial z}-\alpha_s\rho_s g-f_i\end{aligned} \tag{5}$$

$$\alpha_f+\alpha_s=1 \tag{6}$$

where U is the horizontal velocity for both phases, $\rho_{mix} = \alpha_s \rho_s + \alpha_f \rho_f$ is the density of the mixture, t is time, x axis is taken as the horizontal direction, z axis is taken as the vertical direction. ρ , α and w are density, volume fraction and settling velocity in the vertical direction, the subscripts f and s correspond to fluid phase and solid phase, respectively. ν and ν_T are the molecular viscosity and eddy viscosity. σ_e is the effective stress, τ_v is the viscous shear stress of the mixture, g is the gravitational acceleration and f_i is the momentum transfer between two phases. P is the pressure of mixture, p_f and p_s correspond to the fluid and solid pressure, respectively. The schematic diagram of the complete two-phase model is shown in Fig. 1, in which most of the main simulated processes are included.

2.2 Closures for the model

To solve the two-phase flow equations, the source or closure terms need to be specified. The formulations used for these closure terms follow closely that proposed by Chauchat et al. (2013) and Dong and Zhang (1999).

The turbulence eddy viscosity is calculated using a modified classical mixing length method including the buoyancy effect as it may significantly alter the turbulent flow structure:

$$\nu_T = 0.16 z^2 \left(1 - \frac{z}{h}\right) \frac{\partial u}{\partial z} F_v \tag{7}$$

and similarly, the eddy diffusivity is estimated as:

$$\Gamma_T = \frac{\nu_T F_d}{\sigma_T F_v} \tag{8}$$

where F_v and F_d are the dissipation coefficients of eddy viscosity and eddy diffusivity due to the buoyancy effects caused by suspended sediments (Kranenburg, 1998; Toorman, 2002), σ_T is the turbulent Prandtl-Schmidt number and usually specified as 0.7 or 1.0 (van der Ham and Winterwerp, 2001).

Kranenburg (1998) proposed that both eddy viscosity and eddy diffusivity coefficients can be related to the gradient Richardson numbers as:

$$F_v = (1 + ARi)^{-a} \tag{9}$$

$$F_d = (1 + BRi)^{-b} \tag{10}$$

where A , B , a and b are all empirical coefficients and specified as 2.4, 2.4, -2 and -4 respectively; Ri is the gradient Richardson number, which is defined as:

$$Ri = \frac{-g \dfrac{\partial \rho_{mix}}{\partial z}}{\rho (\dfrac{\partial U}{\partial z})^2} \tag{11}$$

The viscous shear stress for both phases is assumed to be equal here and is given as:

$$\tau_v = \mu_{mix} [\nabla u_m + (\nabla u_m)^{\mathrm{T}}] \tag{12}$$

$$\mu_{mix} = \mu_f (1 + \beta \alpha_s) \tag{13}$$

where $u_m = \alpha_f u_f + \alpha_s u_s$ is the volume averaged velocity and μ_{mix} is the viscosity of the mixture. According to Chauchat et al. (2013), the shear stress of the mixture can be related to the volume averaged velocity gradient by the mixture viscosity. β is the amplification factor for the viscosity of mixture, in which the non-Newtonian effects are included when the fraction of solid phase is large. The specific formulae for β is (Graham, 1981):

$$\beta = \frac{5}{2} + \frac{9}{4}\frac{1}{1+d^*}\left(\frac{1}{2d^*} - \frac{1}{1+2d^*} - \frac{1}{(1+2d^*)^2}\right)\frac{1}{\alpha_s} \tag{14}$$

where d^* is the non-dimensional inter-particle distance and expressed as $d^* = [1-(\alpha_s / \alpha_s^{max})^{1/3}] / (\alpha_s / \alpha_s^{max})^{1/3}$, where $\alpha_s^{max} = 0.625$ is the maximum solid volume of simple cubic packed spheres. Viscosity of the mixture calculated from Equations (13) and (14) can be applied to situations in which the variation of sediment concentration is large and it is also consistent with the classic formula $\mu_{mix} = \mu_f (1+2.5\alpha_s)$ in the dilute case (Einstein, 1905) and with the formulation $\mu_{mix} = \mu_f 9/8[(\alpha_s^{\max} / \alpha_s)^{1/3} - 1]^{-1}$ in the dense case (Frankel and Acrivos, 1967).

In the two-phase model, the Darcy-Gersevanov's expression is used for the drag force:

$$f_i = \frac{\rho_f g}{K}(w_f - w_s) \tag{15}$$

where K is the permeability. According to the derivation of Toorman (1996), the permeability K can be specified as:

$$W = K\alpha_s(\rho_s / \rho_f - 1) \tag{16}$$

where W is the empirical settling velocity near the bed. From Equations (15) and (16), Equation (17) can be obtained:

$$f_i = \frac{\rho_f g}{W}(w_s - w_f)[\alpha_s(\rho_s / \rho_f - 1)] \tag{17}$$

Therefore, the only problem that remains is to find a suitable formula for the flocs settling velocity W. Camenen and Pham van Bang (2011) proposed a formula which ensures a smooth curve of settling velocity during the transition from hindered settling regime to the permeability regime. In the hindered settling regime, the formula is given as:

$$W = w_0(1-\alpha_s)^{n/2}(1-\phi)^{n/2-1}(1-\frac{\phi}{\phi_{\max}}) \quad (18)$$

where w_0 is the settling velocity of mud flocs in dilute situation. n is the fractal dimension and specified as 2.55. $\phi_{\max}$ is the maximum volumetric fraction of mud flocs. As the sediment concentration cannot reach unity and the settling velocity will become almost zero when it reaches gelling concentration (Winterwerp, 2002), the forth term on the right hand of Equation (18) is added and $\phi_{\max}$ is set as 0.85. To make sure the continuity of settling velocity in both regimes, the formula below is used:

$$W = \begin{cases} w_0(1-\alpha_s)^{n/2}(1-\phi)^{n/2-1}(1-\frac{\phi}{\phi_{\max}}), \alpha_s \le \frac{\alpha_s^{gel}}{\chi} \\ W^{gel}(\frac{\chi\alpha_s}{\alpha_s^{gel}})^{-2/(3-n)+1}, \alpha_s > \frac{\alpha_s^{gel}}{\chi} \end{cases} \quad (19)$$

where the value of $\phi_{\max}$ corresponds to the gelling fraction $\alpha_s^{gel} = 0.025$, $\chi = 1.283$ is an empirical coefficient. W equals to W^{gel} when $\alpha_s = \alpha^{gel}$.

It should be noted that the Equations (17) and (19) describe the hindered settling effects of mud flocs of known state (size and concentration). But in a tidal time scale, both floc sizes and settling velocities in the Ems estuary are strongly correlated with SSC (Van der

Lee, 2000). As a first approximation, we decide to adopt a simple flocculation model with floc settling velocities being nonlinearly dependent only on SSC. According to Thorn (1981) a power relationship usually exists between particle mass concentration and settling velocities of mud flocs in the flocculation stage. *i.e.*:

$$w_0 = k_1 C^m \tag{20}$$

where k_1 is the empirical coefficient. C is the sediment mass concentration ($\mathrm{kg/m^3}$) and m is a site-dependent coefficient and needs to be determined empirically.

By combining the Equations (19) and (20), a new drag force closure is obtained. As the effects of both flocculation and hindered settling are presented in this single closure relationship, the transition of settling velocity from flocculation regime to hindered settling regime can be determined continuously during the model run. The complete form of the new closure is presented as Equations (17) and (21):

$$W = \begin{cases} k_1 C^m (1-\alpha_s)^{n/2} (1-\phi)^{n/2-1} (1-\dfrac{\phi}{\phi_{\max}}), \alpha_s \le \dfrac{\alpha_s^{gel}}{\chi} \\ W^{gel} (\dfrac{\chi \alpha_s}{\alpha_s^{gel}})^{-2/(3-n)+1}, \alpha_s > \dfrac{\alpha_s^{gel}}{\chi} \end{cases} \tag{21}$$

Effective stress occurs only when the sediment particles or mud flocs contact with each other, otherwise it vanishes. In the proposed effective stress closure, the effective stress appears when sediment concentration reaches the gelling concentration α_s^{gel} (Chauchat et al., 2013).

$$\sigma_e = \begin{cases} 0, & \alpha_s < \alpha_s^{gel} \\ \sigma_0 [(1 - \dfrac{\alpha_s - \alpha_s^{gel}}{\alpha_s^{\max}})^{-2/(3-n)} - 1], & \alpha_s \geq \alpha_s^{gel} \end{cases} \tag{22}$$

where $\alpha_s^{\max}$ is 0.14 and σ_0 is 0.14 Pa. When sediment concentration α_s is larger than gelling concentration α_s^{gel}, the effective stress develops. Compared to the formula given by Merckelbach and Kranenburg (2004), Equation (22) avoids the limitation that the effective stress never equals to zero.

2.3 Boundary conditions

Bottom boundary condition for shear stress is specified as:

$$(\nu + \nu_T)\frac{\partial \overline{U}}{\partial z}\Big|_{z=z_b} = |u^*| u^* \tag{23}$$

$$\frac{u(z_b)}{u^*} = \frac{\ln(\frac{z_b}{z_0})}{\kappa} \tag{24}$$

where u^* is the friction velocity, z_b is a small distance from the bed which is usually taken as half height of the first computational grid and z_0 is the roughness length (van der Ham and Winterwerp, 2001). κ is the Karman constant.

Boundary condition for the continuity equation of solid phase is given as:

$$\Gamma_T \frac{\partial \alpha_s \rho_s}{\partial z} - \alpha_s \rho_s w_s = \begin{cases} M \rho_s \left(\left| \dfrac{\tau_b}{\tau_{cr}} \right| - 1 \right), & |\tau_b| > \tau_{cr} \\ w_s \rho_s \alpha_s (\mathrm{z}_b) \left(1 - \left| \dfrac{\tau_b}{\tau_{cr}} \right| \right), & |\tau_b| \leq \tau_{cr} \end{cases} \tag{25}$$

where M is the erosion coefficient, τ_b is the bed shear stress, τ_{cr} is the critical bed shear stress for sediment erosion.

3 Model application to the Ems/Dollard Estuary

3.1 Model setup and materials

As discussed in section 1, in estuaries and coastal seas, the size and density of mud flocs during flocculation may change constantly and so is the settling velocity. Therefore, the time scale is an important factor in modeling cohesive sediment transport processes. The past research has identified that floc sizes are closely related to suspended sediment concentration on a tidal time scale, while on the seasonal time scale, the floc sizes are essentially determined by the properties of the sediments (Van der Lee, 2000). The model application here is designed to focus on the tidal time scale so as to examine critically the capability of the developed model.

The Ems estuary has its mouth in the Wadden Sea. Measurement Point A in Fig. 2 was within a straight tidal channel Groote Gat, the average bottom elevation of which is 3.3m below N.A.P (Dutch ordnance datum). The horizontal gradients of SSC are known to be negligible and both horizontal and vertical salinity gradients are also small when the river discharge is low (Van Der Ham et al., 2001). Therefore, the present 1DV two-phase model is expected to be applicable to the measured data at this site.

The data sets for two time periods, one from 02:00 27/Jun/1996 to 02:00 28/Jun/1996 and the other from 00:00 08/Aug/1996 to 00:00 09/Aug/1996, are considered (Van Der Ham et al., 2001). The former is denoted as Data 1 and the latter as Data 2. The time-varying depth-averaged flow velocity U and water depth h for Data 1 and Data 2 are used as the inputs to the model. The fixed time step $t = 1\text{s}$ is used and the number of grid cells is 21. Model results vary little when the model is tested with grids 31 and 42. All the input values between the measured data points are determined using linear interpolation.

Following van der Ham and Winterwerp (2001), a roughness height of $2\times10^{-3}\,\text{m}$ and the erosion rate for mud $M = 1.54\times10^{-8}\,\text{m/s}$ are selected. Critical shear stress for erosion τ_{cr} is specified as $0.1\ \text{Pa}$ which is the averaged critical shear stress suggested by Kornman and De Deckere (1998) based on sediment erosion studies in an adjacent tidal flat. Following van der Ham and Winterwerp (2001), the maximum depth-averaged sediment concentration $C_{\max}$ is applied in both runs to account for the limited sediment availability.

3.2 Results and discussion

3.2.1 *Data 1*

Numerical simulation for the June period with and without the effects of flocculation is denoted as JWF run (June With Flocculation) and JNF run (June No Flocculation), respectively. Equations (17) and (21) are used in JWF run, in which the new drag force closure is adopted to take account of the flocculation effects, while Equations (17) and (19) are used in JNF run, ignoring the flocculation effects. Here we follow van der Ham and Winterwerp (2001) and specify k_1 and m as $1.5\times10^{-3}(\text{m/s})\cdot(\text{g/L})^{-\text{m}}$ and 1.2 for Data 1 and Data 2. It should be mentioned that for Data 1 the settling velocity w_0 is set as $2.2\times10^{-4}\,\text{m/s}$, which is an average settling velocity from JWF run, to make the JWF run and JNF run more comparable. More details about the parameters used in the model simulation can be seen in Table 1 for Data 1 and in Table 3 for Data 2.

Table 1

Fitting parameters used in the simulation of Data 1

Run	Setting velocity $w_0\,(\mathrm{m/s})$	Empirical coefficient $k_1(\mathrm{m/s})\cdot(\mathrm{g/L})^{-\mathrm{m}}$	Site-dependent coefficient m	Erosion rate $M\,(\mathrm{m/s})$	$C_{\max}\,(\mathrm{kg/m^3})$
JNF	2.2×10^{-4}	–	–	1.54×10^{-8}	0.5
JWF	–	1.5×10^{-3}	1.2	1.54×10^{-8}	0.5

Fig. 3 shows the measured and modelled shear stress at 0.4 m above the bed. It can be seen that the model results for both JWF (solid line) and JNF (dashed line) runs compare well with the measured data. It can also be noticed that the shear stress calculated in JWF (solid line) run is almost identical to that in JNF (dashed line) run, which indicates the effects of flocculation process on shear stress is negligible under low sediment concentration. The flow structure is hardly affected when the SSC is less than 1 $\mathrm{kg/m^3}$, a result which is consistent with the conclusion from the work of Van Der Ham et al. (2001).

As both the shear stresses and the critical shear stress are the same, the differences in the predicted distributions of SSC for JWF and JNF runs are mainly due to the differences in the calculated settling velocities w_s in these runs. The measured and modelled variations of sediment concentration at 0.3 m, 0.7 m and 1.4 m above the bed are presented in Fig. 4. The numerical results during the two tidal cycles for both runs (with/without the effects of flocculation) seem to follow broadly the trend of measured data except for an abrupt increase of measured sediment concentration at the very start of the first tidal cycle, which is explained as a local increase of the sediment availability(van der Ham and Winterwerp, 2001). The model results with the effects of flocculation (solid line) matched well with measured data, whereas those without the effects of flocculation process (dashed line) deviate more from the data. It can be noticed that a lower value of sediment concentration during the slack water time is predicted in JNF run, while during the acceleration phase, a much higher sediment concentration is predicted when compared with the measured data. The modelled sediment concentration peaks can be twice as that of the measured data during the acceleration time of the first tidal cycle at 1.4 m. However, this level of discrepancy does not appear between the numerical results of JWF run and the measurements. To quantitatively describe the performance of both runs, the root-mean-square errors are shown in Table 2. JWF run shows the smallest at all levels. The root-mean-square errors calculated by Son and Hsu (2011) are larger than those of JWF run and smaller than those of JNF run at both 0.3 m and 0.7 m.

Table 2
Root-mean-square errors between measured data and model results

Level above the seabed (m)	JWF (Data 1)	JNF (Data 1)	Son and Hsu (2011) (Data 1)	AWF (Data 2)	ANF (Data 2)
0.3	0.284	0.409	0.298	0.156	0.250
0.7	0.146	0.343	0.221	0.109	0.111
1.4	0.121	0.204	-	0.056	0.080

To demonstrate the effect of flocculation, the vertical profile of settling velocities predicted in JWF run at different time are presented in Fig 5. As the settling velocities are constant in JNF run, only settling velocities at 6:00 hour are presented. In JWF run, it can be seen that the settling velocities range from approximately 0.0001 m/s to 0.0016 m/s within a tidal time scale. In the vertical direction, the distribution of settling velocities is consistent with the distribution of SSC. For example, the settling velocities are larger with high SSC at 13:00 and 18:00. In Equation (19) used for JNF run, the first term on the right side is the settling velocity w_0, which is treated as a constant for mud flocs in dilute situation while in Equation (21) used for JWF run, the first term on the right side is $k_1 C^m$ which describes the effect of flocculation on the settling velocity. The computational results show that w_s clearly increases with the increase of $k_1 C^m$ (thus C) as shown in Fig. 5 (for $C \le 3\ \mathrm{kg/m^3}$ the hindered settling effects are unimportant). A lower SSC corresponds to a smaller settling velocity (see Fig 5 at 15:00 and 22:00) and thus less sediment deposited on the bed for JWF run, while for JNF run, the settling velocity is larger than that in JWF due to the use of constant value w_0 in the drag force closure, which causes the amount of sediment deposited on the bed to be overestimated (JNF run). Therefore, variations of sediment concentration modelled in JNF run are smaller than the field measurements. During the acceleration phase when the SSC is high due to the strong flow forcing, JWF run predict a larger settling velocity, which prevents the sediment from being diffused up in the water column, whereas, the settling velocity in JNF run is underestimated resulting in higher predicted sediment concentration peaks than the measured ones.

To further illustrate the vertical SSC profile, model results in JWF run, JNF run and Son and Hsu (2011) along with the measured data are shown in Fig. 6. We follow Son and Hsu (2011) and only show the profiles from 0 to 3.5 m for the convenience of comparison. Generally, all the three modelled SSC profiles decrease away from the bed. A critical characteristic of SSC captured by Son and Hsu (2011) was that during the slack time (at 14h and 2h+1d, a noticeable amount sediment is still suspended in the water column. This is believed to be due to the lower SSC as during slack time, which causes smaller floc size and settling velocity. This phenomenon is somewhat better captured by JWF run in the present model (see vertical profiles at 14h and 2h in Fig. 6). In comparison with JWF run, the predicted SSC in JNF increases sharply from the surface to the bottom.

3.2.2 *Data 2*

Model simulations from 00:00 08/Aug/1996 to 00:00 09/Aug/1996 with and without the consideration of flocculation process are denoted as AWF (August With Flocculation) run and ANF (August No Flocculation) run, respectively. Again, it should be mentioned that, in the ANF run, if the settling velocity w_0 is set as 2.2×10^{-4} m/s as adopted in Data 1, the predicted results cannot even capture the gross features of the measured data. In order to ensure meaningful comparisons, the settling velocity is increased to 5×10^{-4} m/s, which is the value suggested by van der Ham and Winterwerp (2001). All parameters used in the simulation are listed in Table 3.

Table 3
Fitting parameters used in the simulation of Data 2

Run	Setting velocity w_0 (m/s)	Empirical coefficient $k_1 (\mathrm{m/s})\cdot(\mathrm{g/L})^{-\mathrm{m}}$	Site-dependent coefficient m	Erosion rate M (m/s)	$C_{\max}$ (kg/m^3)
ANF	5×10^{-4}	–	–	1.54×10^{-8}	0.25
AWF	–	1.5×10^{-3}	1.2	1.54×10^{-8}	0.25

The modelled shear stresses from both runs match the measurements well. The shear stress is again hardly affected by the flocculation process as expected and is not shown here because it does not add more than that already known from the results for the June data. The predicted time series of sediment concentration for both runs along with measured data at 0.3 m, 0.7 m and 1.4 m above the bed are shown in Fig. 7. The model results generally follow the trend of measured data. However, during the acceleration time (8:00-11:00), the SSC peaks of ANF run are higher at 0.3 m (dashed curve in the third panel of Fig. 7). The results of AWF run, which includes the effects of flocculation by using Equations (17) and (21), fit better with the measurements during both floods and ebbs. In the fourth panel of Fig. 7, the results for AWF run (solid curve) compare well with experimental data, whereas, a lower sediment concentration is predicted in ANF run (dashed curve). It can be concluded that for ANF run, higher sediment concentration peaks are predicted in the lower part of the water column (0.3 m) but a lower SSC is predicted in the upper part of the water column (1.4 m). But it should be noticed that, the model results in AWF (August case) are not as good as those in JWF (June case) when compared to measured data (see Fig 4 and Fig 7). It may be because the maximum sediment concentration in Data 2 is less than 0.5 kg/m^3 and the effects of flocculation decrease when sediment concentration decreases.

To quantitatively show the performances of both runs (AWF and ANF runs), the root-mean-square errors are shown in Table 2. As expected, the values of AWF run are smaller than those of ANF run. A similar explanation can be given as that for the June Data case. The vertical structures of SSC are shown in Fig. 8. It should be mentioned that a critical characteristic found is that a noticeable amount of sediment still suspended in the water column during the slack time, as captured in AWF run. For instance, at 8h or 20h, the SSC profile modelled by AWF run matches well with measured data, whereas, that modelled in ANF run is close to zero and the blue dashed line is coincident with the vertical coordinate. This indicates that the new drag force closure used to describe flocculation effects is appropriate and a reasonable representation of the reality.

4 Conclusion

A one-dimensional-vertical (1DV) Reynolds averaged two-phase model is developed and applied to simulate sediment suspension of Ems/Dollard estuary. The dataset consists of two periods of field measurements of flow and suspended sediment parameters when the tidal currents are dominant and waves are negligible. The model results confirm the previous findings that the flocculation effects are important at the study site but more importantly they have shown that neither treating the settling velocity of the flocs as a constant nor adopting seemingly more sophistic flocculation models gives better results of vertical distribution of suspended sediment concentration than those obtained from the simpler concentration-based settling velocity formulation that is adopted in this work. The vertical profile of SSC can be better captured especially during the slack tide when flocculation is considered. Overall, it can be concluded that more accurate predictions are obtained when the flocculation effects are considered using the new drag force closure. Though the sediment concentration is less than $1\,\mathrm{g/L}$ for both measuring periods and even less than $0.5\ \mathrm{g/L}$ for the August period, the results indicate that the flocculation process should be considered. But the flocculation effects may decrease due to the decrease of sediment concentration (less than 0.5 kg/m^3). The generally acceptable overall agreement between the measured data and numerical predictions (JWF and AWF runs) demonstrate the capability of the model.

The work presented is not designed to test the practical advantages of the two-phase modelling approach over the single-phase approach as the overall suspended sediment concentration in the data is rather low and the coupling between the two phases is too weak. With sediment concentration being less than $1\,\mathrm{kg/m^3}$ for Data 1 and less than 0.5 $\mathrm{kg/m^3}$ for Data 2, the dissipation of turbulence due to the existence of suspended sediment is negligible and the shear stress is hardly affected by the presence of solid phase. However, the flocculation process should be considered. The simulations including flocculation effects show a better agreement with the data than that without consideration of flocculation effects. With the new drag force closure which accounted explicitly for the flocculation process, more accurate settling velocity profiles are obtained and so are the sediment concentration profiles. As to future works, there is a clear need for the two-phase model to be further evaluated using data from estuaries with much higher flocs concentration and more appreciable phase coupling effects.

Acknowledgements

This work is supported by project from NSFC (Grant No. 51620105005).

References

Bian, C., Jiang, W., Quan, Q., Wang, T., Greatbatch, R.J., Li, W., 2013. Distributions of suspended sediment concentration in the yellow sea and the east china sea based on field surveys during the four seasons of 2011. Journal of Marine Systems 121-122, 24-35.

Camenen, B., Pham van Bang, D., 2011. Modelling the settling of suspended sediments for concentrations close to the gelling concentration. Continental Shelf Research 31, S106-S116.

Chauchat, J., Guillou, S., Pham Van Bang, D., Dan Nguyen, K., 2013. Modelling sedimentation–consolidation in the framework of a one-dimensional two-phase flow model. Journal of Hydraulic Research 51, 293-305.

Chen, W., Liu, W., Hsu, M., Hwang, C., 2015. Modeling investigation of suspended sediment transport in a tidal estuary using a three-dimensional model. Applied Mathematical Modelling 39, 2570-2586.

Delandmeter, P., Lewis, S.E., Lambrechts, J., Deleersnijder, E., Legat, V., Wolanski, E., 2015. The transport and fate of riverine fine sediment exported to a semi-open system. Estuarine, Coastal and Shelf Science 167, 336-346.

Dong, P., Zhang, K., 1999. Two-phase flow modelling of sediment motions in oscillatory sheet flow. Coastal Engineering 36, 87-109.

Dyer, K.R., Christie, M.C., Feates, N., Fennessy, M.J., Pejrup, M., van der Lee, W., 2000. An investigation into processes influencing the morphodynamics of an intertidal mudflat, the dollard estuary, the netherlands: I. Hydrodynamics and suspended sediment. Estuarine, Coastal and Shelf Science 50, 607-625.

Einstein, A., 1905. Eine neue bestimmung der moleküldimensionen.

Frankel, N.A., Acrivos, A., 1967. On the viscosity of a concentrated suspension of solid spheres. Chemical Engineering Science 22, 847-853.

Graham, A.L., 1981. On the viscosity of suspensions of solid spheres. Applied Scientific Research 37, 275-286.

Hsu, T., 2004. Toward modeling turbulent suspension of sand in the nearshore. Journal of Geophysical Research 109, 259-265.

Kornman, B.A., De Deckere, E.M.G.T., 1998. Temporal variation in sediment erodibility and suspended sediment dynamics in the dollard estuary. Geological Society, London, Special Publications 139, 231-241.

Kranenburg, C., 1998. Saturation concentrations of suspended fine sediment: Computations with the prandtl mixing-length model, Report No. 5 - 98. TU Delft.

Li, X., Zhu, J., Yuan, R., Qiu, C., Wu, H., 2016. Sediment trapping in the changjiang estuary: Observations in the north passage over a spring-neap tidal cycle. Estuarine, Coastal and Shelf Science 177, 8-19.

Maggi, F., 2013. The settling velocity of mineral, biomineral and biological particles and aggregates in water. Journal of Geophysical Research: Oceans 118, 2118-2132.

Merckelbach, L.M., Kranenburg, C., 2004. Equations for effective stress and permeability of soft mud–sand mixtures. Geotechnique 54, 235-243.

Nguyen, D.H., Levy, F., Pham Van Bang, D., Guillou, S., Nguyen, K.D., Chauchat, J., 2012. Simulation of dredged sediment releases into homogeneous water using a two-phase model. Advances in Water Resources 48, 102-112.

Ono, M., Deguchi, I., Sawaragi, T., 1996. Numerical modeling of sediment transport for various mode. Coastal Engineering Proceedings 1.
Percuoco, V.P., Kalnejais, L.H., Officer, L.V., 2015. Nutrient release from the sediments of the great bay estuary, n.H. USA. Estuarine, Coastal and Shelf Science 161, 76-87.
Son, M., Hsu, T., 2011. The effects of flocculation and bed erodibility on modeling cohesive sediment resuspension. Journal of Geophysical Research 116, C03021.
Talke, S.A., de Swart, H.E., 2006. Hydrodynamics and morphology in the ems/dollard estuary: Review of models, measurements, scientific literature, and the effects of changing conditions. IMAU.
Thorn, M.F.C., 1981. Physical processes of siltation in tidal channels, Hydraulic Modelling applied to Maritime Engineering Problems. ICE, London, pp. 47-55.
Toorman, E., 2002. Modelling of turbulent flow with suspended cohesive sediment. Proceedings in Marine Science 5, 155-169.
Toorman, E.A., 1996. Sedimentation and self-weight consolidation: General unifying theory. Geotechnique 46, 103-113.
Van Der Ham, R., Fontijn, H., Kranenburg, C., Winterwerp, J., 2001. Turbulent exchange of fine sediments in a tidal channel in the ems/dollard estuary. Part i: Turbulence measurements. Continental Shelf Research 21, 1605-1628.
van der Ham, R., Winterwerp, J.C., 2001. Turbulent exchange of fine sediments in a tidal channel in the ems/dollard estuary. Part ii. Analysis with a 1dv numerical model. Continental Shelf Research 21, 1629-1647.
Van der Lee, W.T.B., 2000. Temporal variation of floc size and settling velocity in the dollard estuary. Continental Shelf Research 20, 1495-1511.
van Leussen, W., 1999. The variability of settling velocities of suspended fine-grained sediment in the ems estuary. Journal of Sea Research 41, 109-118.
van Leussen, W., 2011. Macroflocs, fine-grained sediment transports, and their longitudinal variations in the ems estuary. Ocean Dynamics 61, 387-401.
Winterwerp, J.C., 1998. A simple model for turbulence induced flocculation of cohesive sediment. Journal of Hydraulic Research 36, 309-326.
Winterwerp, J.C., 2002. On the flocculation and settling velocity of estuarine mud. Continental Shelf Research 22, 1339-1360.
Xu, C., Dong, P., 2016. A dynamic model for coastal mud flocs with distributed fractal dimension. Journal of Coastal Research.

Figures

Fig.1

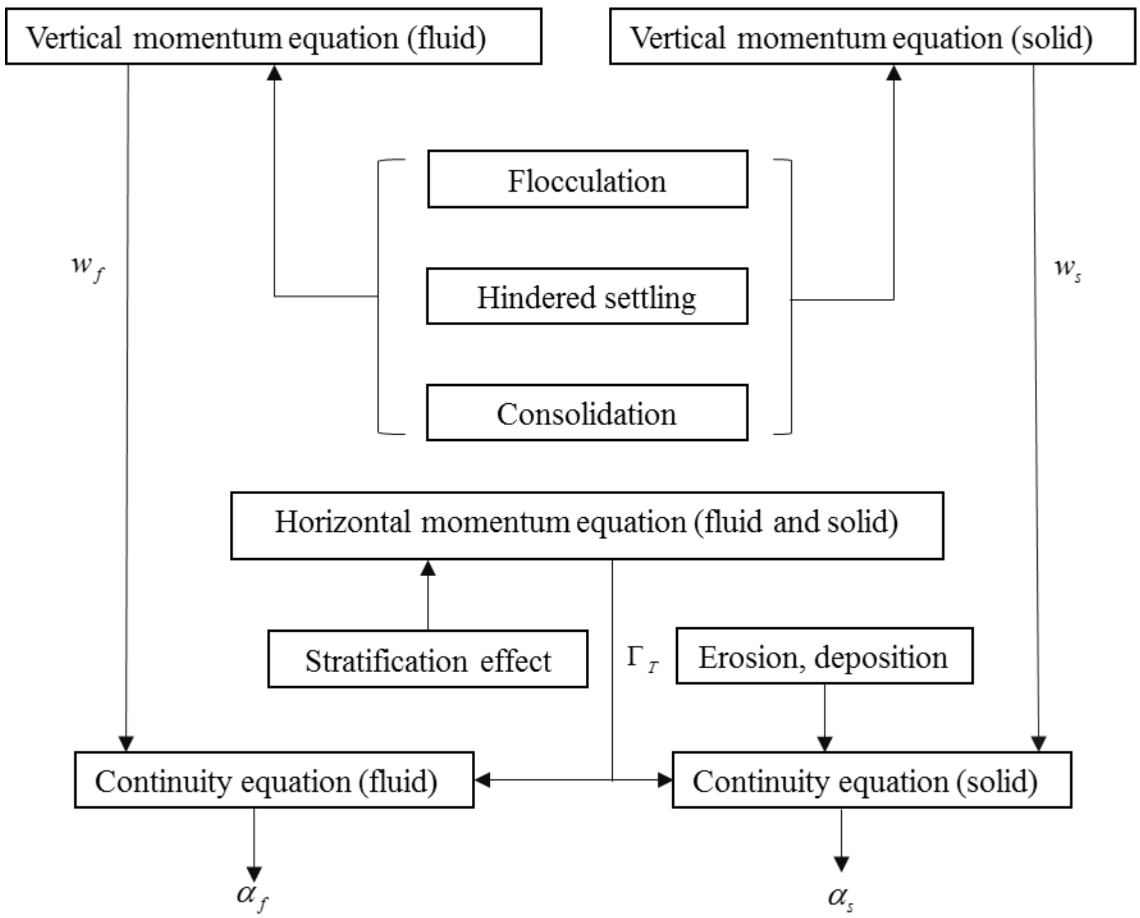

Fig. 1 Schematic diagram of two-phase model

Fig.2

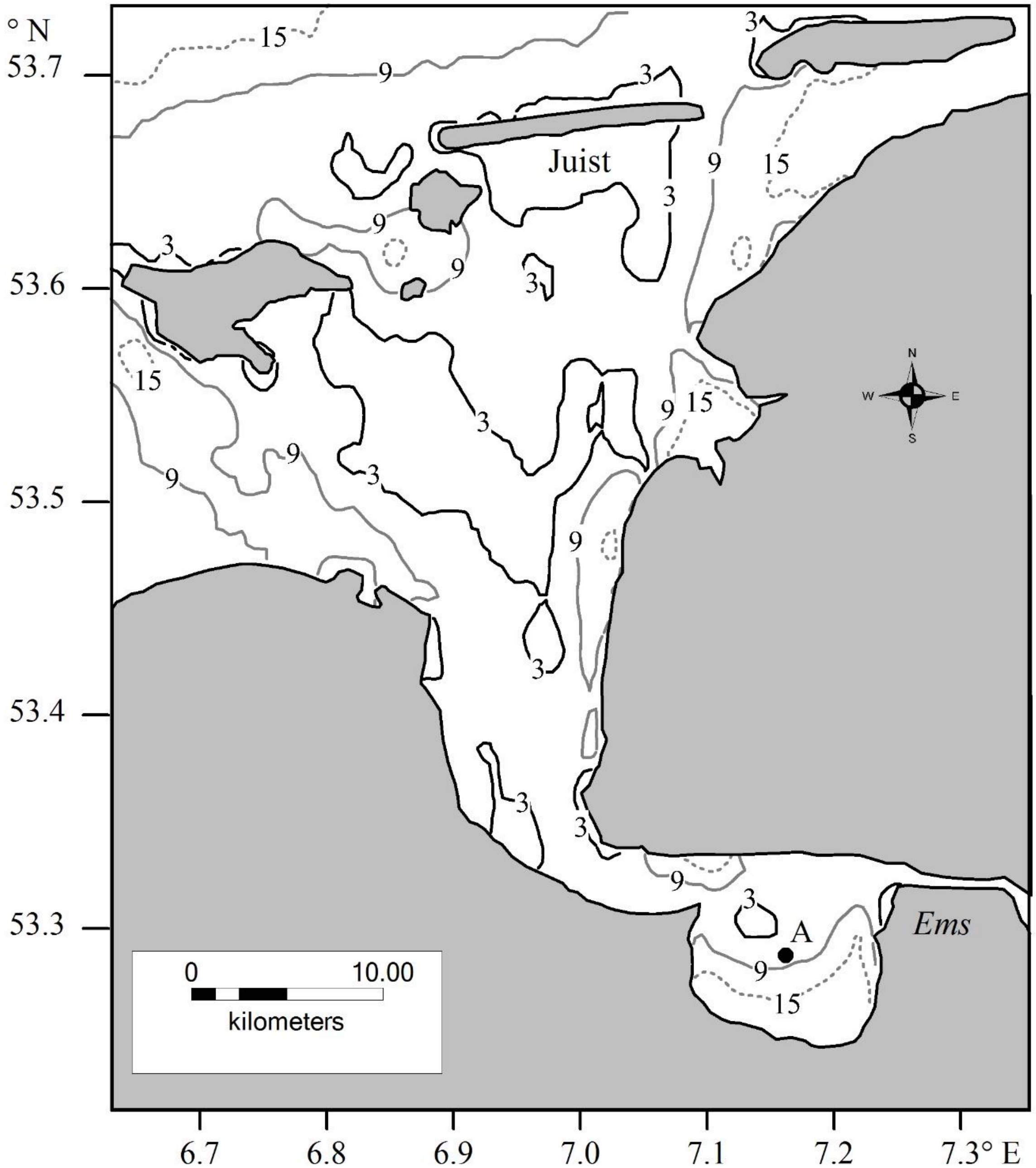

Fig. 2 The Ems/Dollard Estuary and the measuring point

Fig.3

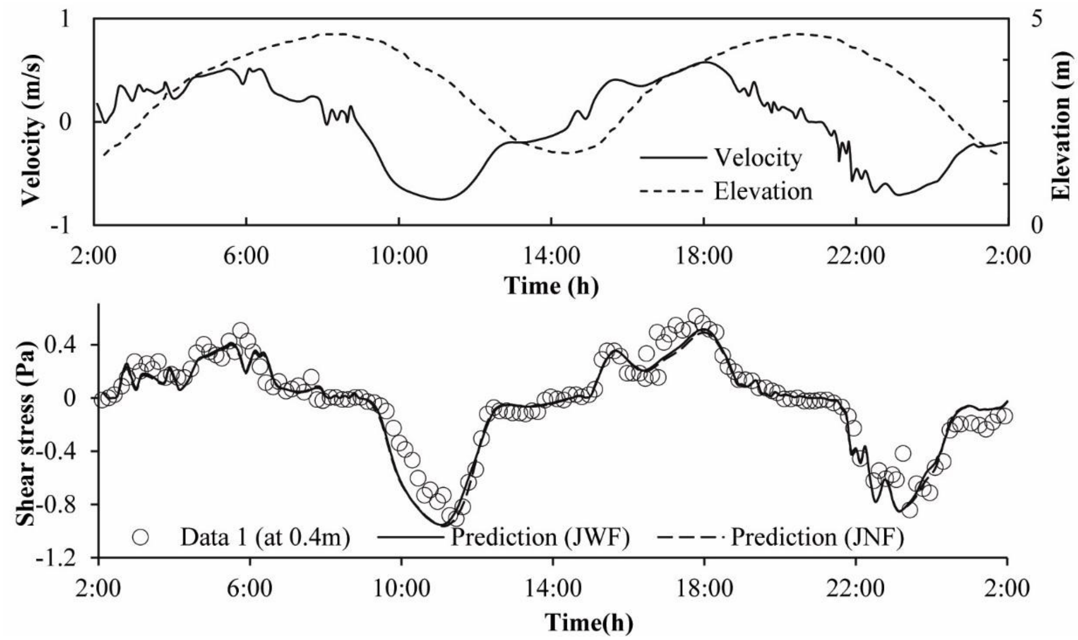

Fig. 3 The measured shear stress by Van Der Ham et al. (2001) at 0.4 m above the bed (cycles) in June measuring period and numerical prediction from run JWF (solid curve with the effects of flocculation) and run JNF (dashed curve without the effects of flocculation). The tidal elevation (dashed curve) and depth-averaged velocity (solid curve) are shown in the first panel.

Fig.4

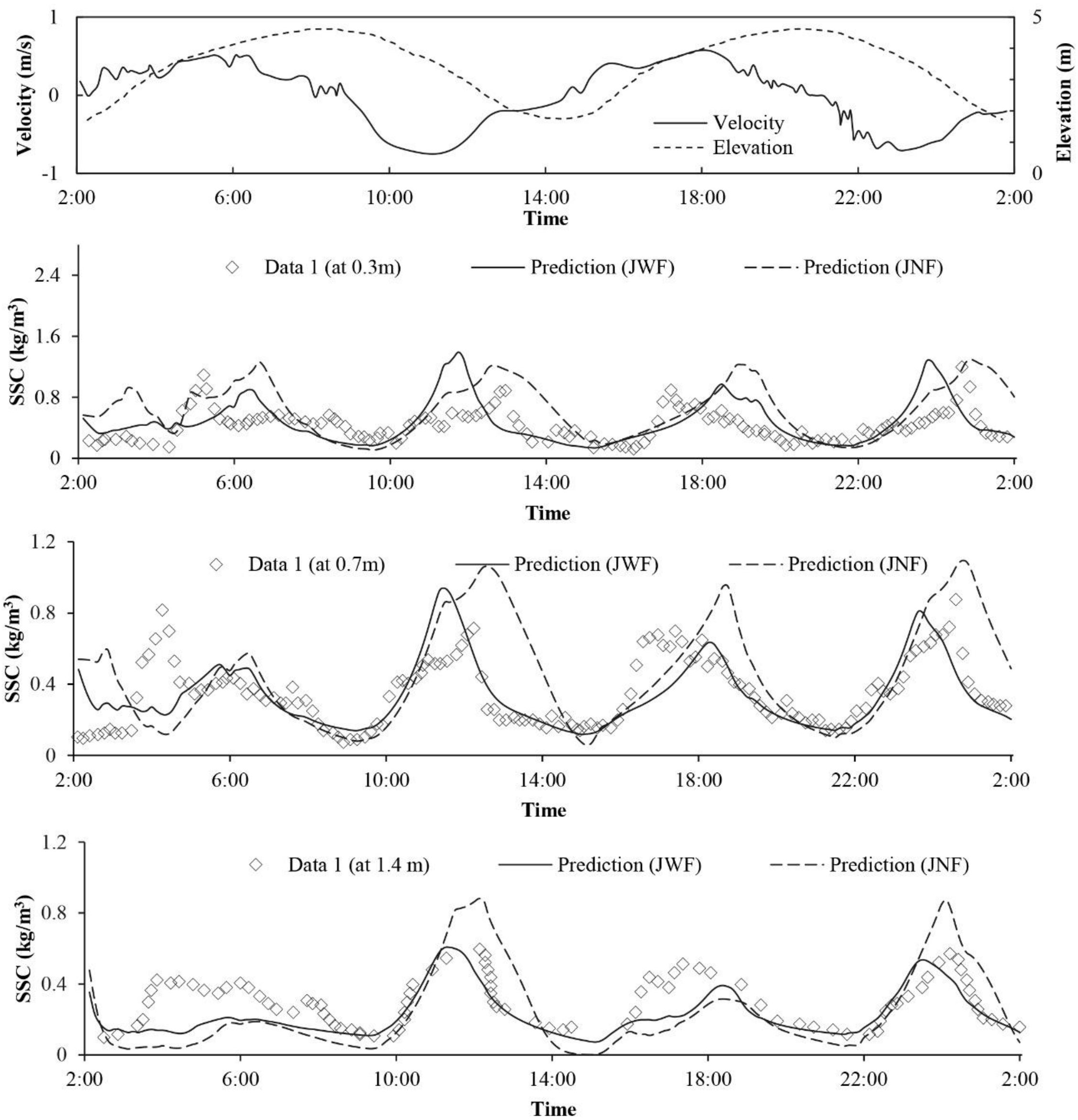

Fig. 4 The measured variations of SSC by Van Der Ham et al. (2001) at 0.3 m (the second panel), 0.7 m (the third panel) and 1.4 m (the fourth panel) above the bed (diamonds) in June measuring period, numerical prediction from run JWF (solid curve) and run JNF (dashed curve). The tidal elevation (dashed curve) and depth-averaged velocity (solid curve) are shown in the first panel.

Fig.5

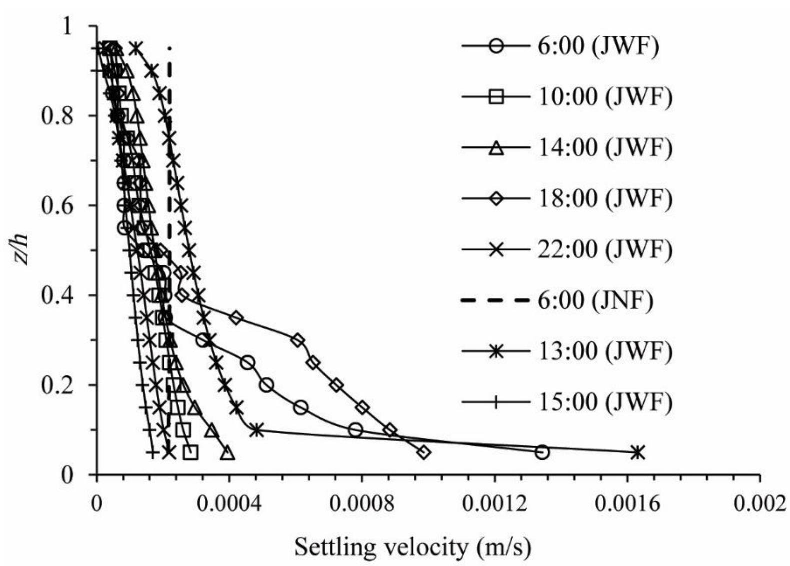

Fig. 5 Vertical profile of settling velocity predicted in JWF and JNF at different time

Fig.6

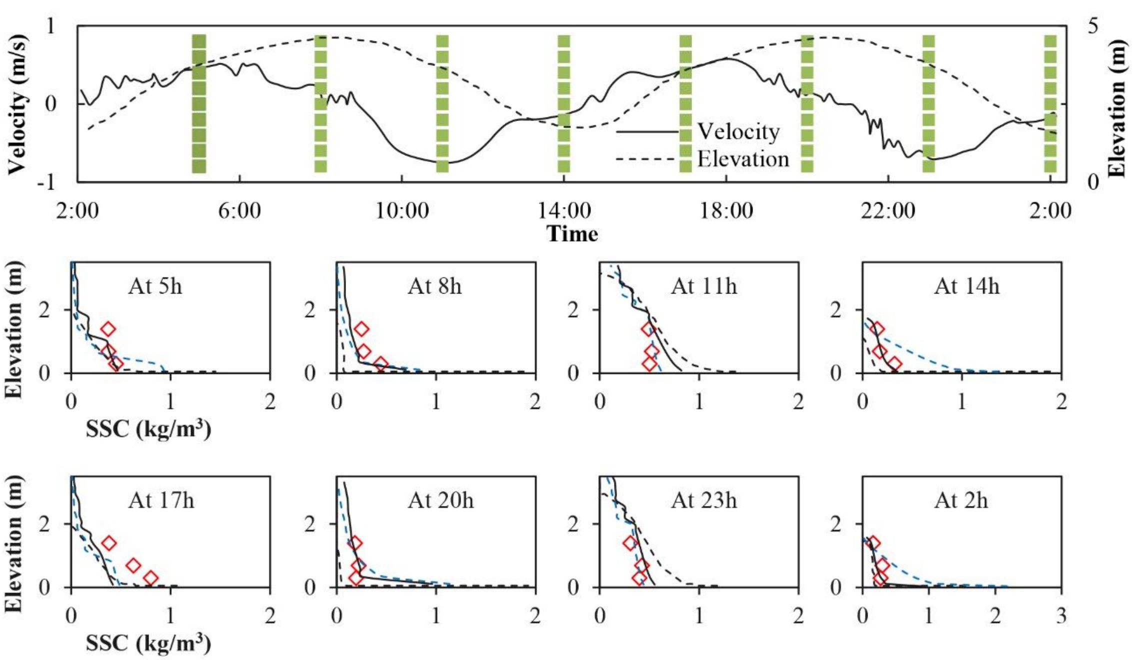

Fig. 6 Measured (diamonds) and modelled sediment concentration profile of run JWF (solid curves), run JNF (blue dashed curves) and model by Son and Hsu (2011) (dashed

curves). The tidal elevation (dashed curve) and depth-averaged velocity (solid curve) are shown in the first panel.

Fig.7

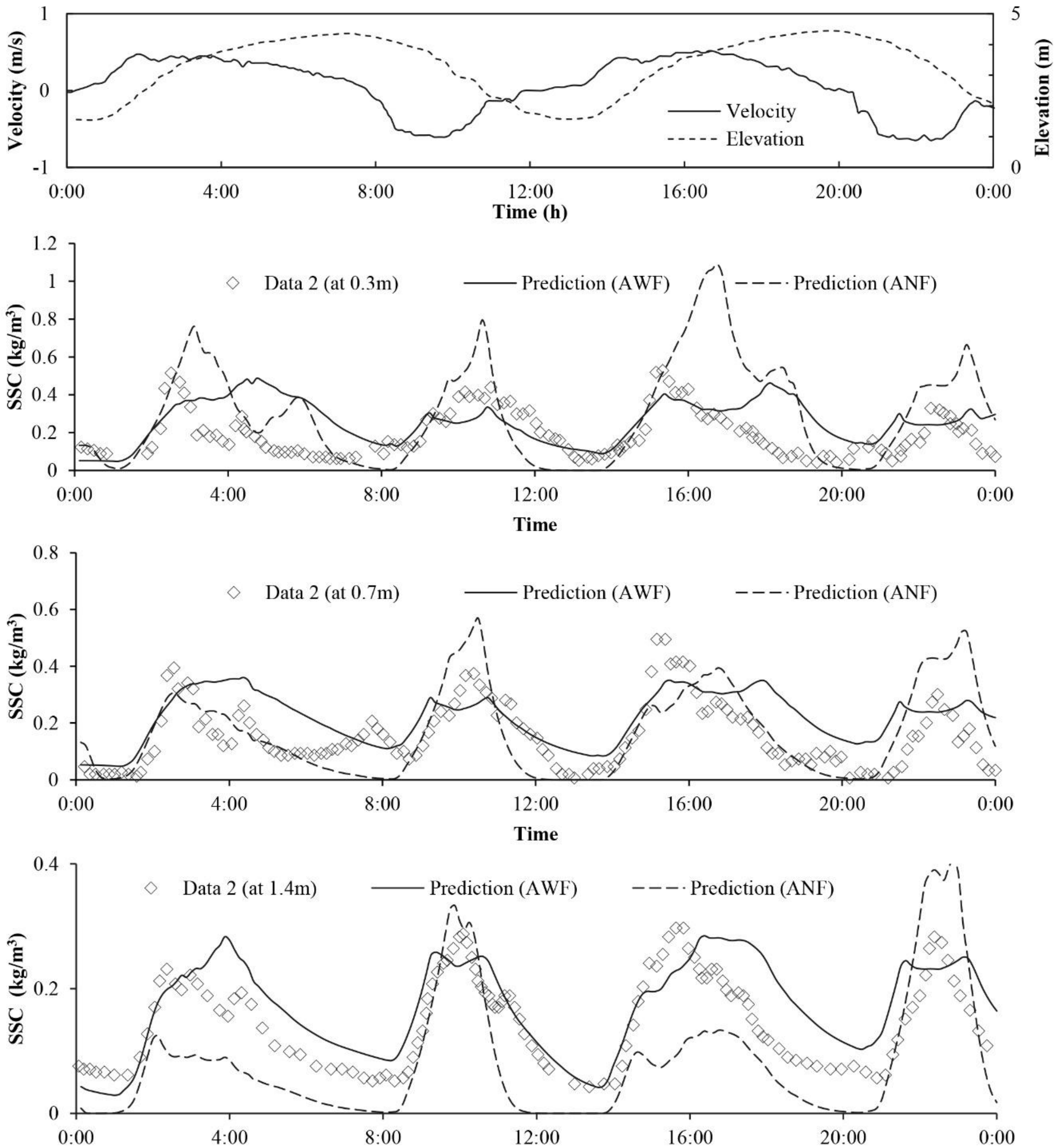

Fig. 7 The measured variations of SSC by Van Der Ham et al. (2001) at 0.3 m (the second panel) 0.7 m (the third panel) and 1.4 m (the fourth panel) above the bed (diamonds) in August measuring period, numerical prediction from run JWF (solid curve)

and run JNF (dashed curve). The tidal elevation (dashed curve) and depth-averaged velocity (solid curve) are shown in the first panel.

Fig.8

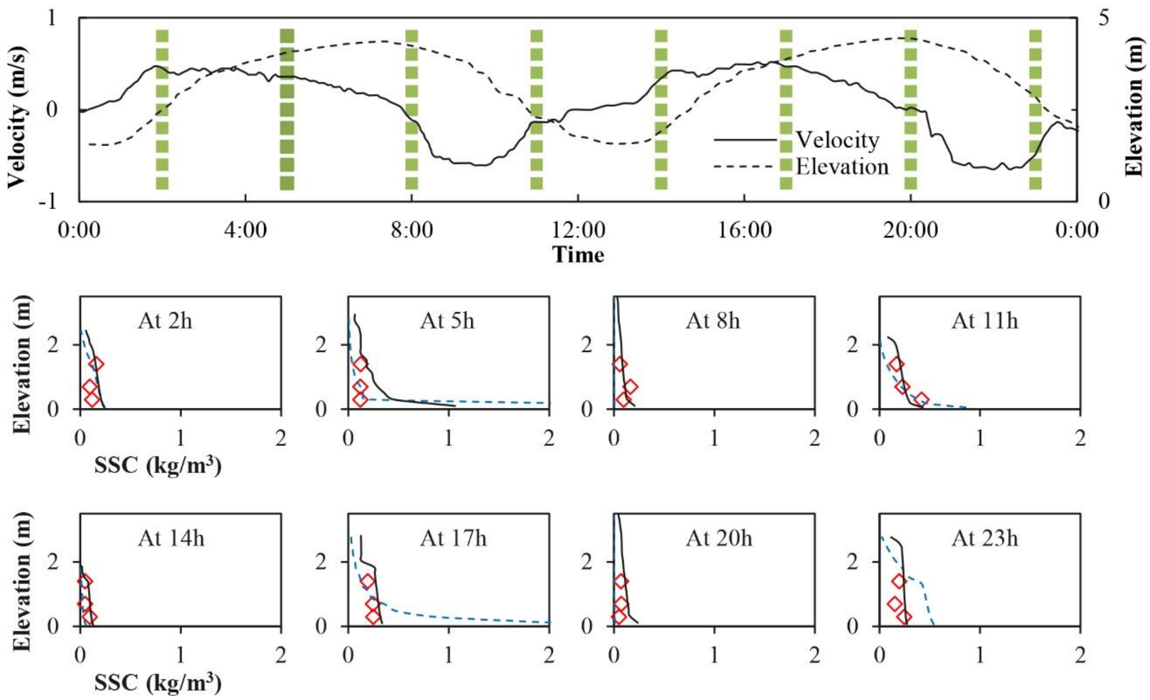

Fig. 8 Measured (diamonds) and modelled sediment concentration profile of run JWF (solid curves) and run JNF (blue dashed curves). The tidal elevation (dashed curve) and depth-averaged velocity (solid curve) are shown in the first panel.

Figure(s)

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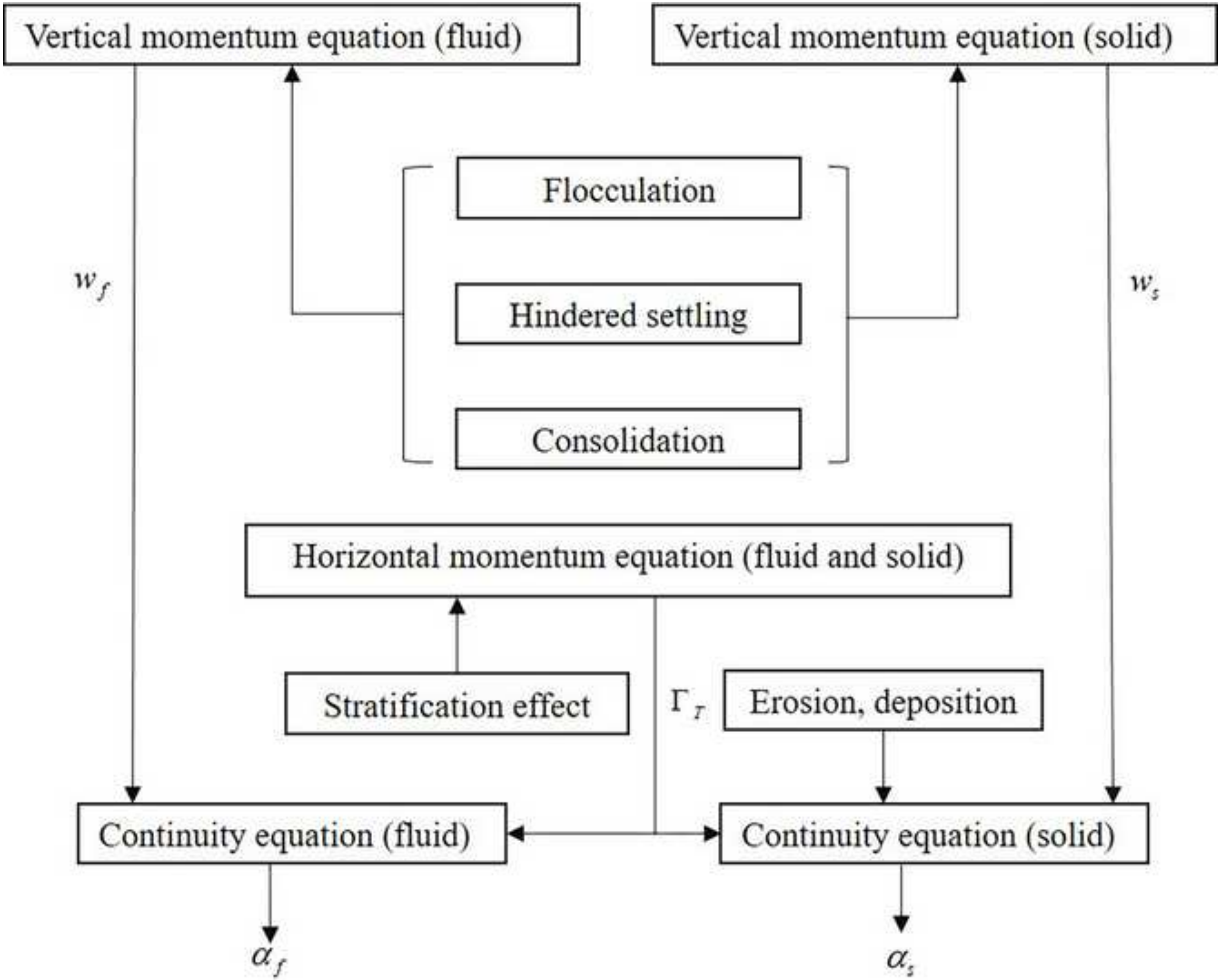

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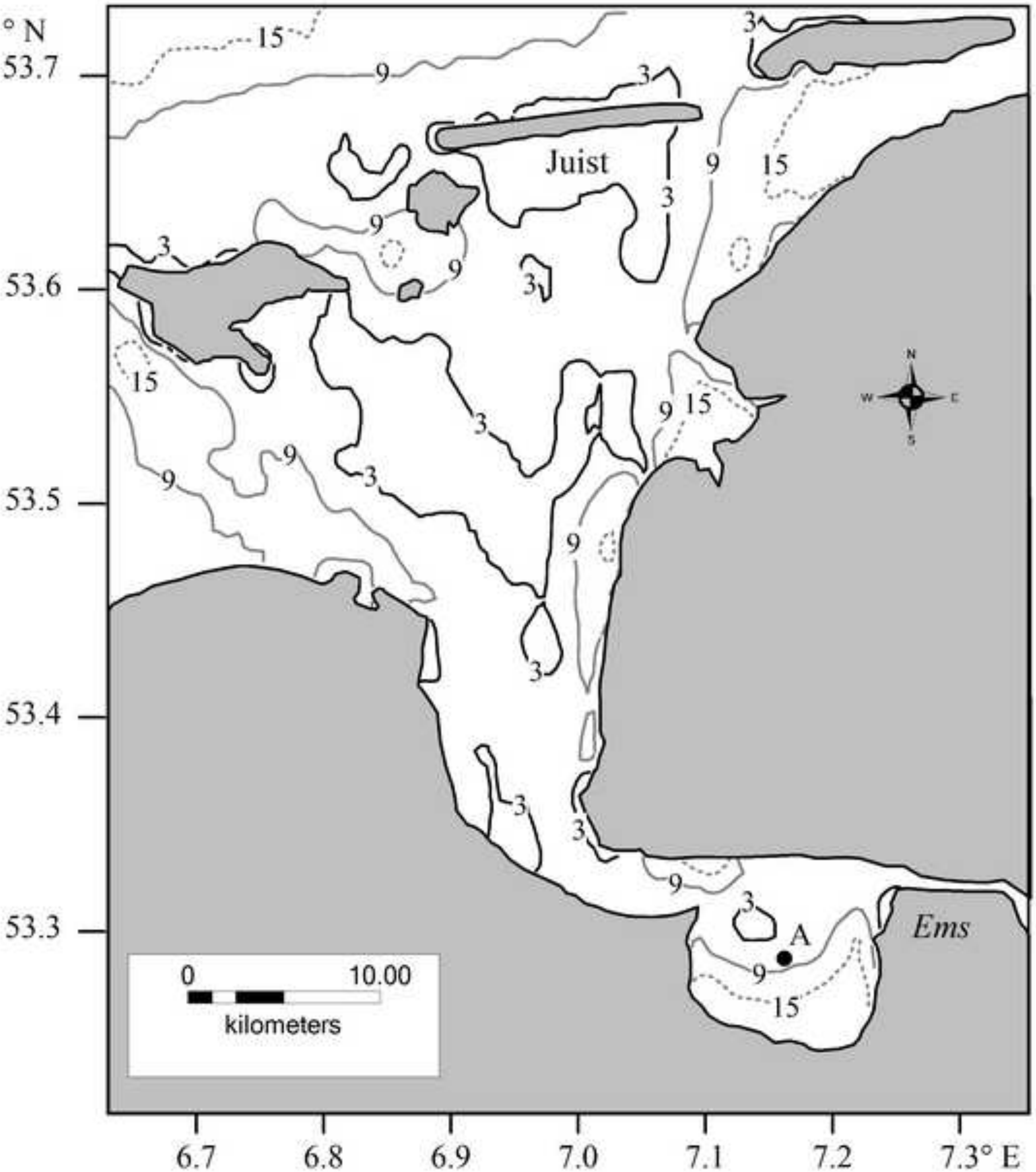

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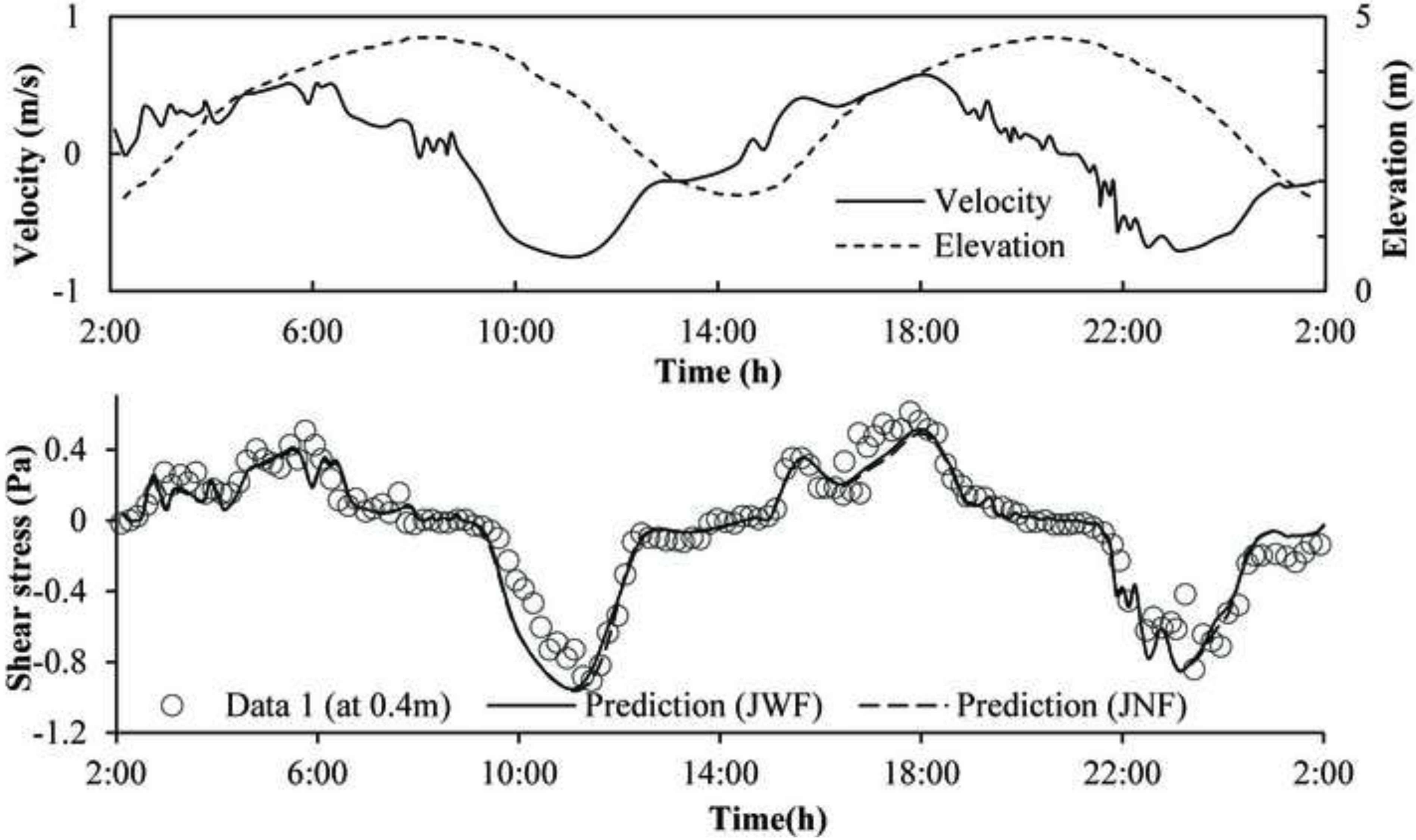

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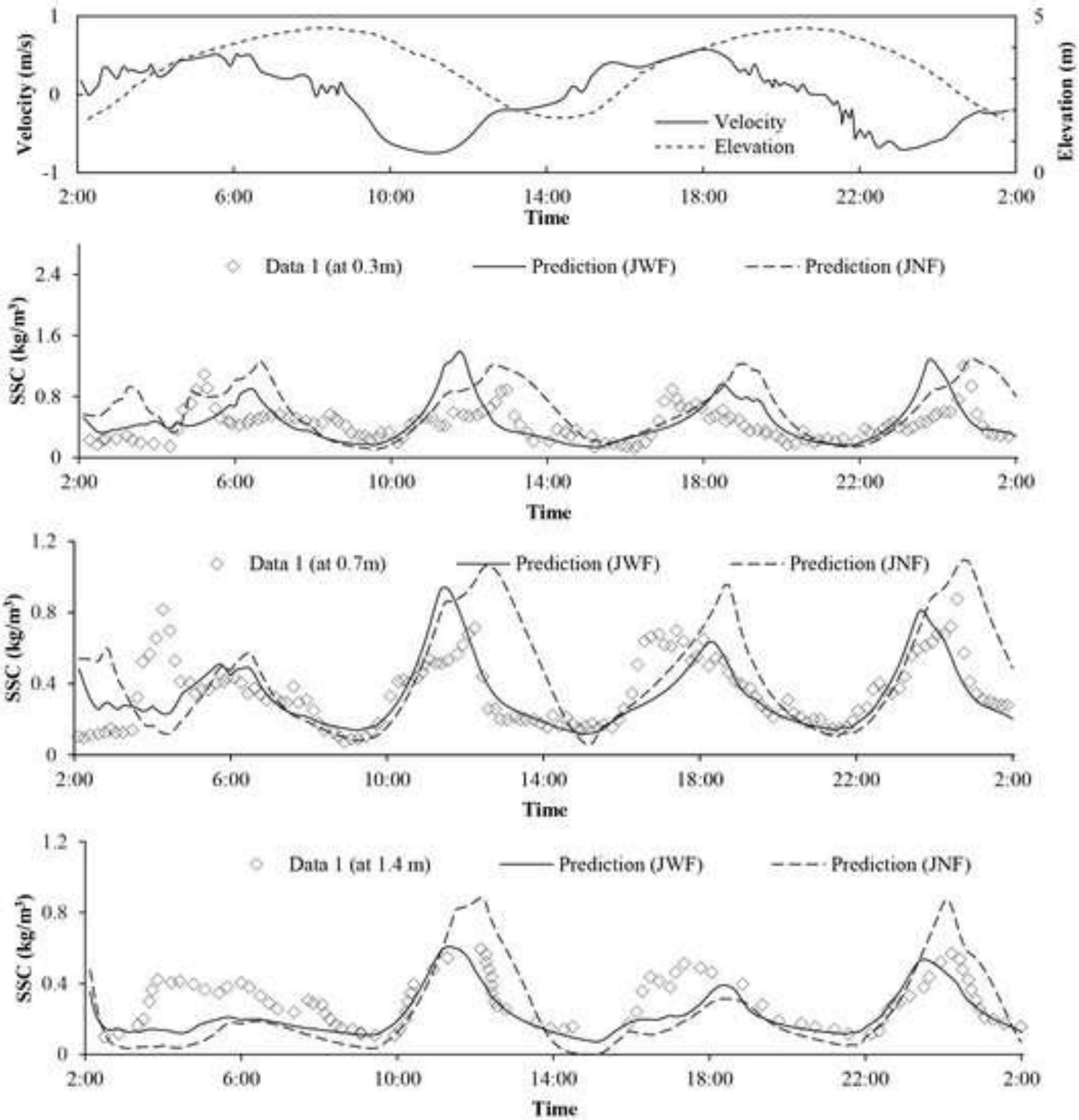

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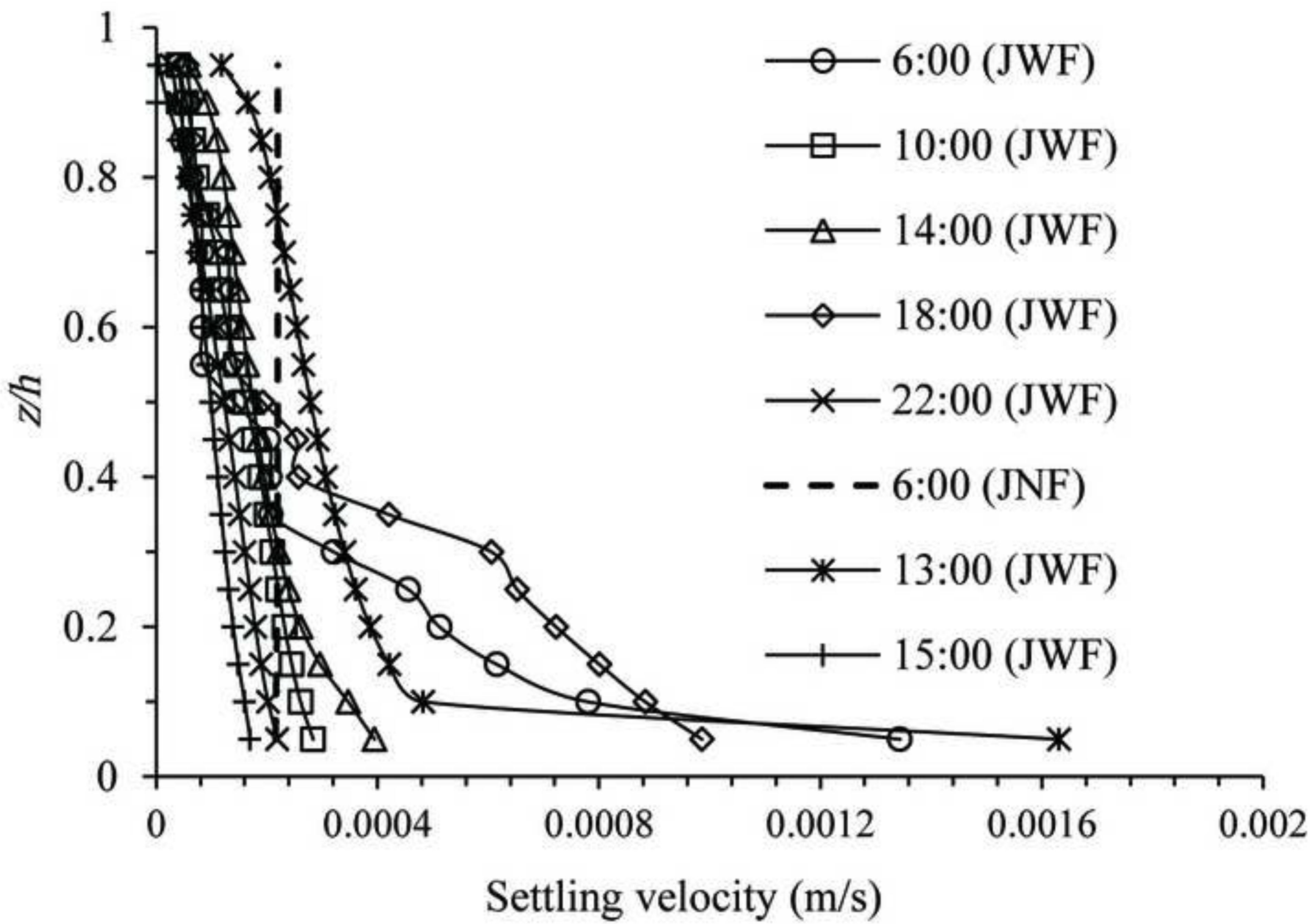

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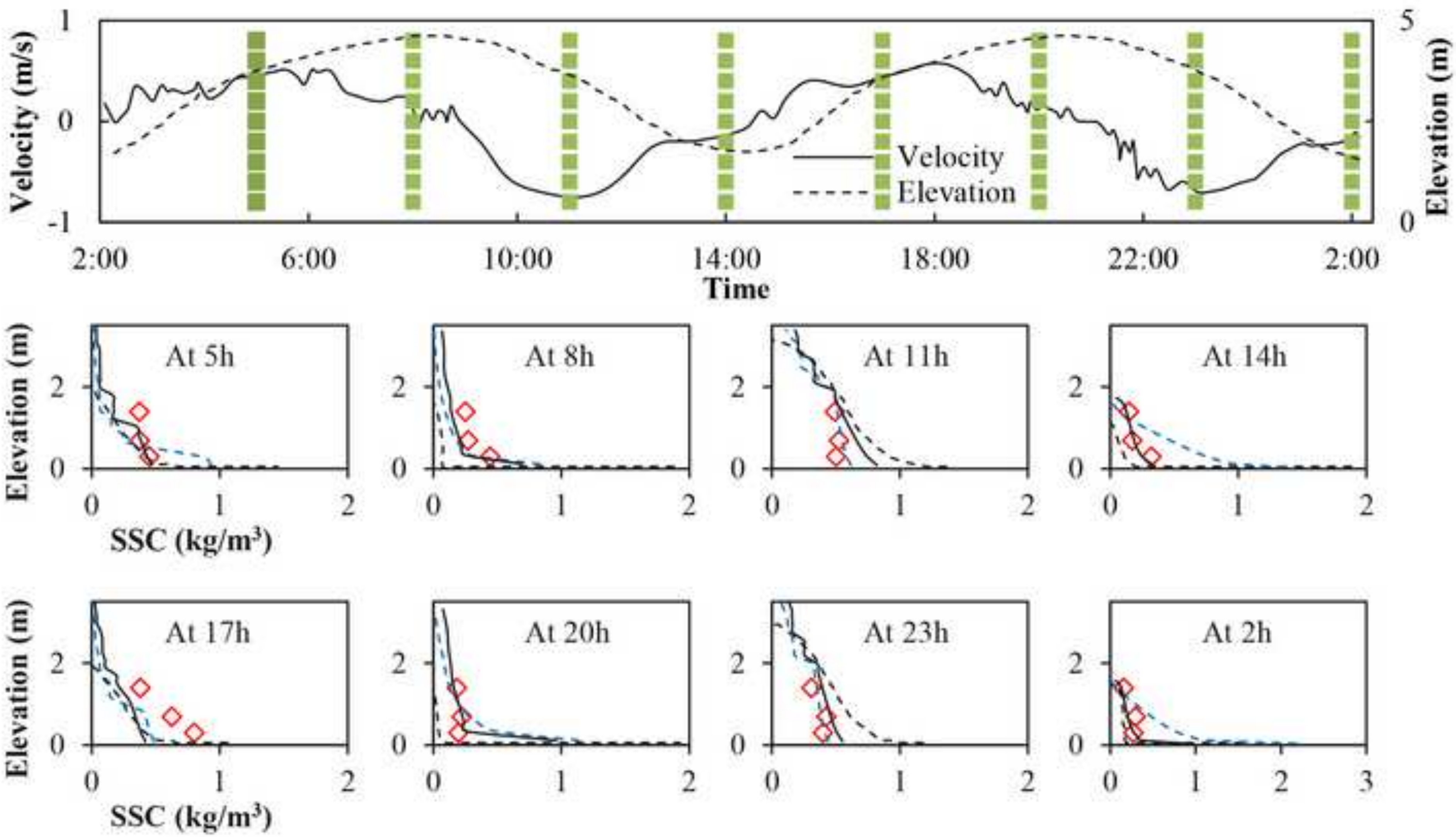

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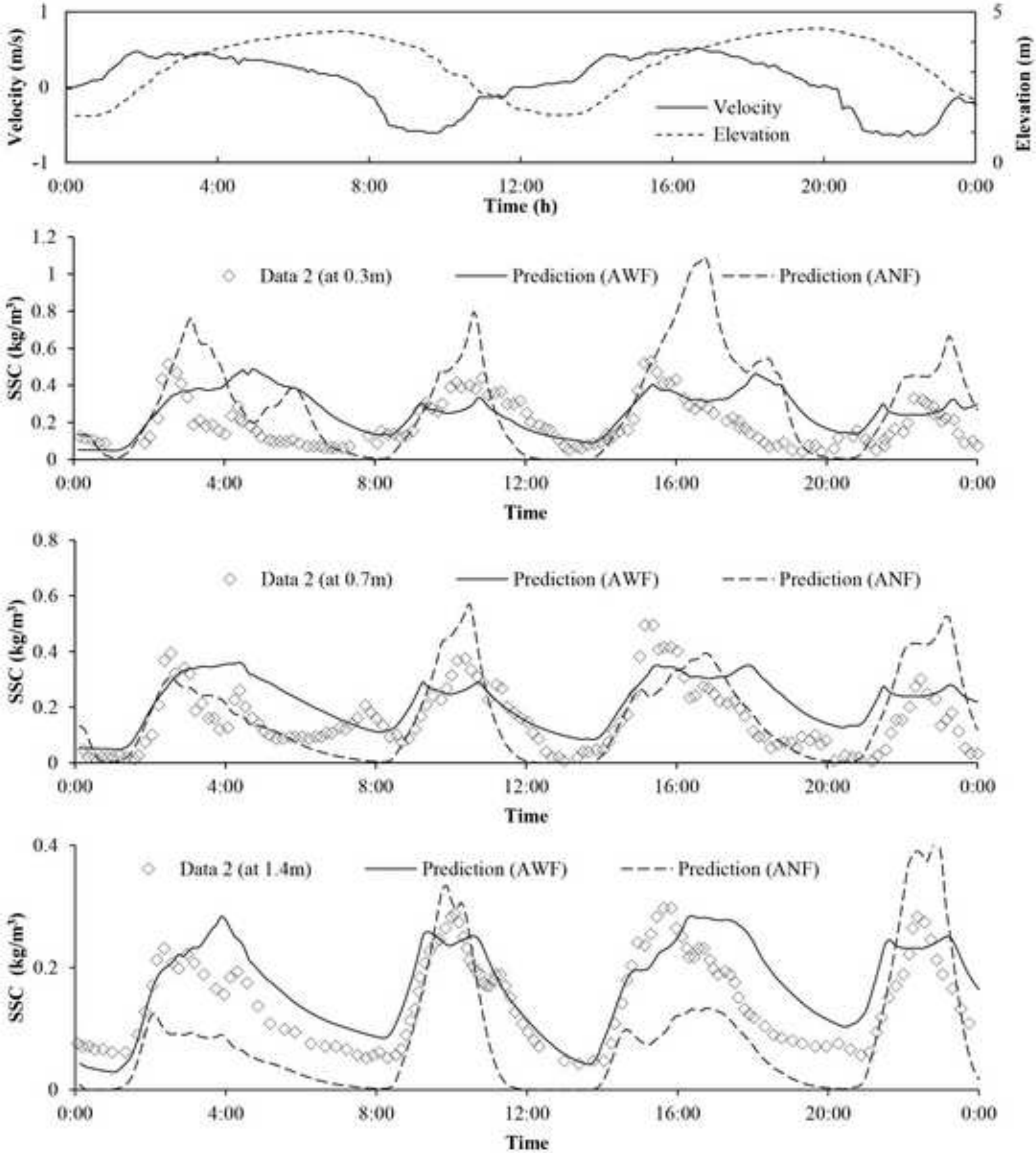

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