

Modelling fine-grained sediment transport in the Mahakam land–sea continuum, Indonesia

Pham Van, Chien; Gourgue, Olivier; Sassi, Maximiliano; Hoitink, Ton; Deleersnijder, Eric; Soares-Frazão, Sandra

DOI

[10.1016/j.jher.2015.04.005](https://doi.org/10.1016/j.jher.2015.04.005)

Publication date

2016

Published in

Journal of Hydro-Environment Research

Citation (APA)

Pham Van, C., Gourgue, O., Sassi, M., Hoitink, T., Deleersnijder, E., & Soares-Frazão, S. (2016). Modelling fine-grained sediment transport in the Mahakam land–sea continuum, Indonesia. *Journal of Hydro-Environment Research*, 13, 103-120. <https://doi.org/10.1016/j.jher.2015.04.005>

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

Accepted Manuscript

Modelling fine-grained sediment transport in the Mahakam land-sea continuum,
Indonesia

Chien Pham Van, Olivier Gourgue, Maximiliano Sassi, A.J.F. Hoitink, Eric
Deleersnijder, Sandra Soares-Frazão



PII: S1570-6443(15)00043-X

DOI: [10.1016/j.jher.2015.04.005](https://doi.org/10.1016/j.jher.2015.04.005)

Reference: JHER 330

To appear in: *Journal of Hydro-environment Research*

Received Date: 20 August 2014

Revised Date: 9 March 2015

Accepted Date: 5 April 2015

Please cite this article as: Pham Van, C., Gourgue, O., Sassi, M., Hoitink, A.J.F., Deleersnijder, E., Soares-Frazão, S., Modelling fine-grained sediment transport in the Mahakam land-sea continuum, Indonesia, *Journal of Hydro-Environment Research* (2015), doi: 10.1016/j.jher.2015.04.005.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 **Modelling fine-grained sediment transport in the Mahakam land-sea**
2 **continuum, Indonesia**

Chien Pham Van ^{1,2,*}, Olivier Gourgue^{3,4}, Maximiliano Sassi⁵, A.J.F. (Ton) Hoitink⁶,
Eric Deleersnijder^{7,8}, Sandra Soares-Frazão¹

¹ Institute of Mechanics, Materials and Civil Engineering (IMMC), Université catholique de Louvain, Place du Levant 1, Louvain-la-Neuve, Belgium

² Faculty of Hydrology and Water Resources, Water Resources University, Tayson 175, Dongda district, Hanoi, Vietnam.

³ Department of Hydrology and Hydraulic Engineering (HYDR), Vrije Universiteit Brussel, Pleinlaan 2, Brussels, Belgium.

⁴ Flanders Hydraulics Research, Flemish Government, Berchemlei 115, Antwerp, Belgium.

⁵ Royal Netherlands Institute for Sea Research, NIOZ, Den Burg, The Netherlands.

⁶ Hydrology and Quantitative Water Management Group, Department of Environmental Sciences, Wageningen University, Droevendaalsesteeg 4, Wageningen, The Netherlands.

⁷ Institute of Mechanics, Materials and Civil Engineering (IMMC), Université catholique de Louvain, Avenue Georges Lemaître 4, Louvain-la-Neuve, Belgium.

⁸ Georges Lemaître Centre for Earth and Climate Research (TECLIM), Earth and Life Institute (ELI), Université catholique de Louvain, Place Louis Pasteur 3, Louvain-la-Neuve, Belgium.

* Corresponding author: email: chien.phamvan@uclouvain.be, telephone: +32/10472124, fax: +32/10472179

Abstract

SLIM is an unstructured mesh, finite element model of environmental and geophysical fluid flows, which is being improved to simulate fine-grained sediment transport in riverine and marine water systems. A 2D depth-averaged version of the model is applied to the Mahakam Delta (Borneo, Indonesia), the adjacent ocean, and three lakes in the central part of the Mahakam River catchment. The 2D code is coupled to a 1D section-averaged model for the Mahakam River and four tributaries. The coupled 2D/1D model is mainly aimed at simulating fine-grained sediment transport in the riverine and marine water continuum of the Mahakam River system. Using the observations of suspended sediment concentration (SSC) at five locations in the computational domain, the modelling parameters are first determined in a calibration step, for a given period of time. A validation step is then performed using data related to another period of time. It is concluded that the coupled 2D/1D model reproduces very well the observed suspended sediment distribution within the delta. The spatial distribution of sediment concentration in the delta and its temporal variation are also discussed.

Keywords

Mahakam land-sea continuum, fine-grained sediment, finite element model, coupled 2D/1D model

1. Introduction

Sediments are inherent components of riverine and marine waters, which are transported under the form of fine- or coarser-grained material. The coarser-grained sediment often occurs during episodic and/or anomalous events, e.g. floods or waves associated with strong onshore winds in deltaic or coastal regions (Gastaldo et al., 1995), and usually involves significant bed evolution or morphological changes. On the other hand, considerable attention has been paid to fine-grained sediment transport due to its important role in the fields of coastal engineering, geomorphology, and aquatic ecology (Lou and Ridd, 1997; Turner and Millward, 2002; Hoitink, 2004; Edmonds and Slingerland, 2010; Buschman et al., 2012). High concentration of fine-grained sediment can impact deltaic morphology (Edmonds and Slingerland, 2010), controlling smooth or rough shorelines, flat or complex floodplains of tidal channels as well as navigation and flood mitigation infrastructure. Fine-grained sediment can also result in the degradation of water quality because of the adsorption of organic chemicals and trace metal (Wu et al., 2005; Mercier and Delhez, 2007; Elskens et al., 2014). Therefore, transport and accumulation of fine-grained sediment require to be assessed quantitatively in order to deal with the potential reduction in water quality, the adsorption of toxic substances, and the aquatic food production (van Zwieten et al., 2006; Chaîneau et al., 2010).

Fine-grained sediment particles are moving over the water column and are continuously interacting with the seabed through entrainment or deposition. The movement of sediment particles is caused by a wealth of forces that cannot be represented in detail in most sediment transport model. The submerged weight (i.e. the difference between the gravitational force and Archimedes' buoyancy) tends to pull the particles downward at any time and location, whereas the hydrodynamic force, due to the water flow around every sediment particle, may point upward or downward, depending on the circumstances. The latter force is usually dominated by the drag due to turbulent motion, but this is not the

48 only phenomenon at work. Clearly, the net sediment flux at the bottom may point
49 downward or upward according to the orientation of the resultant of the forces acting on
50 the sediment particles. The transport of fine-grained sediment inherently indicates
51 complicated processes because of the variation of the flow dynamics and various sediment
52 sources. The latter can consist of (i) sediments originating from terrestrial erosion in the
53 river catchment, riverbed, and river banks, (ii) sediments forming by erosion of coastal
54 areas (van Zwieten et al., 2006), and (iii) sediments re-mobilizing from within the area of
55 interest (Winterwerp, 2013). Moreover, according to Turner and Millward (2002), the
56 transport of fine-grained sediment is particularly complex in deltas and coastal regions,
57 where the prevalence and characteristics of sediment transport are affected by both riverine
58 and marine forcings, e.g. river flow, tide, wind, and waves. Studying fine-grained sediment
59 in a water system under these riverine and marine forcings and various sediment sources is
60 thus one of the major challenges forced by scientists and engineers (Winterwerp, 2013).

61 Understanding of fine-grained sediment transport processes in a riverine and marine
62 water system is limited by the lack of field measurements and the difficulty to obtain such
63 measurements due to the high spatial and temporal variability of the phenomena at stake.
64 This variability in the system results from various factors, e.g. human activities,
65 availability of sediment sources, changes of land use and soil texture in contributing areas,
66 water discharge and tides. Regarding the modelling of such processes, an integrated
67 approach, which allows for a representation of the transfer of sediment from the river to the
68 coastal ocean and the deep margin, is essential and still is a challenging task. Although
69 existing studies primarily investigate sedimentary processes locally, it is now becoming
70 computationally feasible to adopt an integrated system approach, without excessive
71 simplification of the physical processes resolved by the model. In this context, the present
72 research mainly focuses on simulating in a depth-averaged framework the transport of fine-

73 grained sediment and its transport in the delta region of the Mahakam land-sea continuum
74 water system.

75 The Mahakam land-sea continuum is associated with the Mahakam River, which is the
76 second longest river in Kalimantan, Indonesia (Figure 1). Existing studies on fine-grained
77 sediment transport in the Mahakam surface water system are either local, zooming onto
78 particular sites (e.g. Hardy and Wrenn, 2009; Budhiman et al., 2012), or regional, focusing
79 on sedimentary processes in a geological and morphological context (e.g. Gastaldo and
80 Huc, 1992; Gastaldo et al., 1995; Storms et al., 2005). Among the numerical studies
81 performed to investigate the concentration profiles of fine-grained sediment in the modern
82 Mahakam Delta, some have been conducted recently using a three-dimensional finite
83 difference model, ECOMSED, with a structured grid that has a resolution of 200 meters
84 (Hadi et al., 2006; Mandang and Yanagi, 2009). However, such a coarse horizontal grid
85 resolution is unlikely to be suitable to represent both the complex shorelines and the
86 numerous small tidal channels existing in the delta. In addition, these numerical studies
87 validated the modelling parameters over a period of only a few days, and under low flow
88 conditions only, implying that the results obtained in these studies might not be considered
89 as representative of long-term variation of fine-grained sediment in the delta under
90 significant changes of river flow and tides.

91 A model of fine-grained sediment transport in the Mahakam Delta should be able to
92 cope with a wide range of temporal and spatial scales of several physical processes
93 interacting with each other (de Brye et al., 2011). Therefore, the unstructured mesh, finite
94 element model SLIM (Second-generation Louvain-la-Neuve Ice-ocean Model,
95 www.climate.be/slim) is well suited to the task due to its ability to deal with multi-physics
96 and multi-scale processes in space and time, especially in coastal regions (Deleersnijder
97 and Lermusiaux, 2008). This is because unstructured meshes allow for a more accurate
98 representation of complex coastlines and an increase in spatial resolution in areas of

99 interest. SLIM solves the shallow-water and advection-diffusion equations including
100 turbulent source terms by using a discontinuous Galerkin finite element scheme for the
101 spatial discretization and second-order diagonally implicit Runge-Kutta time stepping.
102 Although the model was initially developed for simulating flows in coastal areas (e.g.
103 Bernard et al., 2007; Lambrechts et al., 2008b; de Brye et al., 2010; Pham Van et al., under
104 review), the potential has been widened to simulate sediment transport in estuaries and
105 inland waterways (e.g. Lambrechts et al., 2010; Gourgue et al., 2013).

106 Regarding the Mahakam Delta and adjacent coastal region of the Mahakam land-sea
107 continuum, whose area is of the order of thousands of square kilometers, using a full-
108 fledged three-dimensional (3D) model for simulating the suspended sediment is likely to
109 exceed the available computer resources. Moreover, as the delta is relatively well-mixed
110 (Storms et al., 2005), a two-dimensional (2D) version of SLIM is believed to be sufficient
111 on the delta and adjacent coastal region, and the one-dimensional (1D) version of SLIM is
112 employed for the rest of the domain (i.e. Mahakam River and tributaries upstream of the
113 delta).

114 Coupled 2D/1D models have been widely used for practical applications. For example,
115 Wu and Li (1992) applied a coupled 2D/1D quasi-steady model to study sedimentation in
116 the fluctuating backwater region of the Yangtze River (China). Zhang (1999) used a 2D/1D
117 unsteady model to simulate flow and sediment transport in the offshore area near the
118 Yellow River mouth (China). Martini et al. (2004) applied a coupled 2D/1D model for
119 simulating flood flows and suspended sediment transport in the Brenta River (Veneto,
120 Italy). Wu et al. (2005) combined 2D and 1D numerical models to predict the
121 hydrodynamics and sediment transport in the Mersey Estuary (United Kingdom). More
122 recently, de Brye et al. (2010) developed a coupled 2D/1D finite element model for
123 simulating flow dynamics and salinity transport in the Scheldt Estuary and tidal river
124 network, and then Gourgue et al. (2013) developed a sediment module in the same

125 modelling framework to simulate fine-grained sediment transport. These examples suggest
126 that the transport of fine-grained sediment in the considered system is likely to be dealt
127 with reasonably well by a coupled 2D/1D model.

128 The main objectives of the present study are (i) to simulate the fine-grained sediment
129 transport within the domain of interest comprising the Mahakam River and tributaries,
130 lakes, the delta as well as the adjacent coastal area of the Mahakam land-sea continuum, (ii)
131 to accurately reproduce the measured sediment concentration at different locations in the
132 system, and (iii) to provide a preliminary investigation of the spatial distribution and
133 temporal variation of sediment concentration in the delta and the tidal river network, under
134 different river flow and tidal conditions. Besides these objectives, it has to be emphasized
135 that the present work is the first attempt to simulate the fine-grained sediment transport in
136 the Mahakam Delta and adjacent coastal region using an unstructured grid, finite element
137 model, which allows for taking into account the very complex geometry and topography of
138 computational domain. Furthermore, to the best of our best knowledge, the current study is
139 also the first one, in which the fine-grained sediment transport from riverine to marine
140 regions is included in one single model so as to capture the interactions between the
141 interconnected regions of the system.

142 **2. Model domain**

143 **2.1. Mahakam river-delta-coastal system**

144 The Mahakam Delta is a mixed tidal and fluvial delta, including a large number of actively
145 bifurcating distributaries and tidal channels (Figure 1). The delta is symmetrical and
146 approximately 50 km in radius, as measured from the delta shore to the delta apex. The
147 width of the channels in the deltaic region ranges from 10 m to 3 km. The Mahakam Delta
148 discharges into the Makassar Strait, whose width varies between 200 and 300 km, with a
149 length of about 600 km. Located between the islands of Borneo and Sulawesi, the
150 Makassar Strait is subject to important heat and water transfer from the Pacific to the

151 Indian Ocean by the Indonesian Throughflow (Susanto et al., 2012). Due to the limited
152 fetch in the narrow strait of the Makassar and low-level wind speed, the mean value of the
153 significant wave height is less than 0.6 m and the wave energy that affects the deltaic
154 processes is very low (Storms et al., 2005). Upstream of the delta is the Mahakam River
155 that meanders over about 900 km. Its catchment area covers about 75000 km², with the
156 annual mean river discharge varying from 1000 to 3000 m³/s (Allen and Chambers, 1998).
157 The middle part of the river is extremely flat. In this area, four large tributaries (Kedang
158 Pahu, Belayan, Kedang Kepala, and Kedang Rantau, see Figure 1) contribute to the river
159 flow and several shallow-water lakes (i.e. Lake Jempang, Lake Melintang, and Lake
160 Semayang) are connected to the river through a system of small channels. These lakes act
161 as a buffer of the Mahakam River and regulate the water discharge in the lower part of the
162 river in flood situations, by damping flood surges (Storms et al., 2005).

163 The Mahakam River region is characterized by a tropical rain forest climate with a dry
164 season from May to September and a wet season from October to April. In the river
165 catchment, the mean daily temperature varies from 24 to 29°C while the relative humidity
166 ranges between 77 and 99% (Hidayat et al., 2012). The mean annual rainfall varies
167 between 4000 and 5000 mm/year in the central highlands and decreases from 2000 to 3000
168 mm/year near the coast (Roberts and Sydow, 2003). A bimodal rainfall pattern with two
169 peaks of rainfall occurring generally in December and May is reported in the river
170 catchment (Hidayat et al., 2012). Due to the regional climate and the global air circulation,
171 hydrological conditions in the Mahakam River catchment change significantly, especially
172 in ENSO (El Nino-Southern Oscillation) years such as in 1997, leading to significant
173 variations of flow in the river (Hidayat et al., 2012).

174 **2.2. Tidal regime and salinity in the domain of interest**

175 The tide in the Mahakam Delta is dominated by semidiurnal and diurnal regimes, with a
176 predominantly semidiurnal one. The magnitude of the tide decreases from the delta front to

177 upstream Mahakam River and its value ranges between 1.0 and 3.0 m, depending on the
178 location and the tidal phase (e.g. neap or spring tides). The zone of tidal influence extends
179 up to the lakes region in the middle part of the Mahakam River (Pham Van et al., under
180 review).

181 The limit of salt intrusion is located around the delta apex (Storms et al., 2005; Pham
182 Van et al., 2012a; Budhiman et al., 2012; Budiyanto and Lestari, 2013). Partial mixing of
183 salinity is reported in the delta, based on the vertical distribution of salinity collected at
184 different locations in the middle region of the delta and in the delta front (Storms et al.,
185 2005; Lukman et al., 2006). According to a recent temperature data collection at 29
186 locations in the whole delta, the temperature varies from 29.2 to 30.5°C at the surface and
187 from 29.2 to 30.8°C at the bottom (Budiyanto and Lestari, 2013), revealing that there is no
188 large differences of water temperature in the water column and between stations.

189 Concerning the Mahakam Delta and adjacent coastal region, whose area is of the order
190 of thousands of square kilometers as mentioned previously, using a full-fledged three-
191 dimensional (3D) model for simulating the flow is likely to exceed the available computer
192 resources. Moreover, a very fine grid has to be used to represent many narrow and
193 meandering channels in the delta, thereby increasing the computing time significantly if
194 using 3D models. Thus, a depth-averaged model is designed to be used for simulating the
195 flow dynamics in the delta as well as in the adjacent sea under the present consideration.

196 **2.3. Sediment characteristics in the domain of interest**

197 The deltaic region consists mainly of fine-grained sediment, i.e. particles whose diameter
198 is smaller than 62 μm . Temporal and spatial variations of fine-grained sediment can be
199 influenced by the tides and geometrical factors such as the channel curvature (Dutrieux,
200 1991; Gastaldo and Huc, 1992; Hardy and Wrenn, 2009; Budhiman et al., 2012). Gastaldo
201 and Huc (1992) investigated the sedimentary characteristics of depositional environments
202 within the delta based on core data, showing that fine-grained sediment is the dominant

203 component in the vertical sediment profile. Gastaldo et al. (1995) concluded that fine-
204 grained sediment is very common in both the active fluvial distributaries and in the tidal
205 channels of the Mahakam Delta. Recently, Hardy and Wrenn (2009) also reported that
206 fine-grained sediment is dominant in 200 bottom sediment samples that were collected in
207 the Mahakam Delta and the adjacent continental shelf. The suspended load in the delta
208 channels was found to be mainly fine-grained sediment, while the medium to fine sand was
209 considered to be transported as bedload. Budhiman et al. (2012) concluded that the
210 Mahakam coastal waters have a high load of suspended sediment and dissolved matter
211 according to their in situ measurement and remote sensing data.

212 Recent observations consisting of 106 bed sediment samples that were collected in the
213 period between November 2008 and August 2009 in the Mahakam River reveal that a
214 value of 75% of fine-grained sediment can be found at locations about 120 km upstream
215 from the delta apex (Sassi et al., 2012; 2013). From field measurements, Allen et al. (1979)
216 determined that sediment in the Mahakam River is predominantly fine-grained sediment
217 consisting of silt and clay carried in suspension, with a composition of 70% fine-grained
218 sediment and 30% sand. Those studies show that fine-grained sediments are predominant
219 in the Mahakam River system. That allows models to resort to simple parameterizations of
220 the erosion and deposition processes.

221 Sassi et al. (2013) reported that three-dimensional effects in the suspended sediment
222 distribution are limited at two deltaic bifurcations located around the delta apex, and
223 restricted to an upstream region of the Mahakam River. They also showed that the Rouse
224 number, which is defined as the ratio of sediment settling velocity to the shear velocity of
225 the flow and von Karman constant (≈ 0.41), can be estimated based on the Rouse
226 distribution of suspended sediment concentration (SSC). Using the measured profiles of
227 flow velocity and suspended sediment concentration, Sassi et al. (2013) reported that the
228 Rouse number is typically equal to 0.3 at these two deltaic bifurcations. These

229 considerations suggest that a depth-averaged model can be used to simulate the suspended
230 sediment dynamics in the delta.

231 **3. Hydrodynamic module**

232 **3.1. Computational grid**

233 The computational domain is divided into one-dimensional (1D) and two-dimensional (2D)
234 sub-domains. The 2D sub-domain covers the Makassar Strait, the various channels of the
235 delta, and the three largest lakes in the middle part of the Mahakam River. The Mahakam
236 River and four tributaries are represented as 1D sub-domains (Figure 2). The 2D sub-
237 domain uses an unstructured grid (made of a series of triangles) whose resolution varies
238 greatly in space. It features a very detailed representation of the delta. The spatial
239 resolution is such that there are at least two triangles (or elements) over the channel width
240 of each tidal branch or creek in the delta. The element size varies over a wide range, from 5
241 m in the narrowest branches of the delta to around 10 km in the deepest part of the
242 Makassar Strait. The river network within the 1D sub-domain has a resolution of about 100
243 m between cross-sections. The unstructured grid shown in Figure 2, which comprises
244 60819 triangular elements and 3700 1D line segments, is generated using the open-source
245 mesh generation software GMSH (www.geuz.org/gmsh), which is described in detail in
246 Lambrechts et al. (2008a) and Geuzaine and Remacle (2009).

247 An unstructured grid comprising only the main deltaic channels was used by de Brye et
248 al. (2011) who quantified the division of water discharge through the main channels of the
249 Mahakam Delta. Then, Sassi et al. (2011) used the same unstructured grid for numerical
250 simulations, aimed at studying the tidal impact on the division of water discharge at the
251 bifurcations in the delta. In comparison with the computational grid of the Mahakam Delta
252 reported in the abovementioned previous studies, the current computational grid presents
253 an improvement in the representation of the delta, i.e. most meandering and tidal branches

254 and the creeks in the delta are now taken into account together with the main deltaic
 255 channels.

256 The use of the unstructured grid allows to accurately represent very complex
 257 shorelines. The refinement of the grid resolution takes into account (i) the spatial variation
 258 of bathymetry and (ii) the distance to the delta apex in order to cluster grid nodes in
 259 regions where small scale processes are likely to take place. The use of a model with such
 260 refinement is an important achievement, because a wide range of temporal and spatial
 261 scales of several physical processes interacting with each other in narrow and meandering
 262 tidal branches can be represented in the simulations.

263 3.2. Governing equations

264 In the 2D computational domain, the free surface water elevation η , positive upward, and
 265 the depth-averaged horizontal velocity vector, $\mathbf{u}=(u, v)$, in the hydrodynamic module are
 266 computed by solving the depth-averaged shallow-water equations, i.e.

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (H\mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot (\nabla \mathbf{u}) + f\mathbf{k} \times \mathbf{u} + g\nabla \eta = \frac{1}{H} \nabla \cdot [H\nu(\nabla \mathbf{u})] - \frac{\boldsymbol{\tau}_b}{\rho H} \quad (2)$$

267 where t is the time and ∇ is the horizontal del operator; $H=\eta+h$ is the water depth, with h
 268 being the water depth below the reference level; $f=2\omega \sin \phi$ is the Coriolis parameter, where
 269 ω is the Earth's angular velocity and ϕ is the latitude; \mathbf{k} is the unit upward vector; g , ρ and
 270 ν are the gravitational acceleration, the water density (assumed to be constant under the
 271 Boussinesq approximation) and the horizontal eddy viscosity, respectively; $\boldsymbol{\tau}_b$ is the bottom
 272 shear stress vector which is parameterized using the Chezy-Manning-Strickler formulation,

$$\boldsymbol{\tau}_b = \rho \frac{gn^2 \|\mathbf{u}\|}{H^{1/3}} \mathbf{u} \quad (3)$$

273 with n being the Manning friction coefficient. The Manning coefficient is calibrated to
 274 reproduce the flow dynamics as well as possible.

275 The horizontal eddy viscosity is evaluated using the Smagorinsky eddy
 276 parameterization method (Smagorinsky, 1963).

$$\nu = (0.1\Delta)^2 \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2} \quad (4)$$

277 where Δ is the local characteristic length scale of the element, i.e. the longest edge of a
 278 triangle in the 2D unstructured mesh. Using the Smagorinsky eddy parameterization, the
 279 horizontal eddy viscosity is a function of the gradient of the velocity components and of
 280 the local mesh size. This improves the representation of local subgrid scale phenomena.

281 Although the hydrodynamics in the delta region can be affected to some extent by the
 282 wind, the influence of the wind is not taken into account in this study, because large parts
 283 of the open water in the domain of interest are sheltered from wind action by vegetation. In
 284 the lakes, the effects of wind are not considered too because there are no suitable data for
 285 this region.

286 Several nodes and elements in the computational domain, especially close to the deltaic
 287 area, can undergo wetting and drying processes, depending on the water elevation and tidal
 288 conditions at each time step. Therefore, a special treatment of these transition elements or
 289 moving boundaries is required. In this paper, we use the wetting and drying algorithm
 290 designed by Kärnä et al. (2011). This means that the actual bathymetry (i.e. the water depth
 291 h below the reference level) is modified according to a smooth function $f(H)$ as $h+f(H)$, to
 292 ensure a positive water thickness at any time. The smooth function has to satisfy the
 293 following properties. Firstly, the modified water depth (i.e. $\eta+h+f(H)$) is positive at any
 294 time and position. Secondly, the difference between the real and modified water depths is
 295 negligible when the water depth is significantly positive. Thirdly, the smooth function is
 296 continuously differentiable to ensure convergence of Newton iterations when using an
 297 implicit time stepping. The following function, which satisfies the properties described
 298 above, is used:

$$f(H) = \frac{1}{2} \left(\sqrt{H^2 + \theta^2} - H \right) \quad (5)$$

where θ is a free parameter controlling the smoothness of the transition between dry and wet situations. In our calculations, a value $\theta=0.5$ m is selected for modifying the bathymetry, in order to maintain the positive water depth.

The wetting and drying algorithm designed by Kärnä et al. (2011) satisfies continuity and momentum conservation, and the full mass conservation in a way that is compatible with the tracer equation. This method can also be implemented in an implicit framework, which enables the CPU time to be significantly reduced by using a large time step, as shown in next section. Further information on the wetting and drying algorithm can be found in Kärnä et al. (2011).

In the 1D sub-domain comprising the Mahakam River and tributaries, the continuity and momentum equations are integrated over the river cross-section, yielding the following form:

$$\frac{\partial A}{\partial t} + \frac{\partial(Au)}{\partial x} = 0 \quad (6)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \eta}{\partial x} = \frac{1}{A} \frac{\partial}{\partial x} \left(\nu A \frac{\partial u}{\partial x} \right) - \frac{\tau_b}{\rho H} \quad (7)$$

where A is the cross-sectional area, $H=A/b$ is here the effective flow depth and b is the river width. The eddy viscosity is parameterized using the zero-equation turbulent model, under the form:

$$\nu = \lambda u_* H \quad (8)$$

where λ is a non-dimensional eddy viscosity coefficient that is given the value of 0.16 in the present study (Darby and Thorne, 1996; Pham Van et al., under review), and u_* is the friction shear velocity, which is calculated as $u_*^2 = c_f u^2$, with c_f being a coefficient obtained from Manning's formula ($c_f = gn^2 H^{-1/3}$). The bottom shear stress τ_b in the 1D model is computed as:

$$\tau_b = \rho \frac{gn^2 |u|}{H^{1/3}} u. \quad (9)$$

319 It is worth noting that bed evolution can occur due to the erosion and deposition of
320 sediments, which can in turn influence the flow. However, as reported in our previous
321 study (Pham Van et al., 2012b), the effects of the bed evolution caused by sediment
322 erosion and deposition on the flow are not significant in this case. For example, when
323 including and excluding the bed evolution resulting from sediment erosion and deposition
324 in the model, the difference in the norm of the velocity at different locations (e.g. Muara
325 Karman, Samarinda, Delta Apex, Delta North, and Delta South in Figure 2) is less than
326 0.006 m/s while the difference in water depth is less than 0.005 m. Therefore, the
327 morphological evolution is not considered in the present study.

328 **3.3. Finite element implementation**

329 The governing equations for flow dynamics are solved in the framework of the finite
330 element model SLIM by using an implicit discontinuous Galerkin finite element method
331 that is described in detail in Comblen et al. (2010), de Brye et al. (2010), Kärnä et al.
332 (2011), and the related references therein. Thus, only general information about the finite
333 element implementation is provided here to avoid a repeated description of the model and
334 its capabilities. The computational domain is discretized into a series of triangles or
335 elements as shown in Figure 2. The governing equations are multiplied by test functions
336 and then integrated by parts over each element, resulting in element-wise surface and
337 contour integral terms for the spatial operators. The surface term is solved using the DG-
338 FEM with linear shape function, while a Roe solver is used for computing the fluxes at the
339 interfaces between two adjacent elements to represent the water-wave dynamics in contour
340 terms properly (Comblen et al., 2010). At the interface between the one and two
341 dimensional models, local conservation is warranted by compatible 1D and 2D numerical
342 fluxes (de Brye et al., 2010). At the interface of a bifurcation/confluence point in the 1D
343 model, numerical fluxes are computed by using the continuity of mass and momentum and

344 by imposing the characteristic variables described from eq. (6) and (7) (Pham Van et al.,
345 under review). A second-order diagonally implicit Runge-Kutta method is used for the
346 temporal derivative operator (Kärnä et al., 2011). The time increment $\Delta t=10$ minutes is
347 chosen for all calculations in this study.

348 **3.4. Bathymetry**

349 The bathymetry data obtained in the year 2008 and 2009 are employed to represent the
350 delta, the lakes, and the river. The depth in all channels varies greatly, generally in a range
351 between 5 to 45 m. The depth remains typically about 5 m in the three lakes located in the
352 middle area of the Mahakam River. In the Mahakam River and its four largest tributaries,
353 the observed bathymetry data are used to interpolate the channel cross-section wetted area
354 at different water elevations. Further information on the bathymetry data obtained from
355 fieldwork campaigns and the interpolation procedures can be found in Sassi et al. (2011).
356 The bathymetry data from the global GEBCO (www.gebco.net) database are used in the
357 Makassar Strait and for the adjacent continental shelf.

358 **3.5. Boundary and initial conditions**

359 The tides from the global ocean tidal model TPXO7.1 (Egbert et al., 1994) are imposed at
360 downstream boundaries through elevation and velocity harmonics while the daily time-
361 series of water discharge are provided at the upstream boundary. The open sea downstream
362 boundaries are located far away from the delta, i.e. at the entrance and exit of the Makassar
363 Strait (Figure 2a). As upstream boundary condition, the measured water discharge (Hidayat
364 et al., 2011) is imposed at the city of Melak (for the Mahakam River), where the tidal
365 influence on the flow is negligible, and the other upstream boundaries in four tributaries
366 (Figure 2b). As detailed below, different flow periods are chosen for calibration
367 simulations, aimed at determining the modelling parameters in the suspended sediment
368 transport module, and for validation of those parameters.

369 The initial flow velocity in the computational domain is set equal to zero and an
370 arbitrary value of 0.5 m is used for the initial water elevation, except in the three lakes
371 where a calculated value of water elevation is imposed. A spin up period of one neap-
372 spring tidal cycle (about 15 days) is applied before starting the effective simulations during
373 the period of interest, so as to make sure that all transients effects associated with the
374 initialization are dissipated. This spin up period is largely sufficient, as it was observed that
375 regime conditions are already reached after a few days.

376 3.6. Validation

377 The main parameter to be calibrated in the hydrodynamic module is the Manning
378 coefficient. This parameter is adjusted by comparing model results with continuous
379 observations of water elevation at six stations (*blue dots* in Figure 2), of the velocity at
380 Samarinda station, and of the water discharge at five stations (*red squares* in Figure 2)
381 (Pham Van et al., under review). The optimal values of the bottom friction obtained from
382 the calibration and validation steps consist of (i) a constant value of $0.023 \text{ (s/m}^{1/3}\text{)}$ for the
383 Makassar Strait, (ii) a linearly increasing value in the delta region, from $0.023 \text{ (s/m}^{1/3}\text{)}$ in
384 the coastal region to $0.0275 \text{ (s/m}^{1/3}\text{)}$ in the region from the delta front to the delta apex, (iii)
385 a constant value of $0.0275 \text{ (s/m}^{1/3}\text{)}$ in the Mahakam River and its four tributaries, and (iv) a
386 larger value of $0.0305 \text{ (s/m}^{1/3}\text{)}$ in the lakes.

387 Selected results of flow dynamics, obtained by using the abovementioned optimal
388 values of the Manning coefficient, are shown in Figure 3 illustrating comparisons of the
389 water elevation at Delta North (Figure 3b) and Delta South (Figure 3c) stations and the
390 velocity at Samarinda station (Figure 3d). As shown in Figure 3b-c, the model simulates
391 the observed water elevation at Delta North and Delta South very well. The root mean
392 square (RMS) error of water elevation is less than 10 cm and this error is only about 4% of
393 the observed magnitude of water elevation at the station. In addition, it is obvious that the
394 model also adequately reproduces the observed velocity at Samarinda (Figure 3d) in the

395 period from 11-19-2008 to 12-02-2008. The RMS error of velocity is 0.06 m/s, about 8%
 396 of the observed magnitude of measured velocity. A slight discrepancy of water elevation
 397 and an overestimation of velocity at high tidal situations can be explained by the
 398 uncertainty on the prescribed water discharge at the upstream tributaries and by our model
 399 ignoring secondary flows.

400 **4. Suspended sediment module**

401 **4.1 Governing equations**

402 The two-dimensional depth-averaged equation for SSC takes the form below.

$$\frac{\partial(HC_{ss})}{\partial t} + \nabla \cdot (HuC_{ss}) = \nabla \cdot (H\kappa \nabla C_{ss}) + E - D \quad (10)$$

403 where C_{ss} is the depth-averaged SSC (kg/m^3); κ is the diffusivity coefficient; and E and D
 404 are the erosion and deposition rates, respectively. The difference between erosion and
 405 deposition rates or net sediment exchange is the source term in the governing equation (10),
 406 allowing for a correct representation of the SSC.

407 In the 1D sub-domain, the SSC is determined by solving the cross-section averaged
 408 advection-diffusion equation

$$\frac{\partial(AC_{ss})}{\partial t} + \frac{\partial(AuC_{ss})}{\partial x} = \frac{\partial}{\partial x} \left(A\kappa \frac{\partial C_{ss}}{\partial x} \right) + b(E - D). \quad (11)$$

409 The diffusivity coefficient κ is parameterized using the Okubo formulation (Okubo,
 410 1971)

$$\kappa = c_k \Delta^{1.15}, \quad (12)$$

411 where c_k is an appropriate coefficient. A constant value $c_k=0.018$, which is calibrated from
 412 the best fit to the available salinity data in the model domain (see Appendix A), is applied
 413 to determine the diffusivity coefficient. Note that the characteristic local length scale of the
 414 grid Δ is the length of a segment (i.e. the distance between two river cross-sections) in the
 415 1D mesh.

4.2 Erosion rate

Suspended sediment transport is generally described as a purely physical process, resulting from the response of sediment beds to hydrodynamic forces in coastal regions (Le Hir et al., 2007). Sediment can be eroded from the bed and resuspended into the water column under certain flow conditions. In this study, an infinite sediment supply from the bed is assumed so that only flow conditions control the erosion processes. This approximation is adopted because of the rather limited bed sediment data in the computational domain. Using this approximation, regime conditions are reached after a rather short spin-up period.

The erosion rate E can be determined using different empirical formulas from the literature, adapted to the considered environment. For example, in fine-grained sediment environments, the empirical formula originally proposed by Partheniades (1965) is commonly used for evaluating the erosion rate (e.g. Lang et al. 1989, Sanford and Maa, 2001; Wu et al., 2005; Mercier and Delhez, 2007; Gong and Shen, 2010; Gourgue et al., 2013; Winterwerp, 2013). Thus, in the present consideration, in which fine-grained sediment is mainly focused on, the erosion rate of fine-grained sediment eroded from the bed is also parameterized with the empirical formula introduced by Partheniades (1965) as in many other studies mentioned above.

$$E = \begin{cases} M \left(\frac{\tau_b}{\tau_c} - 1 \right)^m & \text{if } \tau_b > \tau_c \\ 0 & \text{if } \tau_b \leq \tau_c \end{cases} \quad (13)$$

where τ_b is the norm of the bottom shear stress vector $\boldsymbol{\tau}_b$ in the 2D model or the norm of the bottom shear stress τ_b in the 1D model, τ_c is the critical shear stress for sediment erosion, M is the erosion rate parameter, and m is the relevant exponent. The exponent m is set equal to unity, as in the original formulation of Partheniades (1965). Both τ_c and M are related to the physical and chemical characteristics of sediments, e.g. dry density, mineral composition, organic material, and temperature. Typical value of τ_c varies between 0.02

439 and 1.0 N/m^2 (Neumeier et al., 2006; Le Hir et al., 2007). A value $\tau_c=0.1 \text{ N/m}^2$, which is
 440 used by Mandang and Yanagi (2009) for the Mahakam Delta, is adopted herein. This value
 441 is also commonly used as a threshold value in studies of erosion of fine-grained sediment
 442 in rivers and lakes (Kirk Ziegler and Nisbet, 1994; 1995). Typical values of M range from
 443 0.00004 to $0.00012 \text{ kg/m}^2\text{s}$ (Wu et al., 2005; Mercier and Delhez, 2007). The value of this
 444 parameter is optimized using the observed field data of SSC at five locations (Table 1).

445 **4.3 Deposition rate**

446 The deposition rate of fine-grained sediment is calculated according to the formulation by
 447 Einstein and Krone (1962), as in many other studies (e.g. Wu et al., 2005; Mercier and
 448 Delhez, 2007; Mandang and Yanagi, 2009; Gong and Shen, 2010; Winterwerp, 2013):

$$D = P_1 w_s C_{ss} \quad (14)$$

449 where w_s is the setting velocity and P_1 is the probability of deposition. The approach
 450 proposed by Ariathuri and Krone (1976) is applied to compute the probability of
 451 deposition. This means that the probability of deposition is given by

$$P_1 = \begin{cases} 1 - \frac{\tau_b}{\tau_d} & \text{if } \tau_b \leq \tau_d \\ 0 & \text{if } \tau_b > \tau_d \end{cases} \quad (15)$$

452 where τ_d is the critical shear stress for deposition of sediment. The value of the critical
 453 shear stress for the deposition of sediment depends on sediment type and concentration
 454 (Mehta and Partheniades, 1975) and its value ranges between 0.06 and 1.1 N/m^2 .
 455 Regarding the Mahakam water surface system, field investigation of the critical shear
 456 stress for deposition of sediments is rather limited and in order to make the calibration of
 457 parameters as simple as possible, the value of τ_d is set equal to the value of τ_c in this study.

458 The settling velocity is parameterized as a function of sediment concentration, under the
 459 form (Van Leussen, 1999; Wu, 2007).

$$w_s = k_1 C_{ss}^\beta \quad (16)$$

460 where k_I is an empirical parameter and β is the appropriate exponent. The value of k_I can
461 vary in a range between 0.01 and 0.1 (Gourgue et al., 2013). The exponent β can vary over
462 a wide range, depending on the type of particles in suspension and on the flow. Burban et
463 al. (1990) mentioned that an approximate value $\beta=-0.024$ and $\beta=0.28$ could be applied for
464 freshwater and seawater environments, respectively, while its value varies between 0.5 and
465 3.5 according to Van Leussen (1999), and between 1 and 2 according to Wu (2007). In this
466 study, the constant k_I and exponent β are treated as calibration parameters. This means
467 there are three parameters (i.e. M , β , and k_I) that need to be calibrated in the suspended
468 sediment module.

469 **4.4 Finite element implementation**

470 As for the hydrodynamic module, the governing equations, i.e. (10) and (11), for
471 suspended sediment are solved in the framework of the finite element model SLIM by
472 using an implicit discontinuous Galerkin finite element method. The governing equations
473 are discretized on the unstructured mesh shown in Figure 2, using the same discretization
474 as the shallow-water equations. Then, local/global conservation and consistency are
475 warranted for the tracers (White et al., 2008). Stability is ensured by computing the fluxes
476 at the interface between two triangles using an upwind scheme. The same time-stepping
477 scheme is used as in the hydrodynamic module, i.e. second-order diagonally implicit
478 Runge-Kutta with a time step of 10 minutes. At the interface between 1D and 2D sub-
479 domains, local conservation is warranted by compatible 1D and 2D numerical fluxes (de
480 Brie et al., 2010).

481 **4.5 Boundary and initial conditions**

482 The SSC is set equal to zero at the open sea boundaries while a constant value of SSC in
483 the range between 0.03 and 0.25 (kg/m^3) is imposed for the upstream boundary in the
484 Mahakam River and the four tributaries. Because no other data are available, the value at
485 each upstream tributary is simply interpolated from the catchment-area ratio and an

486 averaged SSC value in the river system. The latter is preliminarily estimated from the
487 averaged sediment discharge ($8 \times 10^6 \text{ m}^3/\text{year}$) and annual river discharge (between 1000
488 and $3000 \text{ m}^3/\text{s}$) which are reported in (Allen and Chambers (1998)). In the reality, because
489 sediments are not always available, a long period of small SSC can have an influence on
490 the SSC in the delta. Nevertheless, this does not occur frequently and this drawback of the
491 model has a negligible influence on the results.

492 The initial condition of SSC in the computational domain is set to 0.005 kg/m^3 except in
493 the Makassar Strait, where a nil value is employed. A spin up period of one neap-spring
494 tidal cycle (about 15 days) is applied before the period of interest. The regime condition for
495 SSC is obtained a few days after the hydrodynamic regime conditions.

496 **5. Calibration and validation of the suspended sediment module**

497 **5.1. Available data**

498 The suspended sediment data cover different periods, under varying tidal conditions (i.e.
499 neap and spring tides) in the survey period between November 2008 and August 2009.
500 Surveys took place (Figure 2) over river sections in the city of Samarinda, at two locations
501 downstream of the delta apex bifurcation (denoted by DAN and DAS), and at two
502 locations downstream of the first bifurcation located in the southern branch of the delta
503 apex (denoted FBN and FBS). At each location, the section-averaged values of SSC are
504 determined from data capturing the spatial distribution of suspended sediment, flow
505 velocity and flow depth, all measured at the same time. More detailed information about
506 the measurement and calibration procedures as well as spatial data of SSC in the observed
507 channel sections can be found in Sassi et al. (2012, 2013). Most sediment observations
508 cover a period of 13 hours, i.e. one complete semidiurnal tidal cycle. Only the observations
509 made on 12-26-2008 cover a period of only 7 hours due to technical difficulties. The
510 observed ranges of section-averaged SSC at these locations are summarized in Table 1.

511 Observations of SSC at Samarinda, DAN, DAS, FBN, and FBS in the period from
 512 November 2008 to January 2009 are used for calibration purposes (Section 5.3) while the
 513 sediment data measured on the different dates between February 2009 and October 2009 at
 514 Samarinda are employed to validate the model (Section 5.4). Different simulations are
 515 performed and the computed SSC are compared to the observations at the measurement
 516 locations.

517 **5.2. Different type of errors**

518 To assess the quality of the simulated SSC compared to the observations, different criteria,
 519 i.e. temporal error E_t and Pearson's correlation coefficient r , are calculated at the
 520 measurement stations. The temporal error E_t is applied as a quantitative estimate of the
 521 mean error. The temporal error E_t is computed as:

$$E_t = \frac{\sqrt{\sum_t [(C_{ss})_{data} - (C_{ss})_{model}]^2}}{\sqrt{\sum_t [(C_{ss})_{data}]^2}} \quad (17)$$

522 where \sum_t means the sum over different times, $(C_{ss})_{data}$ and $(C_{ss})_{model}$ are respectively
 523 the observations and computed SSC at a specific station. The Pearson's correlation
 524 coefficient r is used to analyze the correlation and variable trend of model results in
 525 comparison with the field data. The coefficient r is calculated as follows:

$$r = \frac{\sum_t (C_{ss} - C_{ss,m})_{data} (C_{ss} - C_{ss,m})_{model}}{\sqrt{\sum_t (C_{ss} - C_{ss,m})_{data}^2} \sqrt{\sum_t (C_{ss} - C_{ss,m})_{model}^2}} \quad (18)$$

526 where $(C_{ss,m})_{data}$ and $(C_{ss,m})_{model}$ are the mean value of observed and computed SSC,
 527 respectively, at a specific location.

528 **5.3. Calibration results**

529 As mentioned previously, there are three parameters to calibrate, i.e. k_1 , β , and M .
 530 Different constant values of these parameters are tested, in order to obtain the best fit with
 531 the observations of SSC at five stations. The value of each parameter is varied separately,

532 whilst keeping the other once constant. Among different testing values, several constant
533 values for the three parameters (i.e. $k_I=0.04, 0.08, 0.12$; $\beta=1.0, 1.25, 1.30$; and $M=0.00005,$
534 $0.00012, 0.00021, 0.00025$ kg/m²s) are summarized here. Thirty-six simulations associated
535 with combination of these constant parameters values are performed, with the aim to select
536 the best combination of values for the parameters k_I , β , and M in their typical range of
537 variation. Table 2 presents the parameter values for each simulation as well as the temporal
538 error obtained at each station for the calibration period.

539 The temporal error of SSC versus the variable values of M and k_I (and the constant
540 value $\beta=1.25$) is shown in Figure 4 while its value versus the variable values of M and β
541 (and the constant value $k_I=0.08$) is illustrated in Figure 5. It can be observed that the
542 temporal errors at all five stations vary significantly if variable values of parameters are
543 employed. This suggests that the calculated results of SSC are very sensitive to changes in
544 both the erosion rate and the deposition rate, resulting from alternating the value of M and
545 settling velocity (related to k_I and β), respectively. The optimal parameter set is found to
546 be $k_I=0.08$, $\beta=1.25$, and $M=12 \times 10^{-5}$ kg/m²s. This corresponds to simulation a.18, for which
547 comparisons between calculated and observed SSC during the simulation period are shown
548 in Figure 6 and Figure 7.

549 Figure 6 shows the comparison between simulation results and data of SSC at
550 Samarinda station. The model reproduces very well the temporal variation of SSC
551 measured on different dates. The temporal error at this station is only about 0.06. In
552 addition, the model seems to be able to represent the variations of SSC associated with
553 neap-spring tidal cycles, besides the semidiurnal tides. During spring tides, SSC variations
554 are significantly higher due to the strong tidal currents. The correlation coefficient between
555 computed and observed SSC is 0.97, revealing that the model very well reproduces the
556 field data on sediment.

557 Figure 7 depicts the modeled SSC and observations at the four other stations (i.e. DAN,
558 DAS, FBN, and FBS). Again, a very good agreement between computed and observed
559 section-averaged SSC is obtained for the two considered measurement dates. The
560 maximum temporal error at these channel sections is only about 0.20. The coefficient r is
561 very close to unity (> 0.96) at all these four stations.

562 Figure 8 shows the interquartile range of SSC at five stations, which is a measure of
563 statistical dispersion, equal to the difference between the first and third quartiles, of all
564 simulations in Table 2. The simulation corresponding to the best parameter combination
565 set (simulation a.18) is within the interquartile range at all five considered stations. The
566 interquartile range represents the uncertainty in simulations due to the variability of the
567 investigated parameters, and is considered here to represent the uncertainty associated with
568 the best parameter set. Uncertainty typically increases for high SSC values and
569 observations mostly fall within these bounds.

570 In general, a very good agreement is achieved between the simulation results and
571 observed data at all five stations. The values of the parameters corresponding to simulation
572 a.18 are considered as the optimal ones in the calibration stage.

573 **5.4. Validation results**

574 To validate the model, a simulation for a longer period, six months from February to
575 August 2009, is performed and the results are compared with the observations at
576 Samarinda (Figure 9). An excellent agreement is achieved between the simulated and
577 observed SSC for the three sets of observations corresponding with the validation period.
578 The temporal error is 0.21, which is only slightly greater than the error in the calibration
579 step (simulation a.18). The correlation coefficient r between observed and computed SSC
580 is 0.92, which is slightly smaller than the value in simulation a.18, but still indicating a
581 strong positive correlation. A positive value of the covariance between computed and

582 observed SSC is also arrived at, revealing that the model correctly reproduces the variation
583 trend observed in situ.

584 As shown in Figure 9, the tide is the key factor controlling SSC variation at both short
585 and medium time-scales at Samarinda station. Both field observations and simulation
586 results show temporal variations of SSC to be controlled by the semidiurnal tide and its
587 associated spring-neap cycle. A decrease of SSC corresponding to the low-flow period
588 between July and August 2009 is observed, during which the river flow varies between
589 1200 and 2300 m³/s.

590 During the low-flow period (Figure 9d), simulations overestimate the observations
591 during ebb and underestimate the observations during flood. These discrepancies may be
592 related to several factors. First, the water discharge imposed at the tributaries was
593 estimated using a rainfall-runoff model that may be plagued with significant uncertainties
594 during the low-flow period, as concluded by Pham Van et al. (2012a). The simulation
595 results of SSC corresponding to the low-flow suggest that the river discharge used in the
596 simulation seems to be overestimated. Second, the contribution of the tidal motion from
597 multiple channels in the delta into the Mahakam River can differ with the seasons. Finally,
598 using a constant roughness coefficient in the simulations may not be entirely appropriate
599 during low-flow conditions.

600 **6. Discussion**

601 Figure 10 illustrates the time-series of daily averaged SSC at Samarinda station during the
602 years 2008-2009. The temporal variation of SSC is obtained by using the optimal values of
603 parameters calibrated and validated in the previous section (i.e. setup of simulation a.18).
604 For comparison, results obtained from a rating curve of the form $C_{ss} = pQ^q$ (Asselman,
605 1999) are also shown. Note that Q is the water discharge (m³/s), and p and q are
606 empirically derived regression coefficients. Based on the best linear-fit for the five
607 observations at Samarinda, the values $p=0.0136$ and $q=0.23$ are obtained and these values

608 are applied in the calculations. The figure (i.e. Figure 10) shows the increased level of
609 detail that can be obtained with the simulations compared to a simple rating curve
610 approach. During high-flow, both the model and the rating curve simulate the effect of the
611 seasonal variation of river flow reasonably well. However, during the low-flow period,
612 daily averaged SSC variation influenced by the tide, can only be captured by the model.

613 Temporal variations of SSC associated with the variable river discharge appear to be
614 well-represented by the model. For instance, the temporal variation of SSC at Samarinda
615 (see Figure 10) showed that the SSC remains higher during the high flow period from
616 November to April 2009, corresponding to the rainfall period. Moreover, multiple peaks of
617 SSC occurred during the periods December-January and April-May corresponding to the
618 two rainfall peaks in the river catchment (Hidayat et al., 2012).

619 Figure 11 shows an example of the spatial distribution of the computed SSC in the
620 Mahakam River and in the whole delta, obtained from the model at the ebb tidal phase of
621 neap tide, i.e. at 13:50:00 on 03-10-2009. The figure illustrates the significant variation of
622 SSC along the river and in the delta. In the upstream area of the Mahakam River, where the
623 influences of the tide on flow dynamics is smaller than in the delta, and the river flow is a
624 dominant factor controlling sediment transport, high values of SSC are obtained. Close to
625 the delta, where the tidal effects are strong and the flow dynamics is more complicated,
626 SSC changes significantly in space. The figure shows a gradual decrease of SSC from the
627 mouth of the Mahakam River to the delta shore.

628 The simulation results show that SSC in the Mahakam Delta varies in a range between
629 0.001 and 0.16 (kg/m^3). This range is similar to the in situ values obtained by Budhiman et
630 al. (2012) who reported that SSC near the water surface varies from 0.006 to 0.182 (kg/m^3)
631 based on their field measurements performed in May and August 2008 and in August 2009,
632 at 119 field sampling sites distributed in the whole delta. In addition, the computed range
633 of SSC is also in good agreement with the two-week field campaign in September 2003

634 reported by Storms et al. (2005) who show that SSC in water samples at various sites in the
635 southern river branch and adjacent river mouth of the Mahakam River varies between
636 0.005 and 0.15 (kg/m³).

637 The settling velocity is an important parameter in estimating the net sediment exchange
638 from a river bed or sea bed (Van Leussen, 1999; Wu, 2007). According to Burban et al.
639 (1990), the settling velocity of fine-grained sediment in fresh and sea water environments
640 is often affected by varying factors related to flow shear stress, sediment concentration,
641 salinity, organic matter, *pH*, temperature, and organisms. Observations of such
642 abovementioned physical, chemical, and biological quantities are often limited (Mercier
643 and Delhez, 2007; Winterwerp, 2013; Elskens et al., 2014), especially in coastal regions
644 like the Mahakam Delta. In this deltaic region, the settling velocity of sediment is known
645 to be a strong function of sediment concentration, which is highly variable in a holistic
646 model such that presented here. The best model results were obtained if the settling
647 velocity was simply parameterized by using a power function of the sediment
648 concentration (i.e. $w_s = 0.08C_{ss}^{1.25}$). The computed settling velocity in the delta varies over a
649 wide range between 0.001 and 8.5 mm/s, which is in the typical range of settling velocity
650 for fine-grained sediments in estuarine and deltaic regions (Burban et al., 1990; Lou and
651 Ridd, 1997; Van Leussen, 1999). The effects of salinity, organic matter, *pH*, temperature,
652 and organisms on the settling velocity of fine-grained sediments would be probably
653 considered in the next stages of the research, when field measurements of these physical,
654 chemical, and biological quantities are performed.

655 The SSC calculations presented here are carried out by using one sediment layer or class
656 only, in which only fine-grained sediment is considered. To realistically simulate the
657 effects of particle size variations in the water column, different sediment classes could be
658 included in a future modelling effort. Fine-grained sediment particles may stick together
659 and form flocs when they collide (Winterwerp, 1998), because of turbulence and the action

660 of electrostatic forces, as well as the polymers resulting from biological processes that are
661 adsorbed onto the surfaces of the fine-grained sediment particles (Wu, 2007; Van Leussen,
662 1999). The associated processes may result in variability in sizes and settling velocities of
663 the flocs in space and time. Investigating the influence of flocculation processes is also
664 foreseen in the future to better understand the suspended matter dynamics in the delta as
665 well as in the Makassar Strait, as suggested by Eisma et al (1989). Sassi et al. (2012)
666 suggested that flocculation processes are also important in the tidal river, upstream of the
667 delta.

668 **7. Summary and conclusions**

669 A coupled 2D/1D model including shallow-water and advection-diffusion equations in the
670 framework of the finite element model SLIM has been successfully applied to reproduce
671 suspended sediment transport in the Mahakam land-sea continuum. The aims of the study
672 were to simulate fine-grained sediment transport within the domain of interest of the
673 system, to accurately reproduce the measured SSC at different locations in the delta, and to
674 represent spatial and temporal variations of SSC under the combined influences of river
675 flow and tides in such a complex system. Calibration simulations were performed to
676 establish the best performing values of parameters in the suspended sediment transport
677 module. The model was also validated additionally. A very good agreement was achieved
678 between the computed and observed variation of SSC at different measurement stations in
679 the system, both for the calibration and the validation periods.

680 The simulation results corresponding to the best parameter set showed that the temporal
681 error of SSC was less than 0.20 and the correlation coefficient between computed and
682 observed sediment concentrations was close to unity. These simulation results were also
683 well within the interquartile range of the measurements, at all five measurement stations.
684 This demonstrates that the coupled 2D/1D model of the SLIM reproduced very well the
685 suspended sediment transport across the land-sea continuum.

686 Simulation results over a year in 2008-2009 showed that the model was able to
 687 accurately simulate the temporal variation of SSC in response to the variation of the river
 688 flow. Comparisons of model results with field observations reported in previous studies for
 689 the Mahakam Delta were all favorable.

690 **Acknowledgements**

691 The present study was carried out in the framework of the project “Taking up the
 692 challenges of multi-scale marine modelling” which is funded by the Communauté
 693 Francaise de Belgique under contract ARC 10/15-028 (Actions de recherche concertées)
 694 with the aim of developing and using SLIM (www.climate.be/slim). Computational
 695 resources have been provided by the supercomputing facilities of the Université catholique
 696 de Louvain (CISM/UCL) and the Consortium des Equipements de Calcul Intensif en
 697 Fédération Wallonie Bruxelles (CECI) funded by the Fond de la Recherche Scientifique de
 698 Belgique (F.R.S-FNRS). Eric Deleersnijder and Sandra Soares-Frazão are honorary
 699 research associates with this institution. The authors would like to thank Prof. Iwan
 700 Suyatna (Mulawarman University, Indonesia) for sharing the measurement salinity data
 701 used for the numerical simulations herein.

702 **Appendix A: Estimating the dispersion coefficient using salinity data**

703 To simulate the salinity transport in the computational domain, the coupling between
 704 section-averaged and depth-averaged advection-diffusion equations is applied. These
 705 equations are written in the following forms:

$$\frac{\partial(AS)}{\partial t} + \frac{\partial(AuS)}{\partial x} = \frac{\partial}{\partial x} \left(A\kappa \frac{\partial S}{\partial x} \right) \quad (19)$$

$$\frac{\partial(HS)}{\partial t} + \nabla \cdot (HuS) = \nabla \cdot (H\kappa \nabla S). \quad (20)$$

706 where S (-) is the sectional-averaged salinity in the 1D sub-domain or depth-averaged
 707 salinity in the 2D sub-domain and, again, κ is the diffusivity coefficient that is

708 parameterized under the form of eq. (12). It must be emphasized that equations (19) and
709 (20) are also solved in the framework of the finite element model SLIM by using a
710 discontinuous Galerkin finite element method (with linear shape functions) for the spatial
711 operators and a second-order diagonally implicit Runge-Kutta for the temporal operators.

712 Salinity data were collected in the period between August 2009 and January 2010 at 60
713 locations in the tidal channels of the delta and in the delta shore (Figure 2). At each
714 location, salinity was measured in situ at the water surface using water checker Horiba.
715 This dataset covers a representative range of salinity conditions, with values ranging
716 between 2.1 and 34.8 PSU and water depths varying from 1.0 to 42 meters (Suyatna et al.,
717 2010).

718 The measurement data of salinity mentioned above are used to determine the optimal
719 value of coefficient c_k in eq. (12). The simulation period ranges from July 2009 to end of
720 measurement time, i.e. January 2010. The setup of the hydrodynamic module and the
721 optimal value of the Manning coefficient described in Section 3 are employed to reproduce
722 the flow dynamics in the system. The daily water discharge at the upstream Mahakam
723 River varies between 480 (low-flow conditions) and 5400 m³/s (high flow conditions). A
724 value of 35 PSU is imposed in the deepest parts of the computational domain (Makassar
725 Strait) while freshwater is entering the domain at upstream boundaries of the Mahakam
726 River and tributaries. The regime condition for salinity is also obtained after a spin up
727 period of one neap-spring tidal cycle (about 15 days).

728 Several simulations using constant values of c_k in a range between 0.008 and 0.06 are
729 performed. The best match between computed and observed salinity is achieved as shown
730 in Figure 12 when a value $c_k=0.018$ is employed. The RMS error of salinity in this case is
731 3.4 PSU, about 10% of observed magnitude of salinity. A few points still lie significantly
732 above the perfect matching line (Figure 12). These points correspond to sampling sites near
733 the coast of the northern area of the delta. In view of the rather limited amount of observed

734 salinity data, $c_k=0.018$ is considered to be the appropriate approximate value for
735 determining the diffusivity coefficient in studying SSC in the delta.

736 The diffusivity coefficient κ corresponding to $c_k=0.018$ varies in a range between 0.21
737 and 80 (m^2/s) in the delta while its value equals 3.6 (m^2/s) in the river and tributaries. The
738 latter value is obtained by replacing the mesh size of element in the 2D sub-domain by the
739 length of a segment in the 1D sub-domain. These values of the diffusivity coefficient are in
740 the typical range of dispersion coefficient for the estuaries and coastal regions, as
741 mentioned in Fischer et al. (1979).

742 References

- 743 Allen, G. P., Chambers, J. L. C., 1998. Sedimentation in the modern and Miocene
744 Mahakam delta. *Indonesian Petroleum Association*, Jakarta, p. 236.
- 745 Allen, G. P., Laurier, D., Thouvenin, J., 1979. Etude sedimentologique du delta de la
746 Mahakam. *TOTAL Compagnie Française des Petroles, Notes et Mémoires*, Paris, N° 15,
747 154p.
- 748 Ariathuri, R., Krone, R.B., 1976. Finite element model for cohesive sediment transport.
749 *Journal of Hydraulic Engineering*, 102(3), 323-338.
- 750 Asselman, N. E. M., 1999. Suspended sediment dynamics in a large drainage basin: the
751 River Rhine. *Hydrological processes*, 13, 1437-1450.
- 752 Bernard, P. E., Chevaugéon, N., Legat, V., Deleersnijder, E., Remacle, J.-F. 2007. High-
753 order h-adaptive discontinuous Galerkin methods for ocean modeling. *Ocean Dynamics*,
754 57, 109-121 (+Erratum, 2007, 57, 579-580).
- 755 Budhiman, S., Salama, S. M., Vekerdy, Z., Verhoef W., 2012. Deriving optical properties
756 of Mahakam Delta coastal waters, Indonesia using *in situ* measurements and ocean
757 color model inversion. *ISPRS Journal of Photogrammetry and Remote Sensing*, 68,
758 157-169.
- 759 Burban, P.-Y., Xu, Y.-J., McNeil, J., Lick W., 1990. Settling speeds of flocs in fresh water
760 and seawater. *Journal of Geophysical Research*, 95(C10), 18213-18220.
- 761 Budiyanoto, F., Lestari, 2013. Study of metal contaminant level in the Mahakam Delta:
762 Sediments and dissolved metal perspectives. *Journal of Coastal Development*, 16 (2),

- 763 147-157.
- 764 Buschman, F.A., Hoitink, A.J.F., De Jong, S.M., Hoekstra, P., Hidayat, H., Sassi, M. G.,
765 2012. Suspended sediment load in the tidal zone of an Indonesian river. *Hydrology and*
766 *Earth System Sciences*, 16 (11), 4191-4204.
- 767 Chaîneau, C.-H., Miné, J., Suripno, 2010. The integration of biodiversity conservation with
768 oil and gas exploration in sensitive tropical environments. *Biodiversity and*
769 *Conservation*, 19(2), 587-600.
- 770 Comblen, R., Lambrechts, J., Remacle, J.-F., Legat V., 2010. Practical evaluation of five
771 partly discontinuous finite element pairs for the non-conservative shallow water
772 equations. *International Journal for Numerical Methods in Fluids*, 63, 701-724.
- 773 de Brye, B., de Brauwere, A., Gourgue, O., Kärnä, T., Lambrechts, J., Comblen, R.,
774 Deleersnijder E., 2010. A finite-element, multi-scale model of the Scheldt tributaries,
775 river, estuary and ROFI. *Coastal Engineering*, 57, 850-863.
- 776 de Brye, B., Schellen, S., Sassi, M., Vermeulen, B., Deleersnijder, E., Hoitink, A.J.F., 2011.
777 Preliminary results of a finite-element, multi-scale model of the Mahakam Delta
778 (Indonesia). *Ocean Dynamics*, 61, 1107-1120.
- 779 Darby, S. E., Thorne, C. R., 1996. Predicting stage-discharge curves in channels with bank
780 vegetation. *Journal of Hydraulic Engineering*, 122(10), 583-586.
- 781 Deleersnijder, E., Lermusiaux P., (Editors) 2008. Multi-scale modeling: Nested-grid and
782 unstructured-mesh approaches. *Ocean Dynamics (Special issue)*, 58, 335-498.
- 783 Dutrieux, E., 1991. Study of the ecological functioning of the Mahakam delta (east
784 Kalimantan, Indonesia). *Estuarine, Coastal and Shelf Science*, 32(4), 415-420.
- 785 Edmonds, D. A., Slingerland, R. L., 2010. Significant effect of sediment cohesive on delta
786 morphology. *Nature Geoscience*, 3, 105 – 109.
- 787 Eisma, D., Kalf, J., Karmini, M., Marok, W.G., Van Put, A., Bernard, P., Van Grieken, R.,
788 1989. Dispersal of suspended matter in Makassar Strait and the Flores Basin.
789 *Netherlands Journal of Sea Research*, 24(4), 383-398.
- 790 Egbert, G.D., Bennet, A.F., Foreman, M.G.G., 1994. TOPEX/POSEIDON tides estimated
791 using a global inverse model. *Journal of Geophysical Research*, 99(C12), 24821-24852.
- 792 Elskens, M., Gourgue, O., Baeyens, W., Chou, L., Deleersnijder, E., Leermakers, M., de
793 Brauwere, A., 2014. Modelling metal speciation in the Scheldt Estuary: Combining a

- 794 flexible-resolution transport model with empirical functions. *Science of The Total*
795 *Environment*, 476-477, 346-358.
- 796 Einstein, H.A., Krone, R.B., 1962. Experiments to determine modes of cohesive sediment
797 transport in salt water. *Journal of Geophysical Research*, 67, 1451-1461.
- 798 Fischer, H. B, List, E.J., Koh, R.C.Y., Imberger, J., Brooks, N.H., 1979. Mixing in inland
799 and coastal waters. Academic Press, New York.
- 800 Gastaldo, R.A., Huc, A.-Y., 1992. Sediment Facies, Depositional Environments, and
801 distribution of Phytoclasts in the Recent Mahakam River Delta, Kalimantan, Indonesia.
802 *Palaios*, 7 (6), 574-590.
- 803 Gastaldo, R.A., Allen, G. P., Huc, A.-Y., 1995. The tidal character of fluvial sediments of
804 the modern Mahakam River delta, Kalimantan, Indonesia. *Spec. Publs int. Ass.*
805 *Sediment*, 24, 171-181.
- 806 Geuzaine, C., Remacle, J.-F., 2009. GMSH: a finite element mesh generator with built-in
807 pre-and post-processing facilities. *International Journal for Numerical Method in*
808 *Engineering*, 79(11), 1309-1331.
- 809 Gourgue, O., Baeyens, W., Chen, M. S., de Brauwere, A., de Brye, B., Deleersnijder, E.,
810 Elskens, M., Legat V., 2013. A depth-averaged two-dimensional sediment transport
811 model for environmental studies in the Scheldt Estuary and tidal river network. *Journal*
812 *of Marine Systems*, 128, 27-39.
- 813 Gong, W., Shen, J., 2010. A model diagnostic study of age of river-borne sediment
814 transport in the tidal York River Estuar. *Environmental Fluid Mechanics*, 10, 177-196.
- 815 Hardy, M. J., Wrenn, J. H., 2009. Palynomorph distribution in modern tropical deltaic and
816 shelf sediments–Mahakam Delta, Borneo, Indonesia. *Palynology*, 33(2), 19-42.
- 817 Hadi, S., Ningsih, N.S., Tarya, A., 2006. Study on seasonal variation of cohesive
818 suspended sediment transport in estuary of Mahakam Delta by using numerical model.
819 *Jurnal Teknik Sipil*, 13(1), 11-22.
- 820 Hidayat, H., Vermeulen, B., Sassi, M., Torfs, P.J.J.F., Hoitink, A.J.F., 2011. Discharge
821 estimation in a backwater affected meandering river. *Hydrology and Earth System*
822 *Sciences Discussions*, 8, 2667-2697.

- 823 Hidayat, H., Hoekman, D.H., Vissers, M.A.M., Hoitink, A.J.F., 2012. Flood occurrence
824 mapping of the middle Mahakam lowland area using satellite radar. *Hydrology and*
825 *Earth System Sciences*, 16(7), 1805-1816.
- 826 Hoitink, A.J.F., 2004. Tidally-induced clouds of suspended sediment connected to shallow-
827 water coral reefs. *Marine Geology*, 208(1), 13-31.
- 828 Kärnä, T., de Brye, B., Gourgue, O., Lambrechts, J., Comblen, R., Legat, V., Deleersnijder,
829 E., 2011. A fully implicit wetting–drying method for DG-FEM shallow water models,
830 with an application to the Scheldt Estuary. *Computer Methods in Applied Mechanics*
831 *and Engineering*, 200, 509-524.
- 832 Kirk Ziegler, C., Nisbet, B.S., 1994. Fine-grained sediment transport in Pawtuxet River,
833 Rhode Island. *Journal of Hydraulic Engineering*, 120(5), 561-576.
- 834 Kirk Ziegler, C., Nisbet, B.S., 1995. Long-term simulation of fine-grained sediment
835 transport in large reservoir. *Journal of Hydraulic Engineering*, 121(11), 773-781.
- 836 Lambrechts, J., Comblen, R., Legat, V., Geuzaine, C., Remacle, J.-F., 2008a. Multiscale
837 mesh generation on the sphere. *Ocean Dynamic*, 58, 461-473.
- 838 Lambrechts, J., Hanert, E., Deleersnijder, E., Bernard, P.-E., Legat, V., Remacle, J.-F.,
839 Wolanski, E., 2008b. A multi-scale model of the hydrodynamics of the whole Great
840 Barrier Reef. *Estuarine, Coastal and Shelf Science*, 79, 143-151.
- 841 Lambrechts, J., Humphrey, C., McKinna, L., Gourgue, O., Fabricius, K.E., Mehta, A.J.,
842 Lewis, S., Wolanski, E., 2010. Importance of wave-induced bed liquefaction in the fine
843 sediment budget of Cleveland Bay, Great Barrier Reef. *Estuarine, Coastal and Shelf*
844 *Science*, 89, 154-162.
- 845 Lang, G., Shubert, R., Markofsky, M., Fanger, H.U., Grabemann, I., Neumann, H.L.,
846 Riethmuller, R., 1989. Data interpretation and numerical modeling of the mud and
847 suspended sediment experiment 1985. *Journal of Geophysical Research*, 94(C10),
848 14318-14393.
- 849 Le Hir, P., Monbet, Y., Orvain, F., 2007. Sediment erodability in sediment transport
850 modelling: Can we account for biota effects?. *Continental Shelf Research*, 27, 1116-
851 1142.
- 852 Lou, J., Ridd, P.V., 1997. Modelling of suspended sediment transport in coastal area under
853 waves and currents. *Estuarine, Coastal and Shelf Science*, 45, 1-16.

- 854 Lukman, Yoga, G.P., Widiyanto, T., Ridwansyad, I., Nomosatryo, S., 2006. Physical
855 characteristics and mangrove community in the north part of Mahakam Delta in East
856 Kalimantan-Indonesia. *Limnotek*, 13(1), 1-8.
- 857 Mandang, I., Yanagi, T., 2009. Cohesive sediment transport in the 3D-hydrodynamic-
858 baroclinic circulation model in the Mahakam Estuary, East Kalimantan, Indonesia.
859 *Coastal Marine Science*, 32(3), 1-13.
- 860 Martini, P., Carniello, L., Avanzi, C., 2004. Two dimensional modelling of flood flows and
861 suspended sediment transport: the case of Brenta river, Veneto (Italy). *Natural Hazards
862 and Earth System Sciences*, 4, 165-181.
- 863 Mehta, A.J., Partheniades, E., 1975. An investigation of the depositional properties of
864 flocculated fine sediments. *Journal of Hydraulic Research*, 12(4), 361-381.
- 865 Mercier, C., Delhez, E.J.M., 2007. Diagnosis of the sediment transport in the Belgian
866 Coastal Zone. *Estuarine, Coastal and Shelf Science*, 74, 670-683.
- 867 Neumeier, U., Lucas, C. H., Collins, M., 2006. Erodibility and erosion patterns of mudflat
868 sediments investigated using annular flume. *Aquatic Ecology*, 40(4), 543-554.
- 869 Okubo, A., 1971. Oceanic diffusion diagram. *Deep-Sea Research*, 18, 789-802.
- 870 Partheniades, E., 1965. Erosion and deposition of cohesive soils. *Journal of the Hydraulic
871 Division*, 91, 105-139.
- 872 Pham Van, C., de Brye, B., Soares-Frazão, S., Deleersnijder, E., Hoitink, A.J.F., Sassi, M.,
873 Hidayat, H., 2012a. Modelling of salinity distribution and water age in the Mahakam
874 Delta, Indonesia. *International Conference on Estuaries and Coasts: ICEC2012*, Hanoi,
875 Vietnam, 120-127.
- 876 Pham Van, C., de Brye, B., Soares-Frazão, S., Deleersnijder, E., 2012b. Preliminary results
877 of a numerical model of suspended sediment in the Mahakam Delta. *Coastlab12*, Ghent,
878 Belgium, 259-260.
- 879 Pham Van, C., de Brye B., Deleersnijder, E., Hoitink, A.J.F., Sassi, M.G., Spinewine, B.,
880 Hidayat, H., Soares-Frazão, S. Simulations of flow in the tropical river-lake-delta
881 system of the Mahakam land-sea continuum, Indonesia. *Journal of Hydrodynamics*,
882 under review.
- 883 Roberts, H.H., Sydow, J., 2003. Later quaternary stratigraphy and sedimentology of the
884 offshore Mahakam delta, East Kalimantan (Indonesia). *Tropical Deltas of Southeast
885 Asia: Sedimentology, Stratigraphy, and Petroleum Geology*, 76, 125-145.

- 886 Sanford, L.P., Maa, J.P.Y., 2001. A unified erosion formulation for fine sediments. *Marine*
887 *Geology*, 179, 9-23.
- 888 Sassi, M., Hoitink, A.J.F., de Brye, B., Vermeulen, B., Deleersnijder, E., 2011. Tidal
889 impact on the division of river discharge over distributary channels in the Mahakam
890 Delta. *Ocean Dynamics*, 61, 2211-2228.
- 891 Sassi, M., Hoitink, A.J.F., Vermeulen, B., 2012. Impact of sound attenuation by suspended
892 sediment on ADCP backscatter calibrations. *Water Resources Research*, 48, W09520,
893 doi:10.1029/2012WR012008.
- 894 Sassi, M., Hoitink, A.J.F., Vermeulen, B., Hidayat, H., 2013. Sediment discharge division
895 at two tidally influenced river bifurcations. *Water Resources Research*, 49(4),2119-2134,
896 doi:10.1002/wrcr.20216.
- 897 Smagorinsky, J., 1963. General circulation experiments with the primitive equations.
898 *Monthly Weather Review*, 91, 99-164.
- 899 Storms, J.E.A., Hoogendoorn, R.M., Dam, R.A.C., Hoitink, A.J.F., Koonenberg, S.B.,
900 2005. Late-Holocene evolution of the Mahakam delta, East Kalimantan, Indonesia.
901 *Sedimentary Geology*, 180, 149-166.
- 902 Susanto, R.D., Ffield, A., Gordon, A., Adi, T.R., 2012. Variability of Indonesian
903 throughflow within Makassar Strait, 2004-2009. *Journal of Geophysical Research*, 117,
904 C09013, doi:10.1029/2012JC008096.
- 905 Suyatna, I., Bratawinata, A.A., Sidik, A.S., Ruchaemi A.A. 2010. Demersal fishes and
906 their distribution in estuarine waters of Mahakam Delta, East Kalimantan. *Biodiversitas*,
907 10(4), 204-210.
- 908 Turner, A., Millward, G.E., 2002. Suspended particles: Their role in estuarine
909 biogeochemical cycle. *Estuarine, Coastal and Shelf Science*, 55, 857-883.
- 910 van Zwieten, P.A.M, Sidik, A.S., Noryadi, Suyatna, I., Abdunnur, 2006. Aquatic food
911 production in the coastal zone: data-based perceptions on the trade-off between
912 mariculture and fisheries production of the Mahakam delta and estuary, East
913 Kalimantan. *Environment and livelihoods in tropical coastal zones*, vol. 219, edited by
914 C. T. Hoanh et al., pp. 219-236, CABI publishing, UK.
- 915 Van Leussen, W., 1999. The variability of settling velocities of suspended fine-grained
916 sediment in the Ems Estuary. *Journal of Sea Research*, 41, 109-118.
- 917 Zhang, S.Q., 1999. One-D and two-D combined model for estuary sedimentation.

- 918 International Journal of Sediment Research, 14(1), 37-45.
- 919 White, L., Legat, V., Deleersnijder, E., 2008. Tracer conservation for three-dimensional,
920 finite-element, free-surface, ocean modeling on moving prismatic meshes. *Monthly*
921 *Weather Review*, 136, 420–442.
- 922 Winterwerp, J. C., 1998. A simple model for turbulence induced flocculation of cohesive
923 sediment. *Journal of Hydraulic Engineering*, 36(3), 309-326.
- 924 Winterwerp, J.C., 2013. The physical analysis of muddy sedimentation processes. *Treatise*
925 *on Estuarine and Coastal Science*, 2, 311-360.
- 926 Wu, W., 2007. *Computational river dynamics*, Tayler & Francis, London, UK.
- 927 Wu, W., Li, Y., 1992. One- and two-dimensional nesting mathematical model for river
928 flow and sedimentation. *The 5th international Symposium on River Sedimentation*,
929 Karlsruhe, Germany, pp. 547-554.
- 930 Wu, Y., Falconer, R., Lin, B., 2005. Modelling trace metal concentration distributions in
931 estuarine waters. *Estuarine Coastal and Shelf Science*, 64, 699-709.

Table 1 Suspended sediment concentration data in the Mahakam River and its delta

Stations	Date	Tide	Range of suspended sediment (kg/m ³)	Data being used for
Samarinda	11-30-2008	Spring	0.012-0.154	calibration
	01-17-2009	Neap		
	03-12-2009	Neap		validation
	05-24-2009	Neap		
	08-06-2009	Neap		
DAN and DAS	12-26-2008	Spring	0.005-0.110	calibration
	01-04-2009	Neap		
FBN and FBS	12-27-2008	Spring	0.001-0.100	calibration
	01-03-2009	Neap		

Table 2 Temporal errors (E_t) at measurement stations in the computational domain

Sim.	Parameters			E_t				
	k_I	β	M ($\times 10^{-5}$)	Samarinda	DAN	DAS	FBN	FBS
a.01			5	0.3628	0.2306	0.2608	0.2922	0.3070
a.02		1.0	12	0.1095	0.2360	0.2495	0.2385	0.1843
a.03			21	0.3447	0.6172	0.6005	0.6003	0.4851
a.04			25	0.4598	0.7636	0.7393	0.7443	0.6107
a.05			5	0.1596	0.1227	0.1569	0.1497	0.1781
a.06	0.04	1.25	12	0.2801	0.5885	0.5776	0.5433	0.5056
a.07			21	0.6268	1.0319	1.0022	0.9863	0.8936
a.08			25	0.7553	1.1960	1.1592	1.1500	1.0385
a.09			5	0.1216	0.1753	0.1935	0.1645	0.2018
a.10		1.30	12	0.3292	0.6638	0.6496	0.6103	0.5785
a.11			21	0.6836	1.1163	1.0840	1.0645	0.9773
a.12			25	0.8140	1.2833	1.2439	1.2313	1.1251
a.13			5	0.5490	0.4550	0.4692	0.4805	0.5055
a.14		1.0	12	0.2423	0.1746	0.2140	0.2167	0.2560
a.15			21	0.0916	0.1842	0.1956	0.2078	0.1426
a.16			25	0.1322	0.2755	0.2705	0.2874	0.1863
a.17			5	0.3769	0.2242	0.2554	0.2846	0.3014
a.18	0.08	1.25	12	0.0608	0.1858	0.2002	0.2034	0.1750
a.19			21	0.2132	0.5046	0.4845	0.4937	0.4067
a.20			25	0.3014	0.6245	0.5974	0.6094	0.5078
a.21			5	0.3410	0.1780	0.2149	0.2471	0.2638
a.22		1.30	12	0.0767	0.2419	0.2491	0.2476	0.2139
a.23			21	0.2582	0.5751	0.5517	0.5586	0.4747
a.24			25	0.3507	0.6986	0.6686	0.6785	0.5797
a.25			5	0.6316	0.5537	0.5663	0.5707	0.5962
a.26		1.0	12	0.4335	0.3131	0.3409	0.3381	0.3841
a.27			21	0.2602	0.1329	0.1776	0.1780	0.2090
a.28			25	0.2009	0.1216	0.1575	0.1658	0.1606
a.29			5	0.4795	0.3499	0.3715	0.3899	0.4097
a.30		1.25	12	0.2420	0.0946	0.1452	0.1599	0.1793
a.31	0.12		21	0.0968	0.2699	0.2641	0.2814	0.2099
a.32			25	0.1223	0.3674	0.3506	0.3697	0.2811
a.33			5	0.4472	0.3063	0.3307	0.3525	0.3712
a.34			1.30	12	0.2038	0.0931	0.1376	0.1536
a.35		21		0.1020	0.3308	0.3190	0.3345	0.2609
a.36		25		0.1542	0.4329	0.4116	0.4293	0.3409

Figures

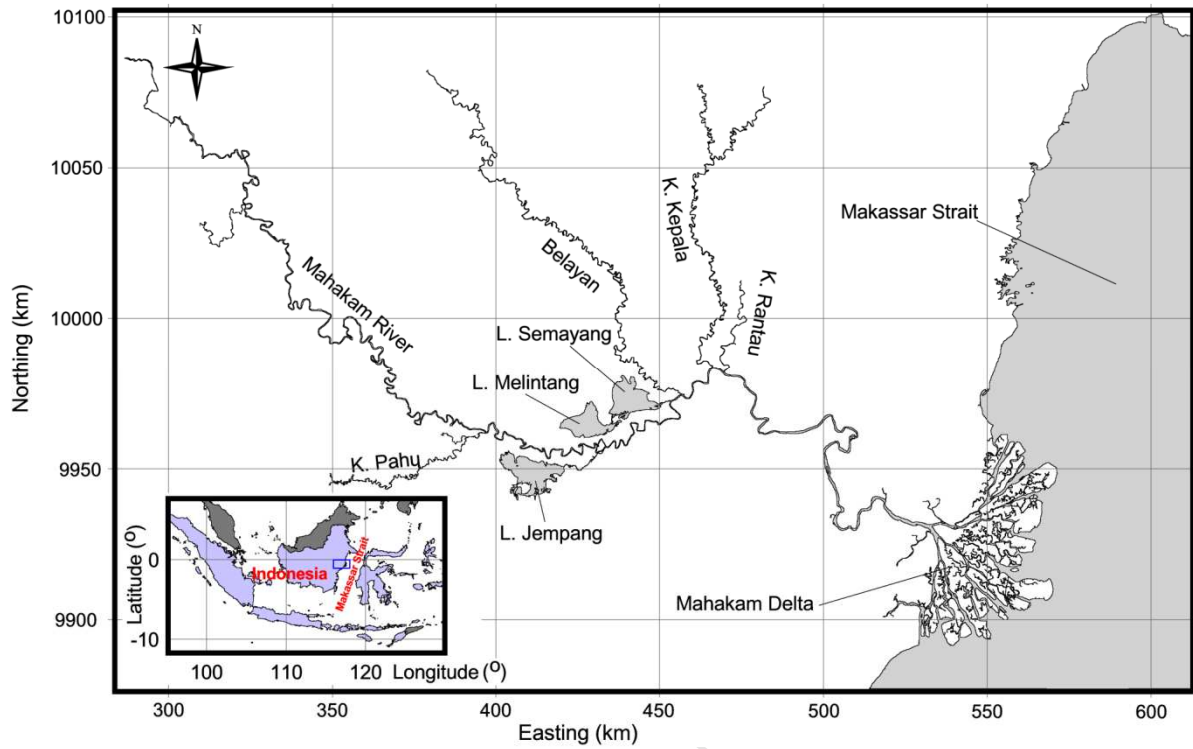


Figure 1. Map of the Mahakam River, main tributaries, and delta

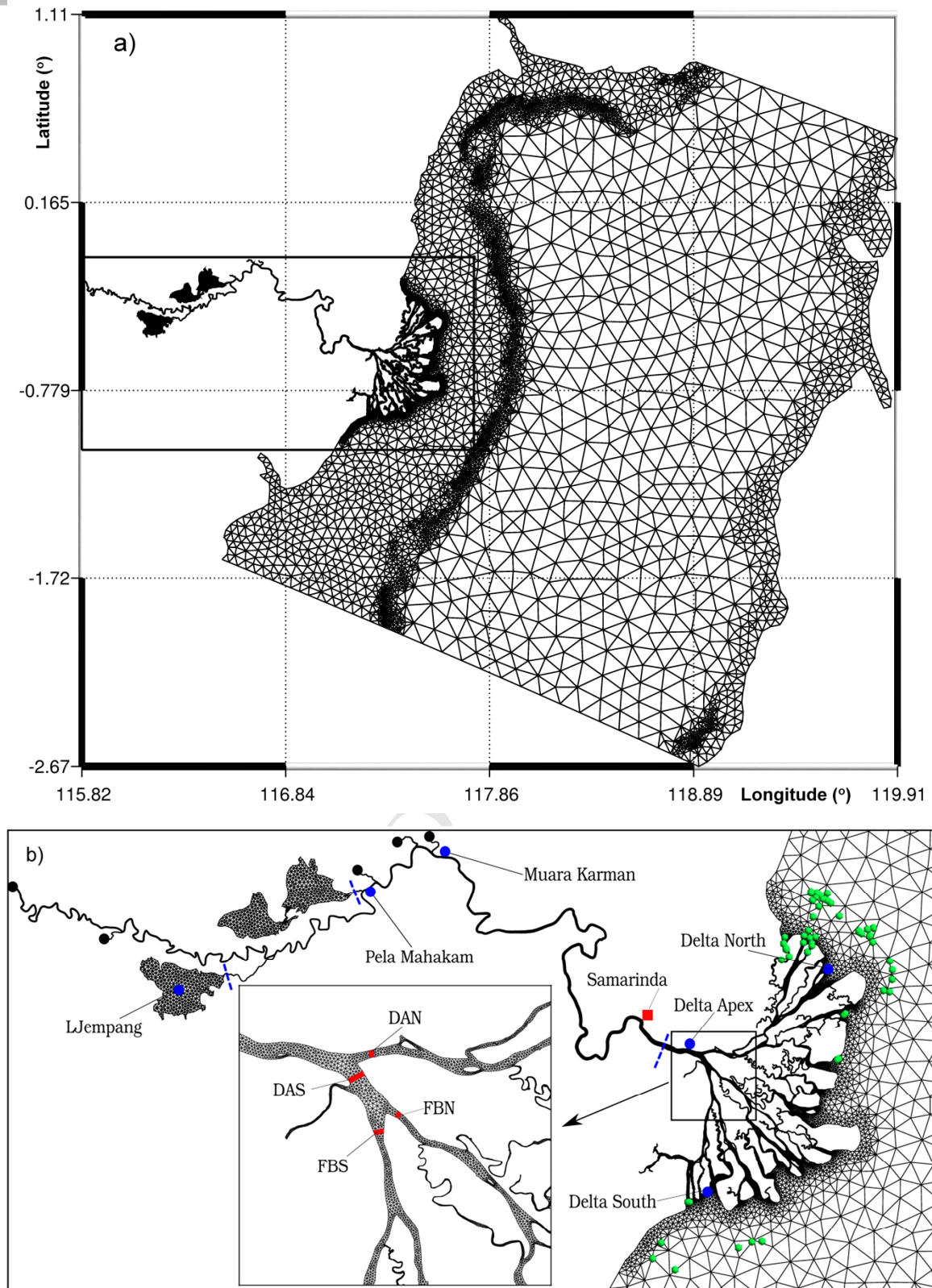


Figure 2. Grid of the model domain: a) complete mesh and b) zoom on upstream domain and delta, also showing the connection between the 1D and 2D models (*dashed-blue lines*), the upstream boundary locations (*back dots*), the sediment and water discharge stations (*red squares*), the water elevation station (*blue dots*), and field sampling sites of salinity (*green dots*)

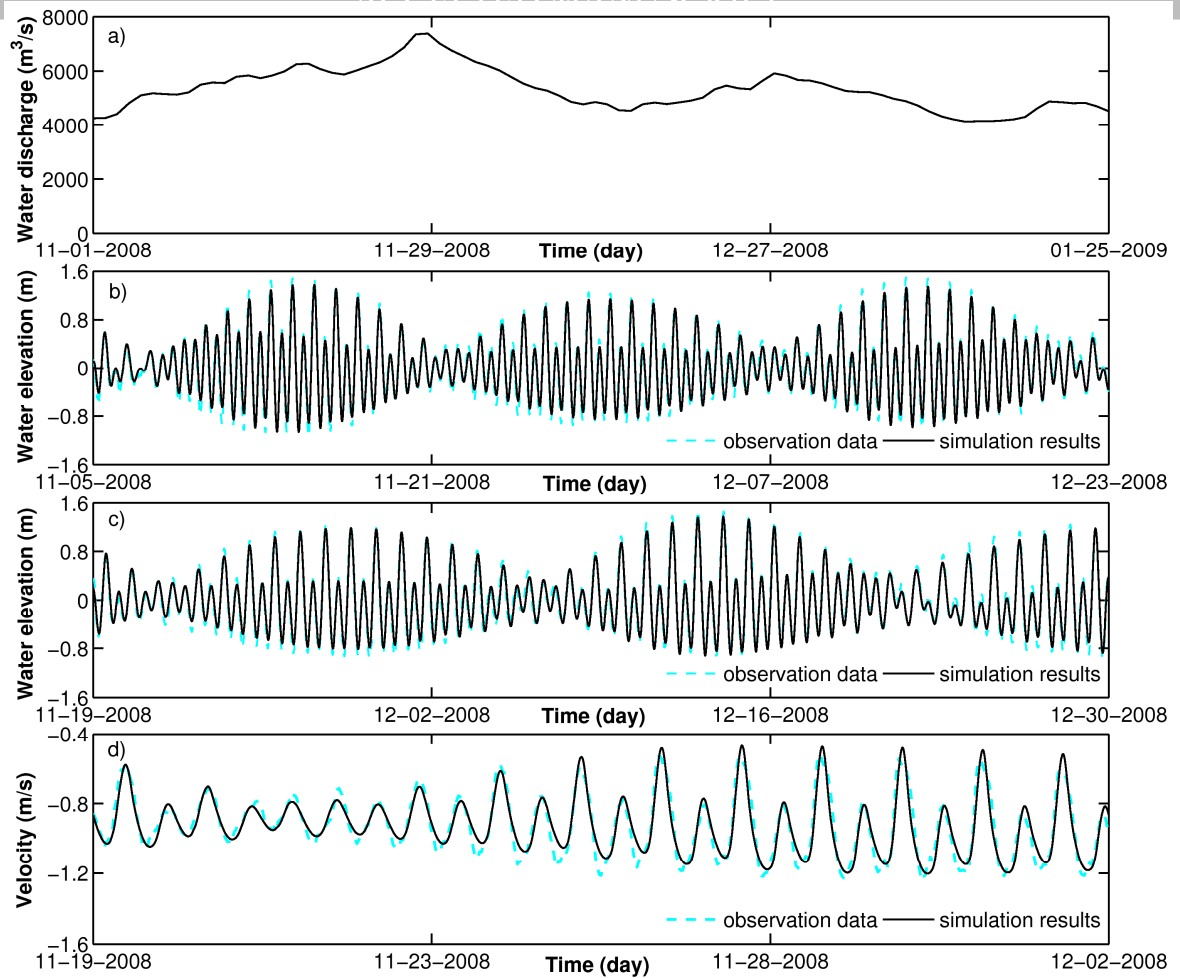


Figure 3. Validation results in the hydrodynamic module: a) water discharge at upstream boundary, b) computed and observed water elevation at Delta North, c) computed and observed water elevation at Delta South, and d) predicted and measured sectional-averaged velocity at Samarinda, where negative velocity coincides with seaward direction

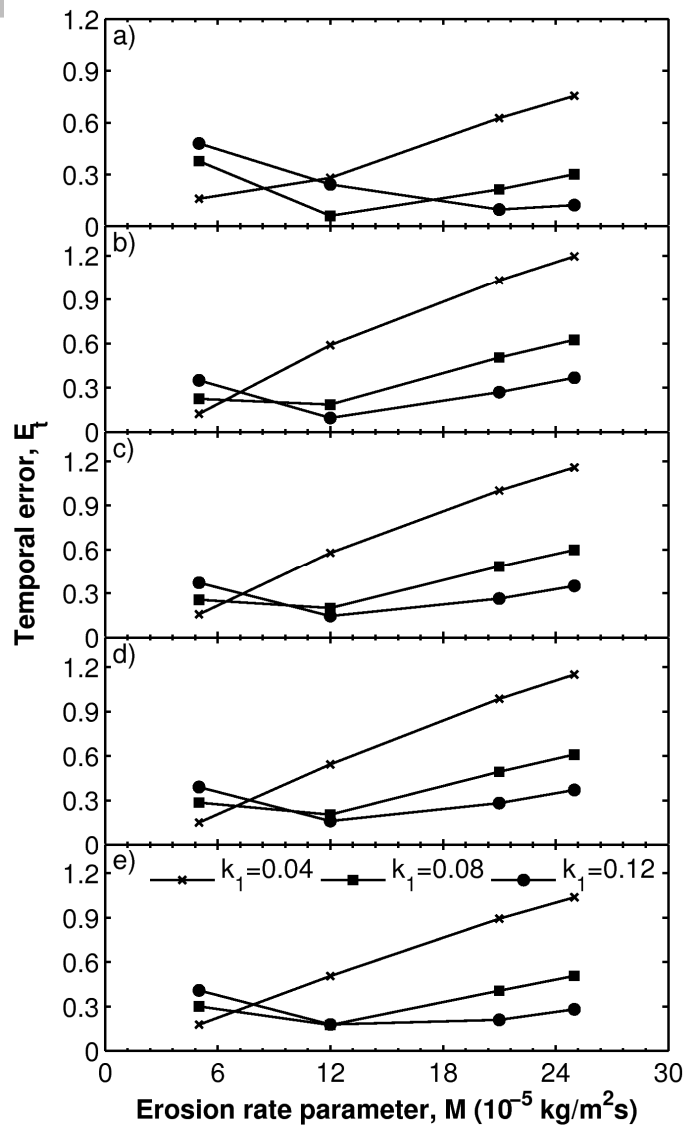


Figure 4. Temporal error of SSC versus the variable values of M and k_1 (and the constant value $\beta=1.25$), at: a) Samarinda, b) DAN, c) DAS, d) FBN, and e) FBS stations

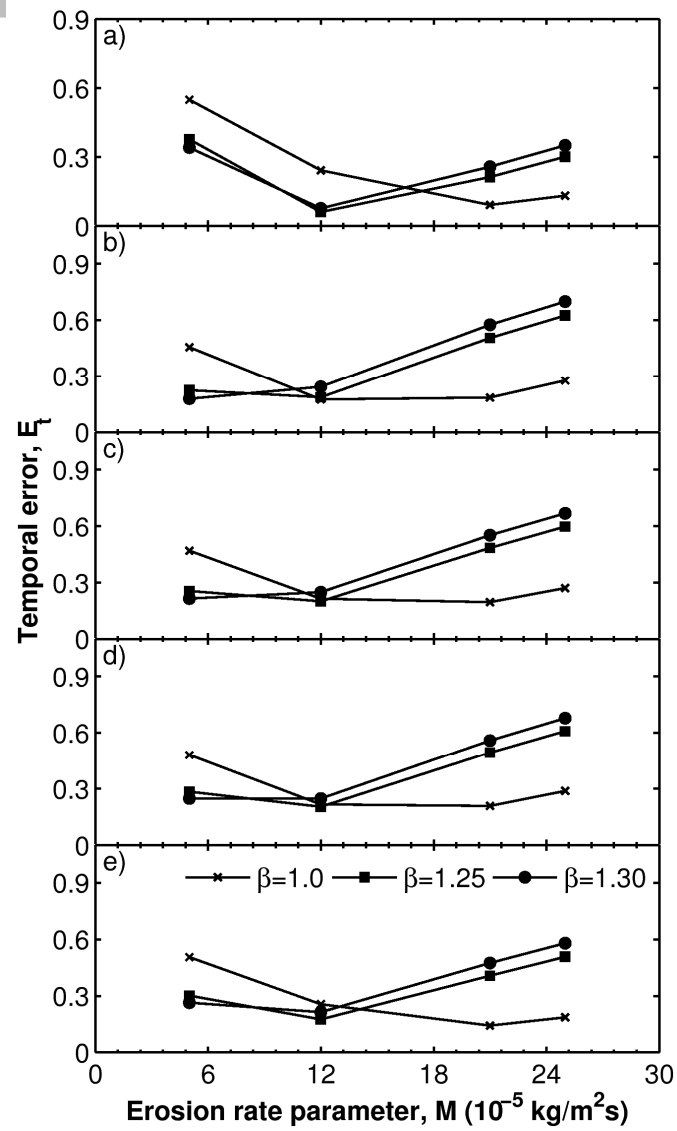


Figure 5. Temporal error of SSC versus the variable values of M and β (and the constant value $k_I=0.08$), at: a) Samarinda, b) DAN, c) DAS, d) FBN, and e) FBS stations

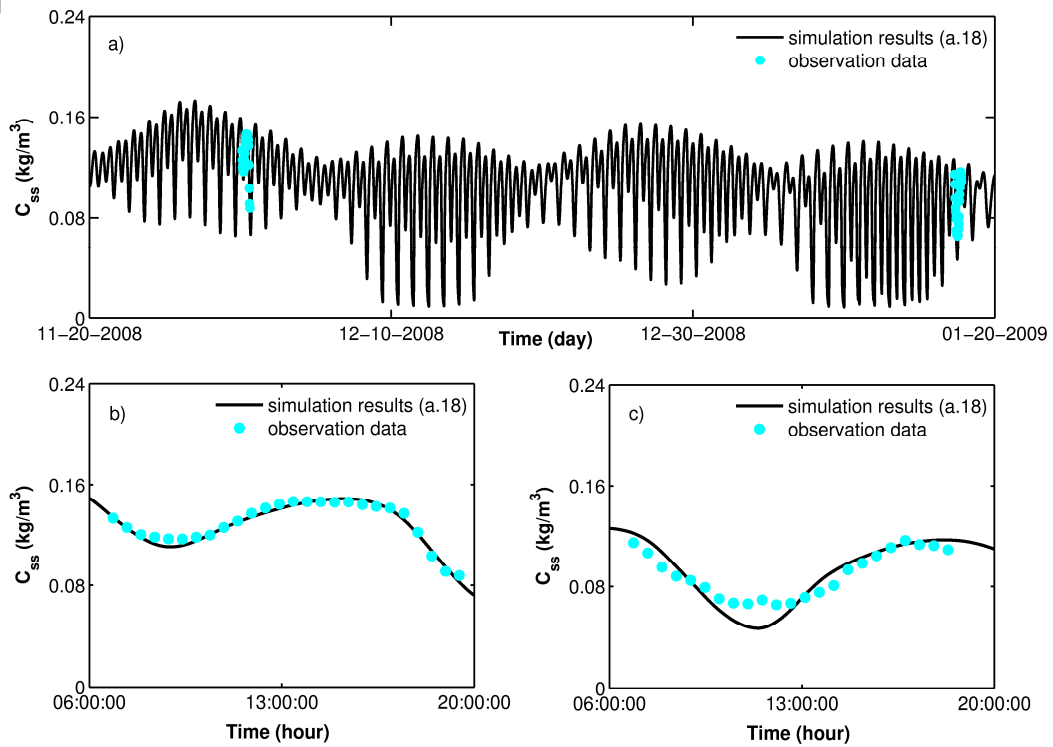


Figure 6. Observed and simulated SSC at Samarinda: a) all simulation period, b) zoom on 11-30-2008, and c) zoom on 01-17-2009 in the calibration step

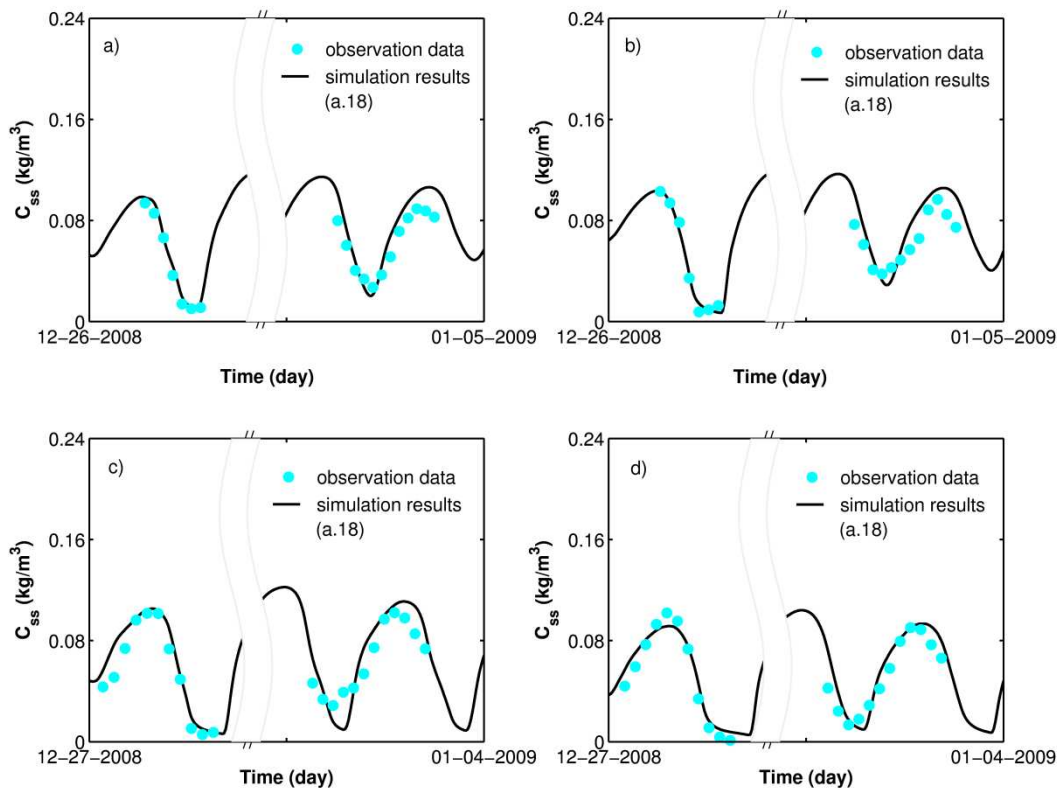


Figure 7. Observed data and simulation results of SSC, at: a) DAN, b) DAS, c) FBN, and d) FBS stations in the calibration step

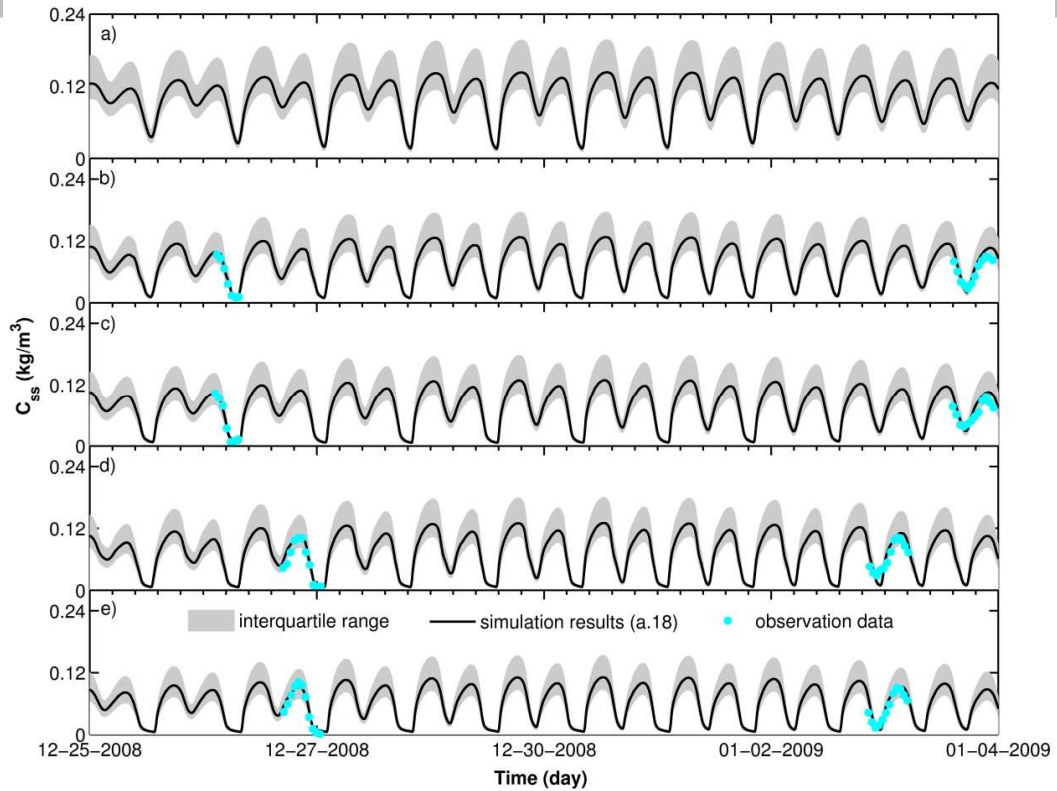


Figure 8. Interquartile range of SSC at: a) Samarinda, b) DAN, c) DAS, d) FBN, and e) FBS stations. At each station, the interquartile range is carried out based on thirty-six simulations in the calibration step

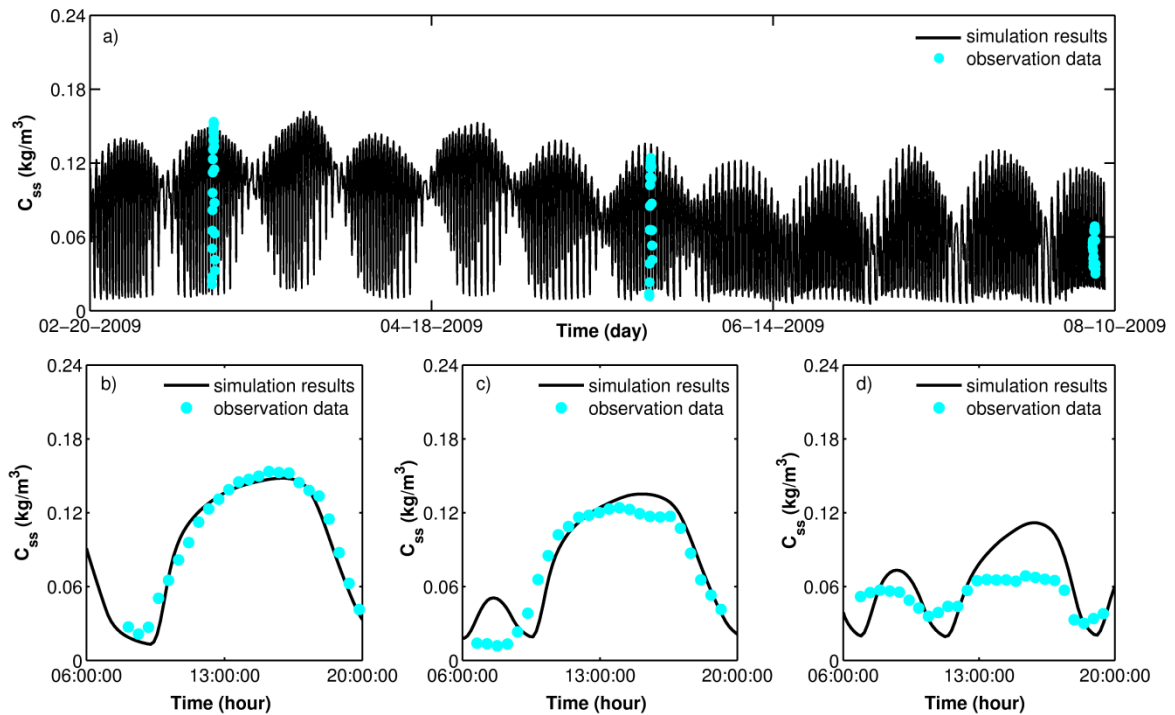


Figure 9. Observed and simulated SSC at Samarinda in the validation step: a) all simulation period of 6 months, b) zoom on 03-12-2009, c) zoom on 05-24-2009, and d) zoom on 08-06-2009. The long-term simulation results are presented for validating the optimal values of parameters (a.18) obtained in the calibration step

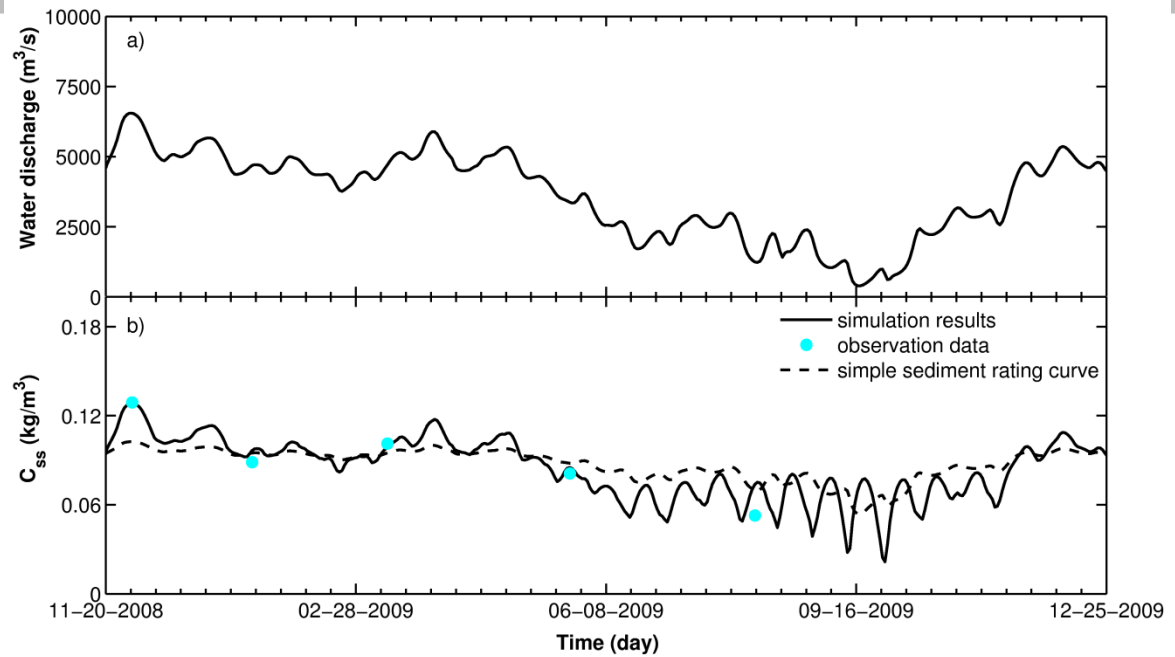


Figure 10. Temporal variation of simulation results in the long period from November 2008 to December 2009: a) daily water discharge and b) daily averaged SSC at Samarinda. The results obtained from a simple sediment curve are presented to show how much detail the model adds compared to its' simple rating curve approach

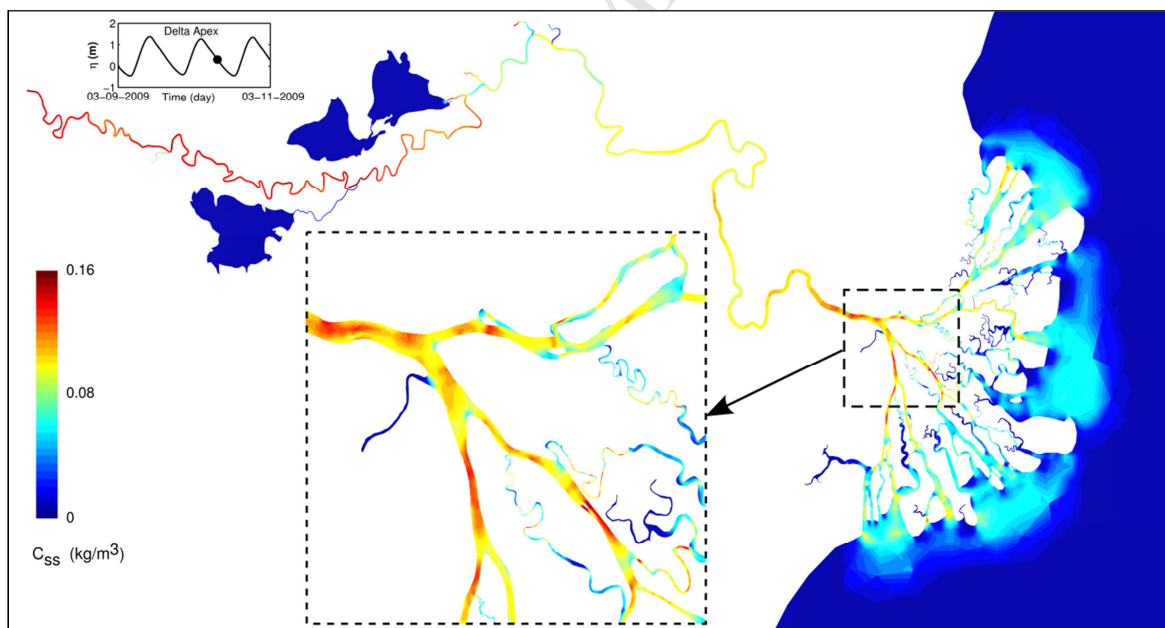


Figure 11. Spatial distribution of SSC in the Mahakam River and in the whole delta, obtained from the model at 13:50:00 on 03-10-2009 that corresponds to the ebb phase of neap tide. Bottom inset is included in order to close view the variation of SSC around the delta apex

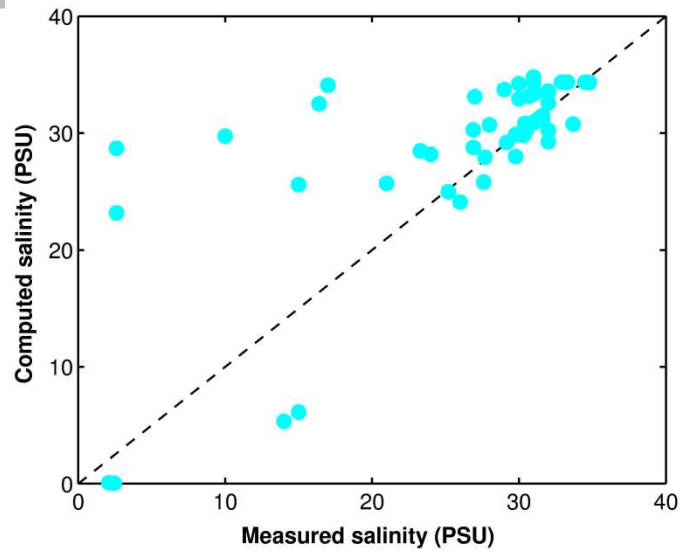


Figure 12. Measured data and computed results of salinity at all field sampling sites. The dash line indicates the perfect fit between computed results and measured data. The computed results are obtained when diffusivity coefficient is parameterized using the Okubo formulation, with the coefficient $c_k=0.018$

Highlights

- An unstructured-mesh, finite element model allows for the multi-scale simulation of fine-grained sediment dynamics in a land-sea continuum.
- Key model parameters are calibrated using field data.
- The model is able to reproduce very well the measurements made at a number of stations.