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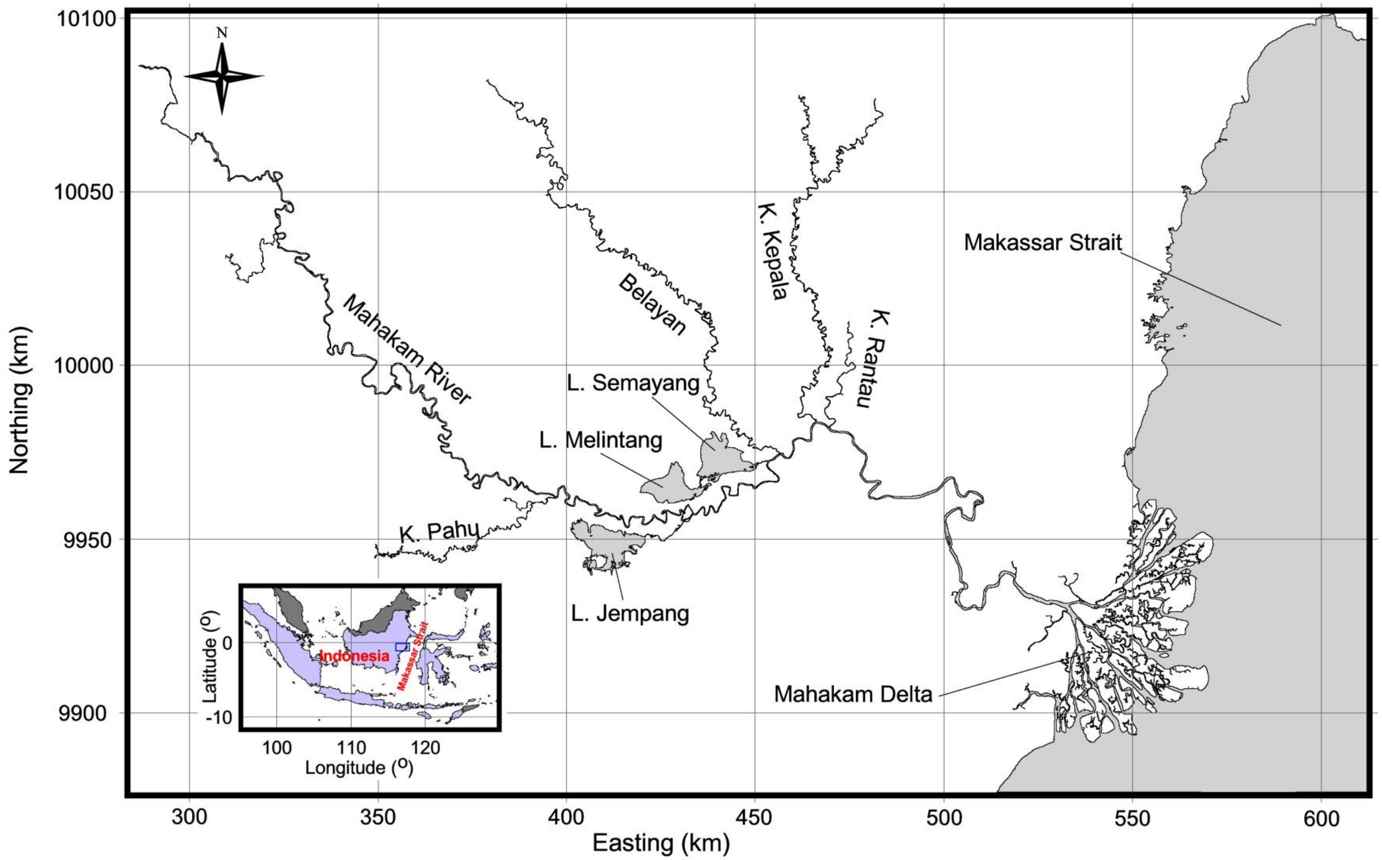
Simulations of suspended sediment transport in the river-delta-coastal continuum, East Kalimantan, Indonesia

Chien Pham Van, Eric Deleersnijder, Sandra Soares-Frazao (UCL)

Olivier Gourgue (VUB)

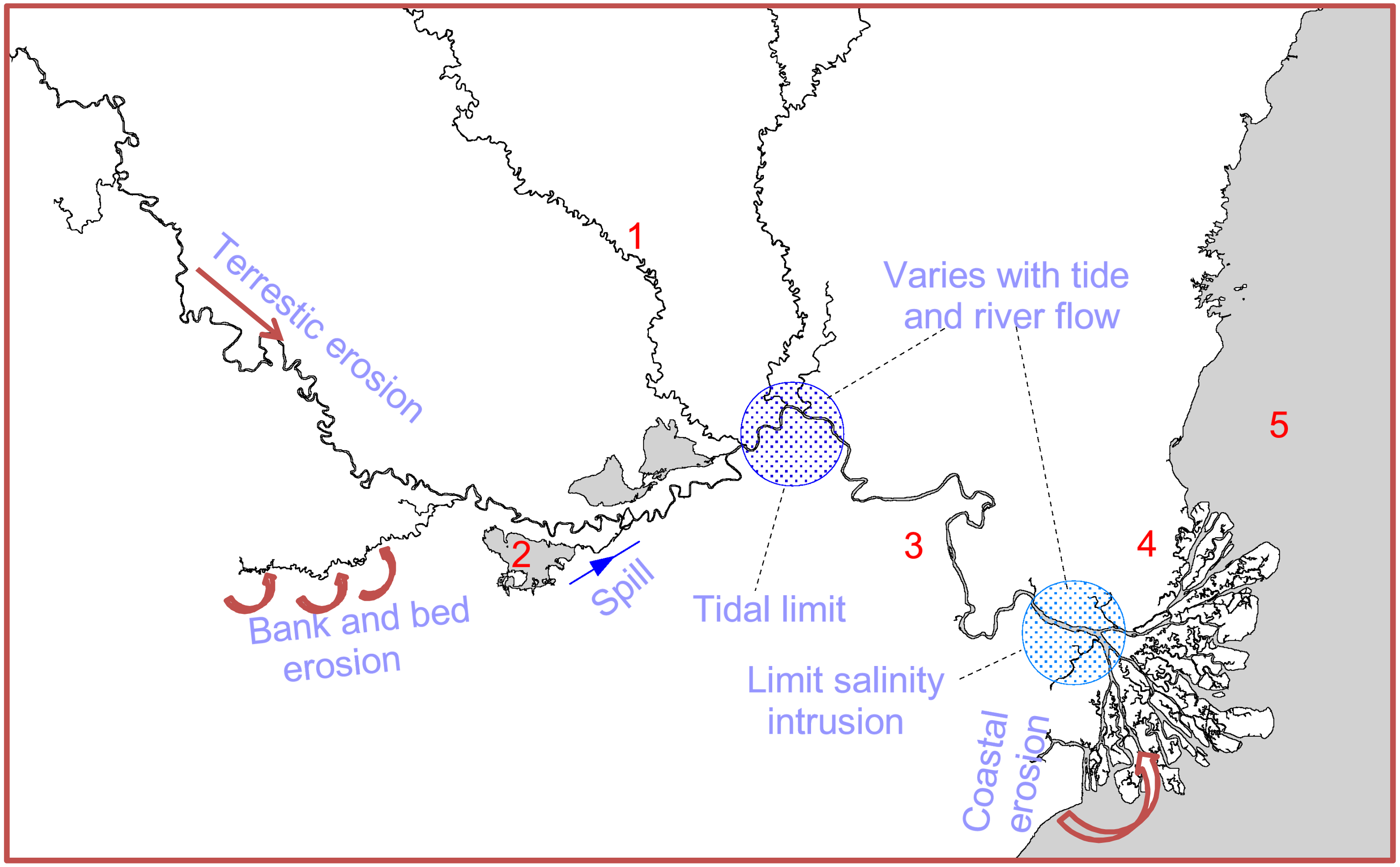
Maximiliano Sassi , Ton Hoitink (WU)

The Mahakam river-delta-coastal continuum system



- located in East Kalimantan, Indonesia
- River: 900 km length, catchment area: 75,000 km^2
- Delta: symmetrical and approximately 50 km in radius + multiple tidal channels
- Makassar Strait: width: 200-300 km, length: 600 km

The Mahakam river-delta-coastal continuum system



- Complex continuum system with different characteristic processes along the river flowing into the Makassar Strait
- Mixture of sand and mud (silt and clay)

Why do we need to study the SSC?

Because …

- High SSC $\rightarrow$ morphology, controlling smooth or rough, flat or complex shorelines, navigation and flood mitigation infrastructures
- Degradation of the water quality because of adsorbing organic chemical and trace of metals
- Studies of SSC are very limited, e.g. either local (zooming in to particular site) or regional (focusing on sedimentary processes in a geological and morphological context)
- A few local numerical studies have only performed for the delta but not representative of long-term variation of SSC under significant changes of river flows and tides
- Observations of SSC are also very limited

Objectives

- To determine a suitable formulation for estimating the erosion rate
- To accurately reproduce the measured SSC at different locations
- To provide preliminarily investigation of the spatial distribution and temporal variation of SSC in the Mahakam river-delta-coastal continuum system

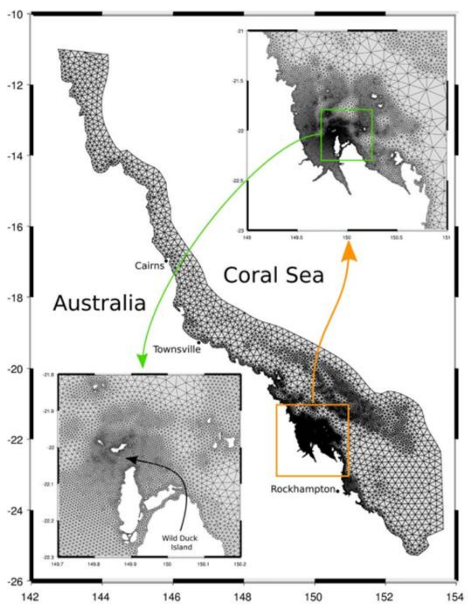
Finite-element SLIM model

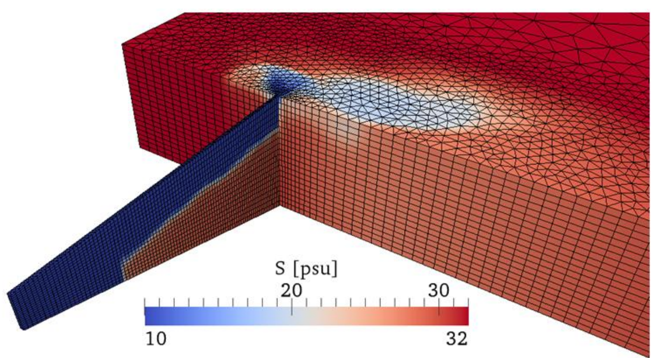
1D model

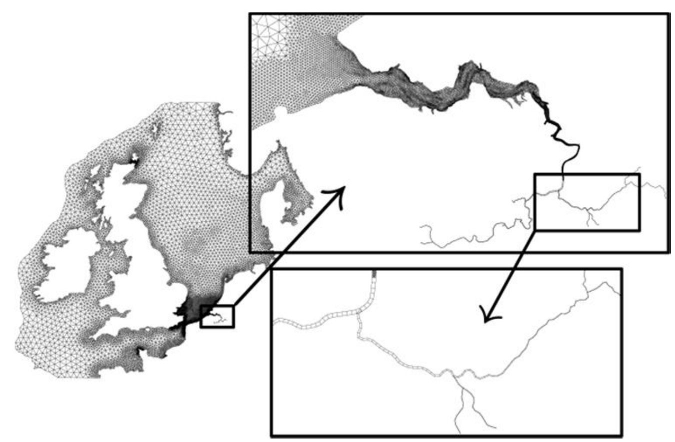
2D model

3D model

- *Hydrodynamic*
- *Salinity*
- Sediment
- Water renewal
- Fecal bacteria
- Radioactive release
- Sea-Ice



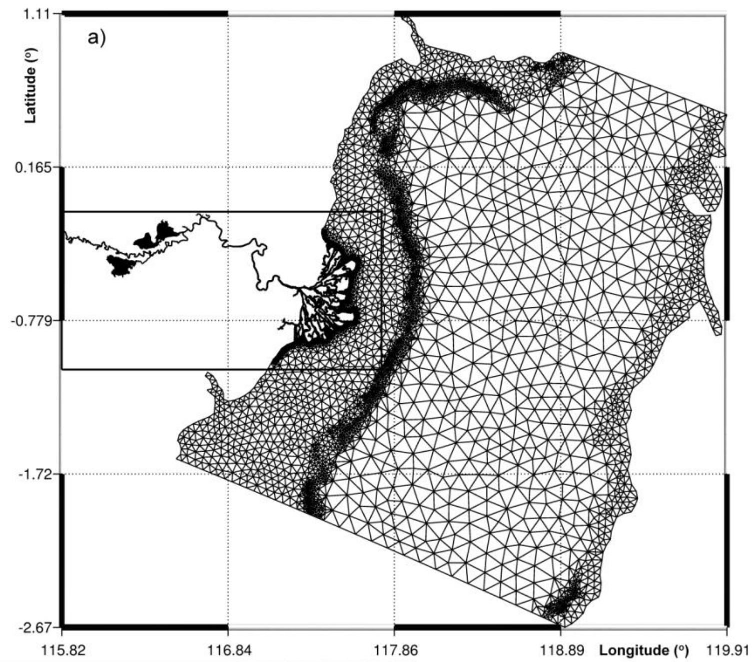


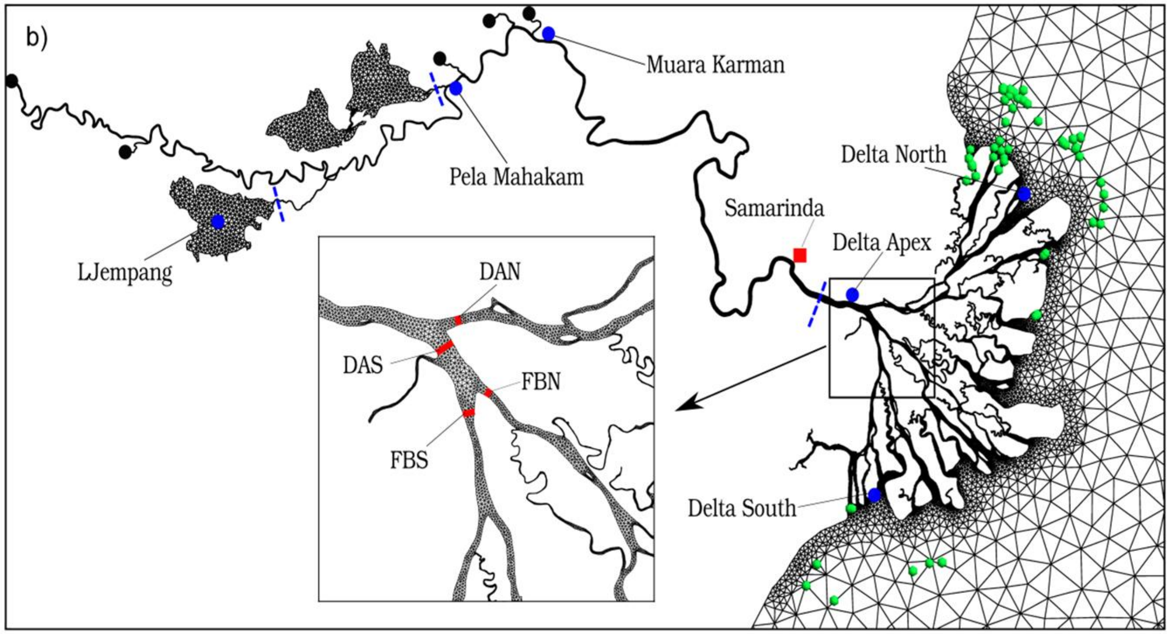


http://www.climate.be/slim

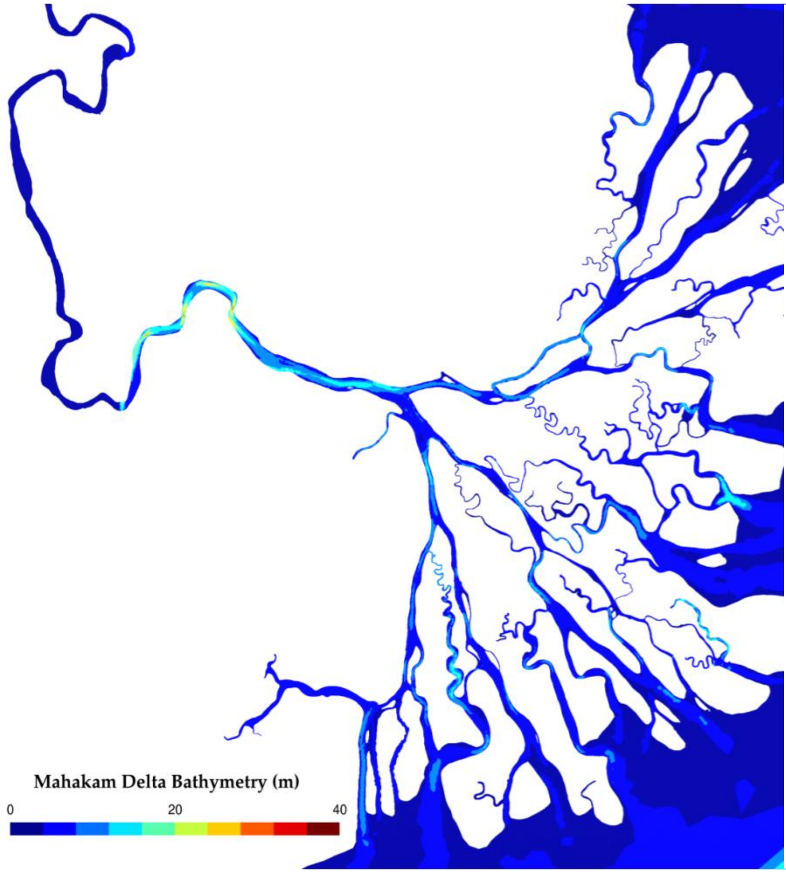
A coupled 2D/1D model	Computational grid

- Highly variable spatial resolution: at least 2 triangles in the smallest branches
- Mesh refinement is into account the change of bathymetry and distance to the delta apex and coastlines
- Mesh size: 5 m to 10 km
- 60819 elements and 3700 line segments

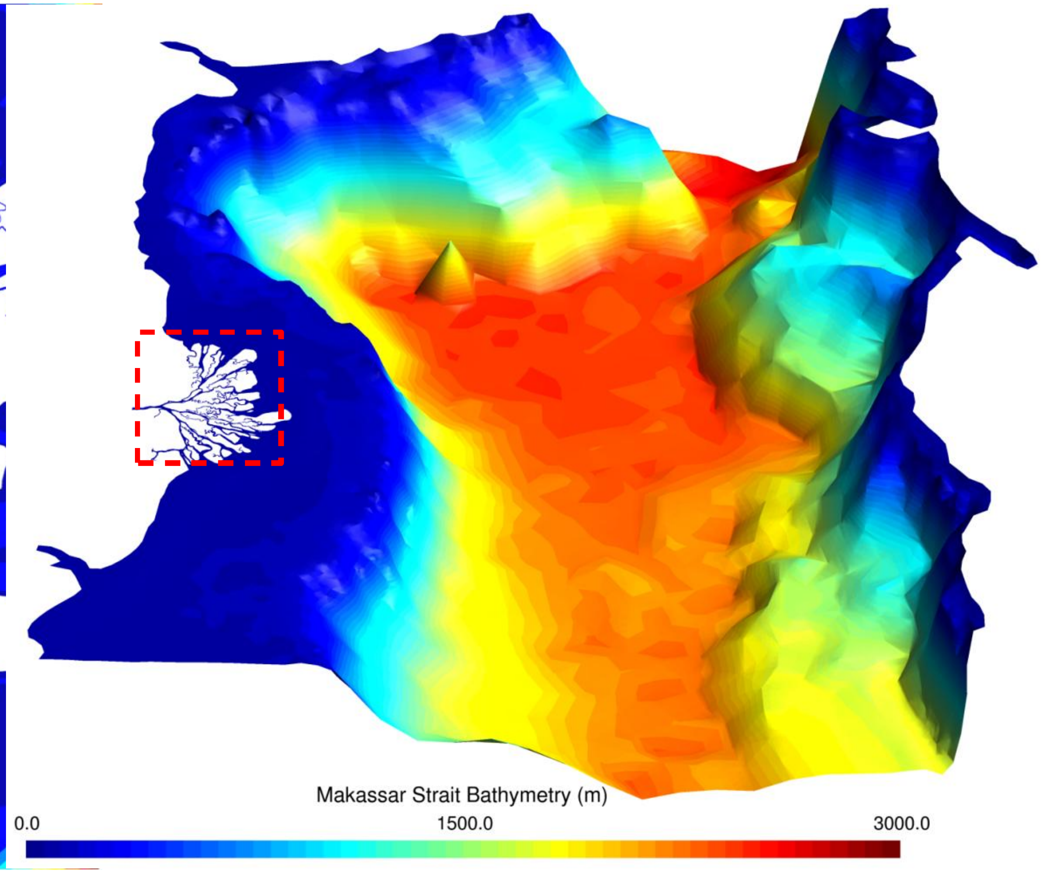




Mahakam Delta



Makassar Strait: from the global GEBCO[1] database



[1] https://www.bodc.ac.uk/data/online_delivery/gebco/

2D depth integrated equations

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

$$\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot (\nabla \mathrm{u}) + f\mathrm{k} \times \mathrm{u} + g \nabla \eta = \frac{1}{H} \nabla \cdot \left[H \nu_{2D} (\nabla \mathrm{u}) \right] - \frac{\tau_b}{\rho H}$$

1D section integrated equations

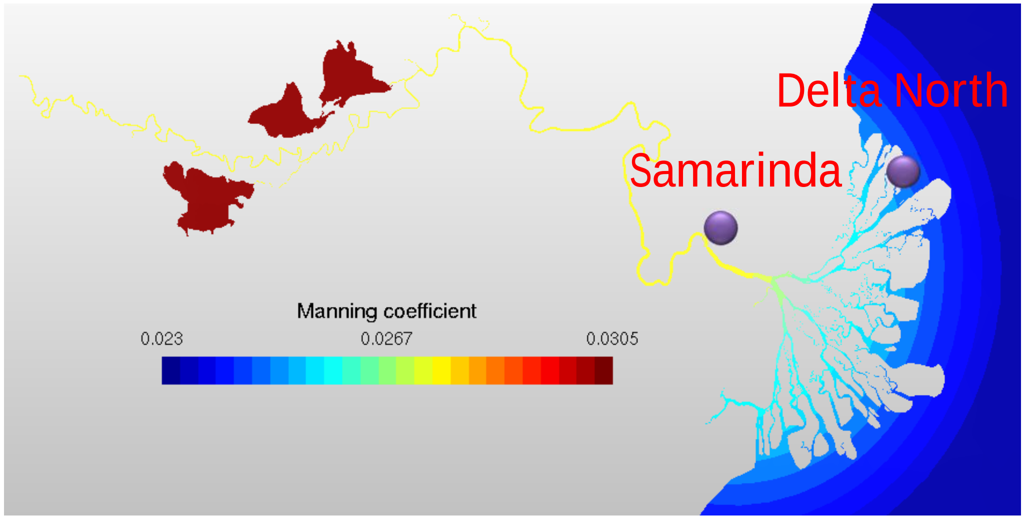
$$\frac{\partial A}{\partial t} + \frac{\partial (Au)}{\partial x} = 0$$

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

Parameterizations

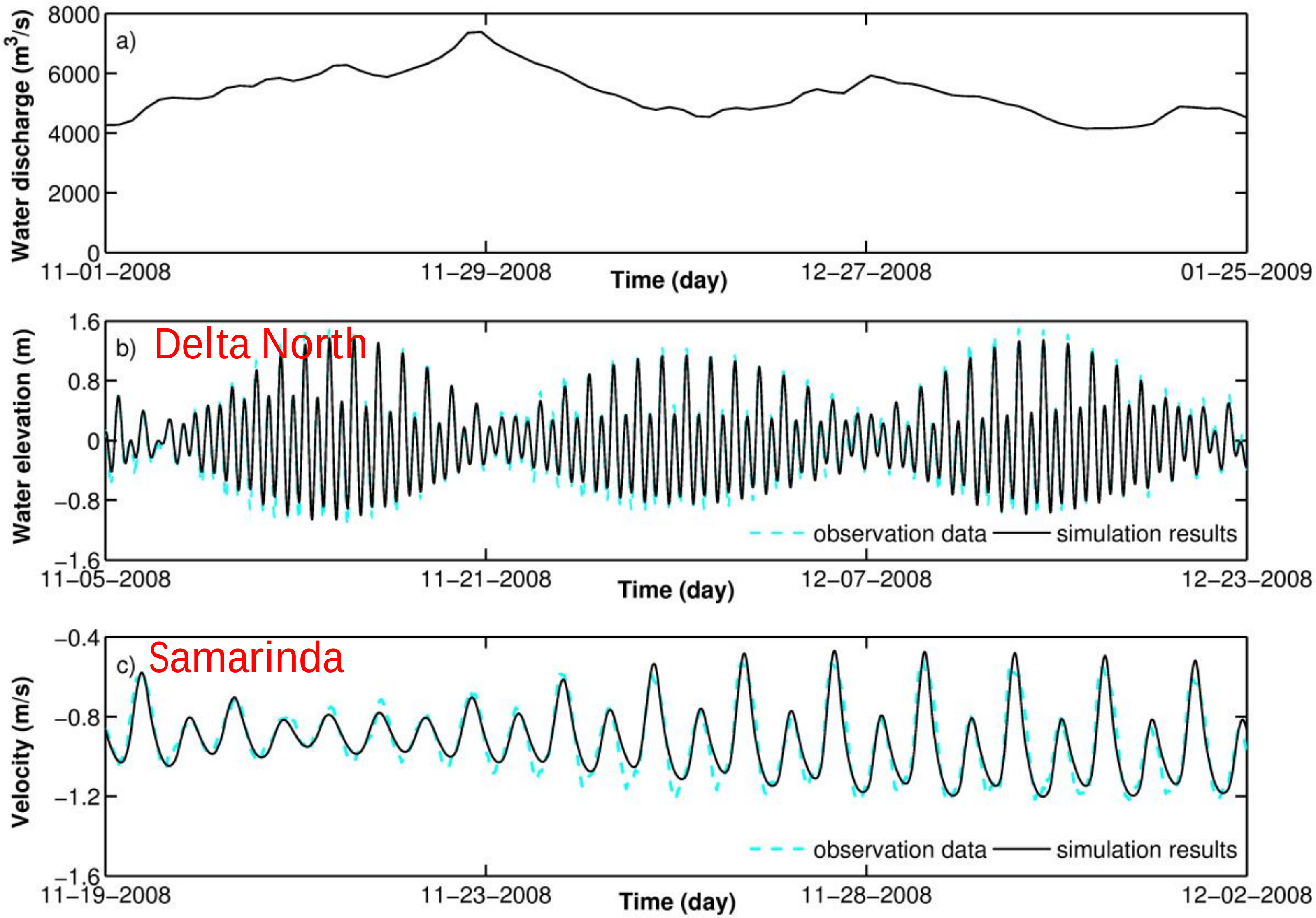
$$\nu_{2D} = (0.1\Delta)^2 \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2}$$

$$\nu_{1D} = 0.16 u_* H, \quad and \quad \tau_b = \rho \frac{g n^2 \|\mathrm{u}\|}{H^{1/3}} \mathrm{u}$$



A coupled 2D/1D model | Hydrodynamic module

❖ *Validation results*



- *2D depth integrated equations*

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

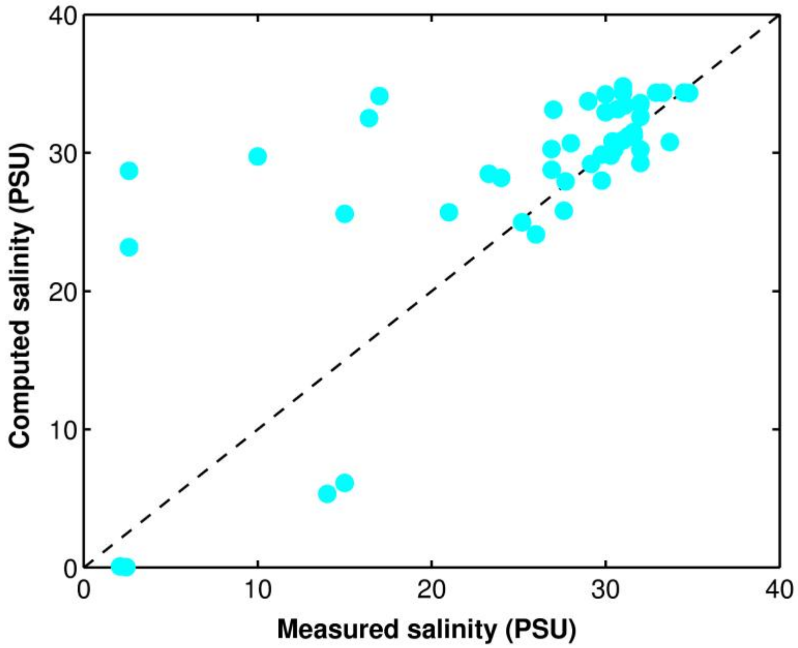
- *1D section integrated equations*

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

- *Parameterizations*

$$\kappa=c_k\Delta^{1.15}, with \;\; c_k=0.018$$

E and *D* are erosion and deposition rate, respectively.



Suspended sediment module	Parameters

- *Option 1:* Considering fine-grained sediments (Partheniades , 1965)

$$E = \max\left[M\left(\frac{\tau_b}{\tau_c} - 1\right), 0\right]$$

$$D = w_s C_{ss}$$

$$w_s = w_{s0} C_{ss}^{\beta}$$

→ M, w_{s0}, β

τ_c=0.1 N/m^2 (Mandang and Yanagi, 2009; Kirk Ziegler and Nisbet, 1994; 1995)

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Sim.	Parameters			E_t				
	w_{s0}	β	M	Samarinda	DAN	DAS	FBN	FBS
a.01	0.04	1	5					
a.02			12					
a.03			21					
a.04			25					
a.05		1.25	5					
a.06			12					
a.07			21					
...			25					

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

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

❖ *Option 2: Considering sediment particle diameter*

$$D = w_s C_{ss}$$

$$E = w_s \left(\alpha C_*\right)$$

$$w_s = \frac{10^{-6}}{d_s}\left[\sqrt{\frac{1}{4}\left(\frac{A1}{B}\right)^{2/A2} + \left(\frac{4}{3}\frac{D_*^3}{B}\right)^{1/A2}} - \frac{1}{2}\left(\frac{A1}{B}\right)^{1/A2}\right]^{A2}$$

$$(or \quad w_s = w_{s0} C_{ss}^{\beta})$$

Equilibrium near-bed sediment concentration	Reference
$C_* = \dfrac{0.331\left(\tau_s^* - 0.045\right)^{1.75}}{1 + \dfrac{0.331}{0.46}\left(\tau_s^* - 0.045\right)^{1.75}}$	*Zyserman and Fredsøe* [1994]
$C_* = 0.65 \dfrac{0.0024\left(\dfrac{\tau_s^*}{\tau_c^*} - 1\right)}{1 + 0.0024\left(\dfrac{\tau_s^*}{\tau_c^*} - 1\right)}$	*Smith and McLean* [1977]
$C_* = 0.015 \dfrac{d_s}{a} \dfrac{1}{D_*^{0.3}} \left(\dfrac{\tau_s^*}{\tau_c^*} - 1\right)^{1.5}$	*van Rijn* [1984]

α *and / or* τ_c^*

Ref.	Sim.	d_s (mm)	w_s (mm/s)	Parameters		E_f				
				τ_c^*	α	Samarinda	DAN	DAS	FBN	FBS
Zyserman and Fredsøe (1994)	b.01	65	w_{s0}=0.08, β=1.25							
	b.02	125								
	b.03	220								
	b.04	65	3							
	b.05	125	9.7							
	...	220	23.2							

Camenen (2007)

Calibration and validation results

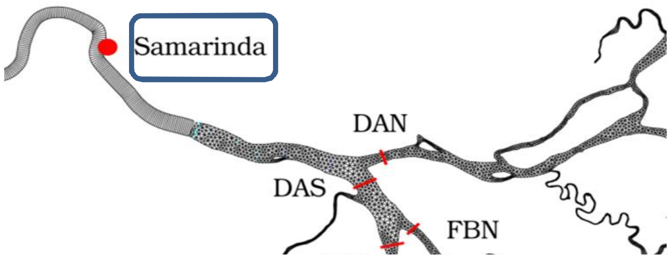
- *Calibration*
  - Period: November 2008 to January 2009
  - Considering different sediment
    - Fine-grained sediments
    - Constant sediment particle diameter
    - Variable sediment particle diameter

- *Validation*
  - Period: from February to October 2009

Calibration results	*Considering fine-grained sediments*

❖ Optimal parameters set

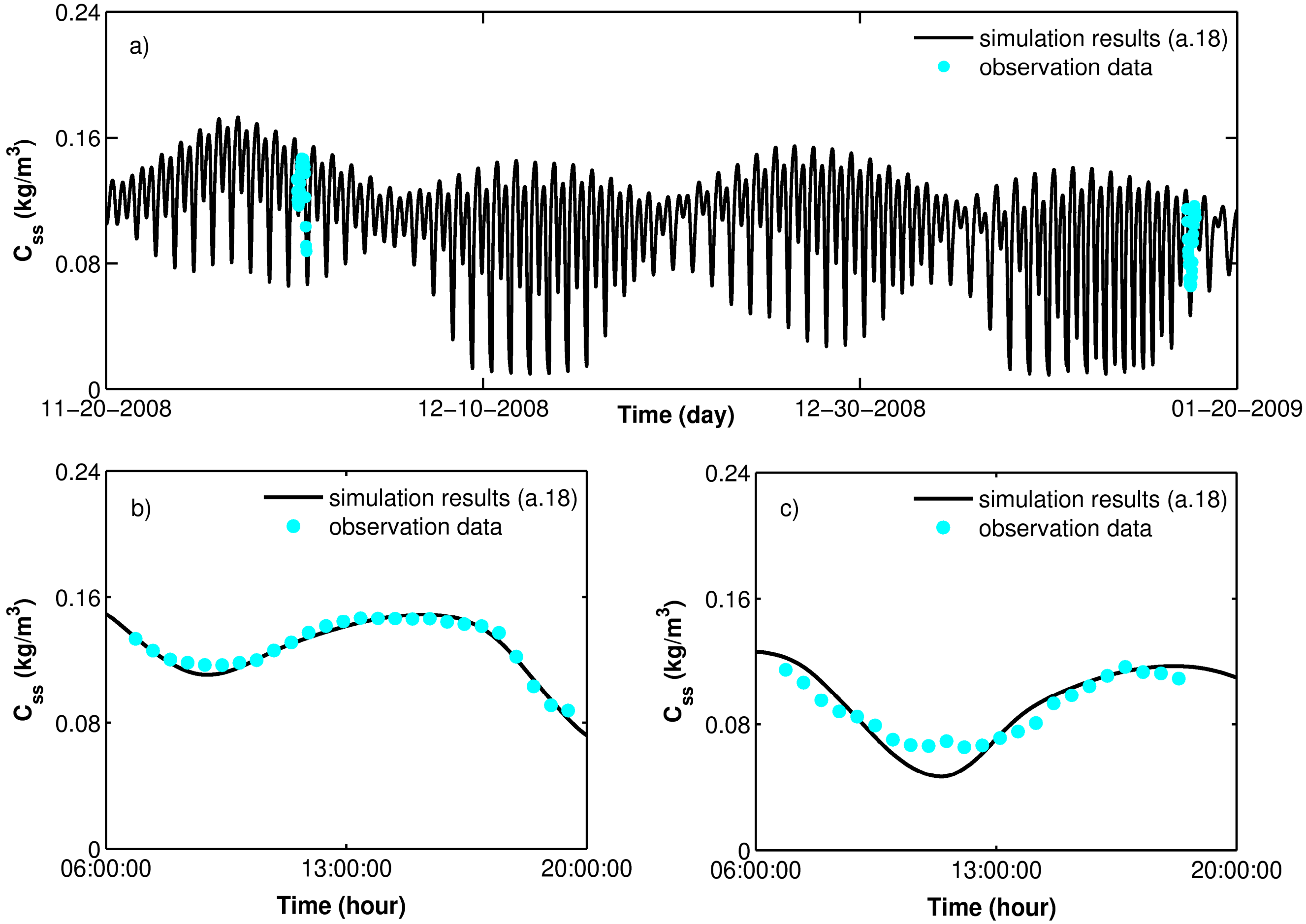
w_{s0} = 0.08, β= 1.25, M = 0.00012 kg/m^2s



❖ Errors

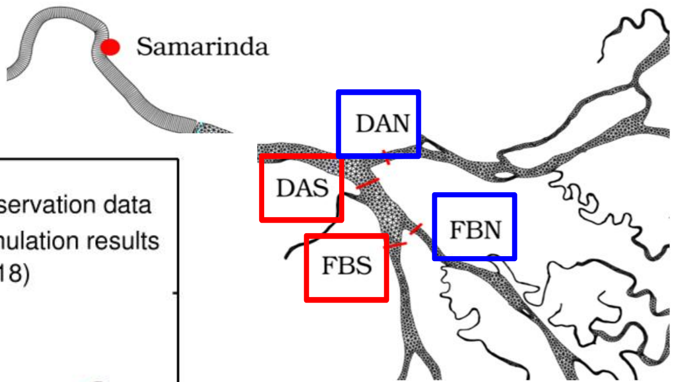
E_t=0.06

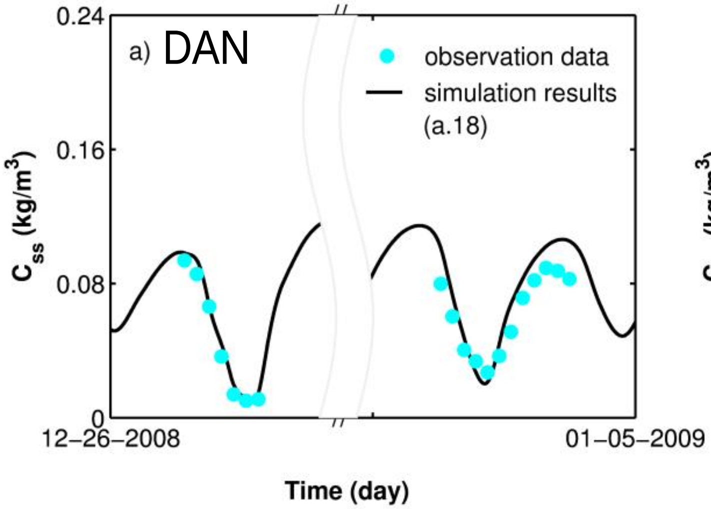
r=0.97

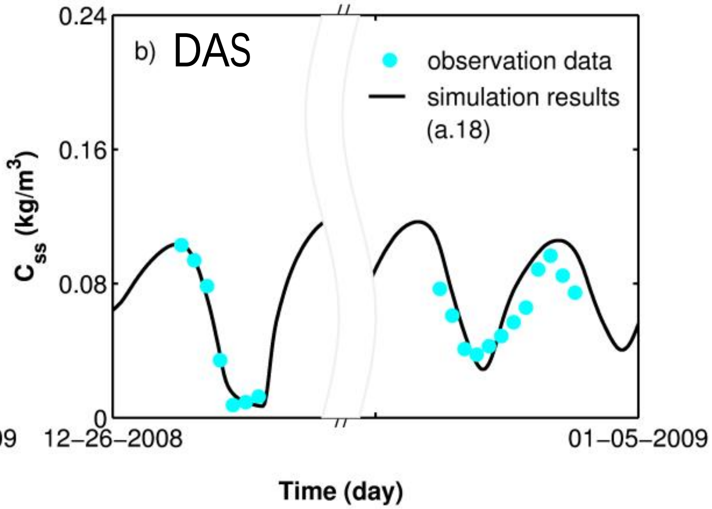


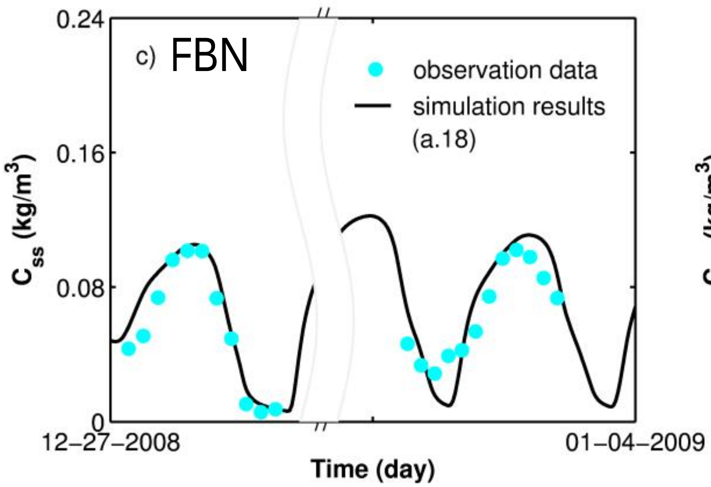
Calibration results	*Considering fine-grained sediments*

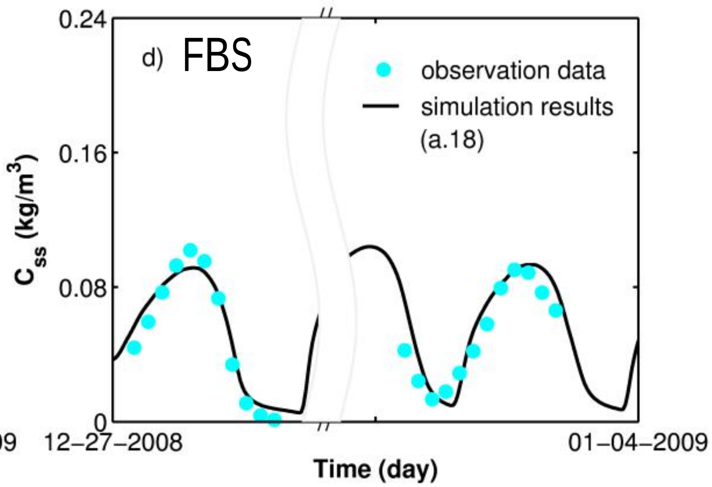
$E_t \leq 0.20, \quad r = 0.96 - 0.98$







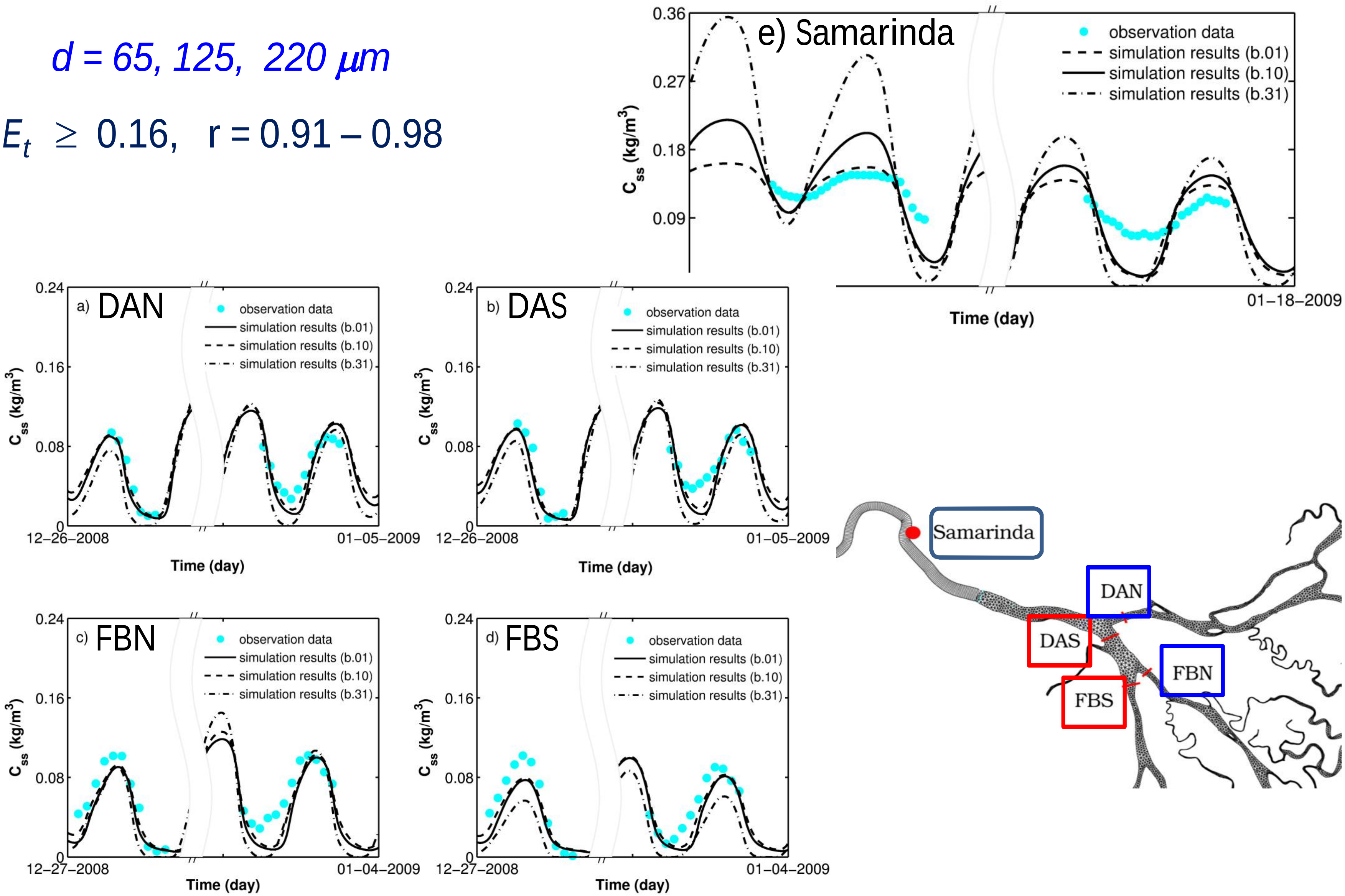




Calibration results | *Considering constant sediment particle diameter*

d = 65, 125, 220 μm

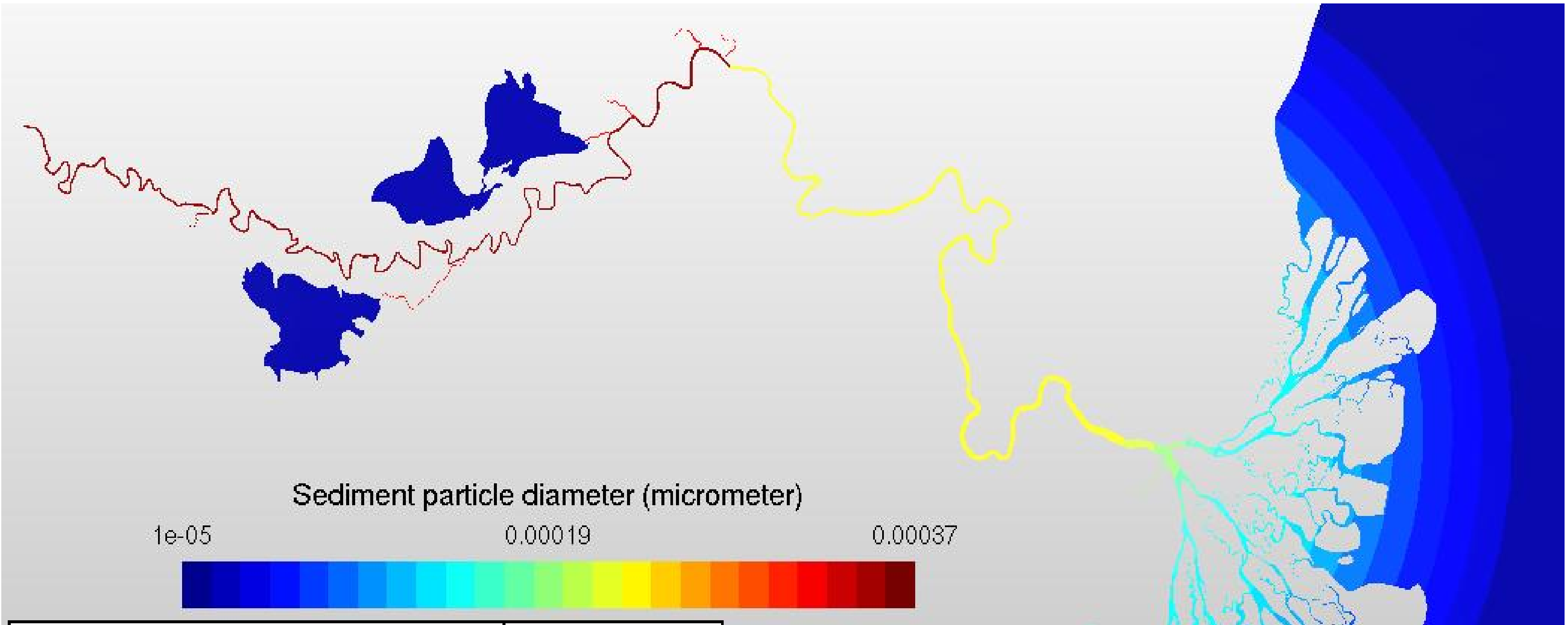
$E_t \geq 0.16$, r = 0.91 – 0.98



b.01= Zyserman and Fredsøe (1994); b.10= Smith and McLean (1977); b.31= van Rijn (1984)

Calibration results	*Considering variable sediment particle diameter*

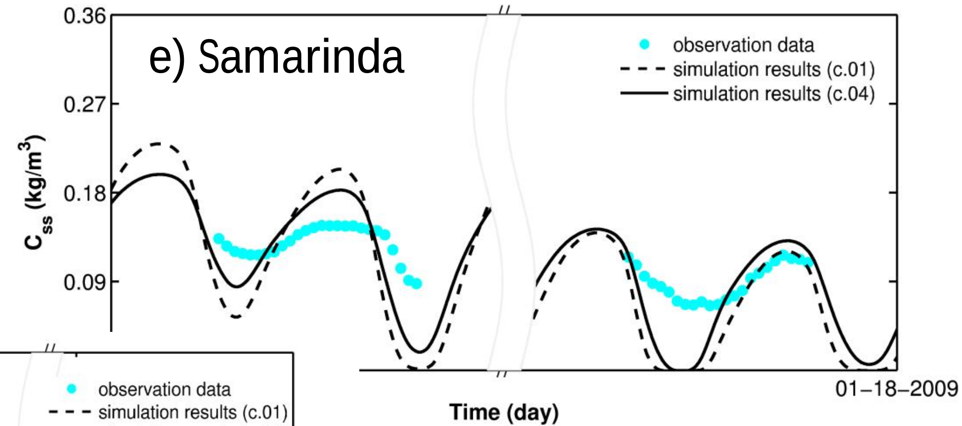
d_{50}=10-370 μm from bed sediment samples (Allen et al., 1976; Sassi et al., 2013)

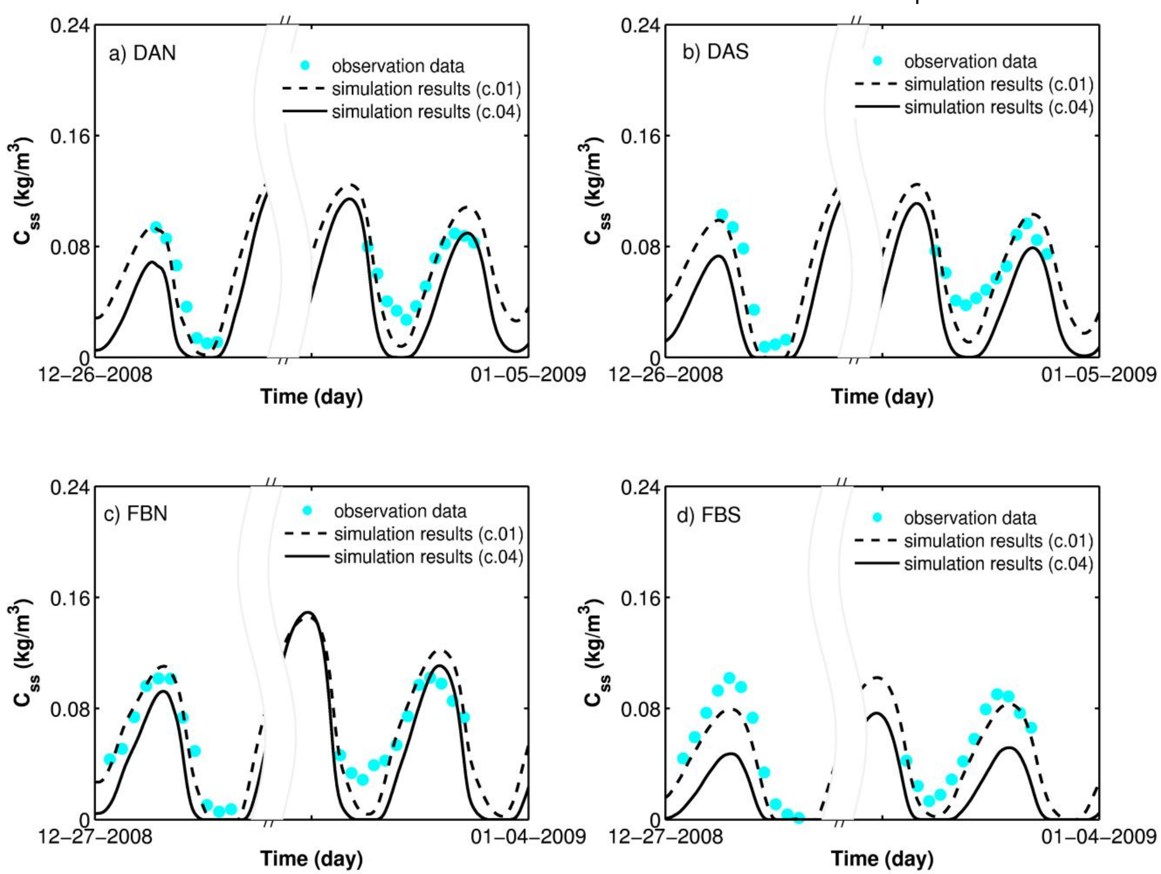


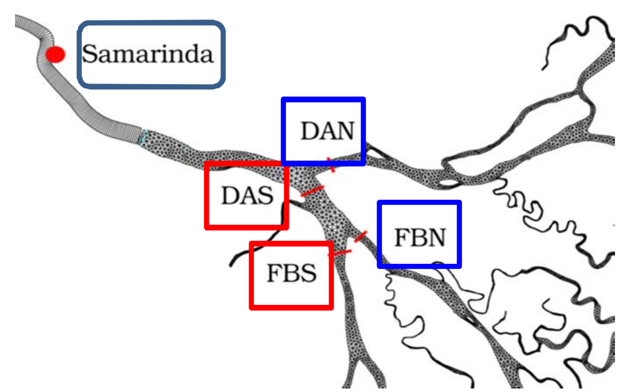
Mahakam River	370-220
Kedang Pahu	370
River Belayan, Kedang Kepala, Kedang Rantau	325
Lakes + Makassar Strait	220-10

Calibration results	*Considering variable sediment particle diameter*

$E_t \geq 0.21$, r = 0.85 – 0.98







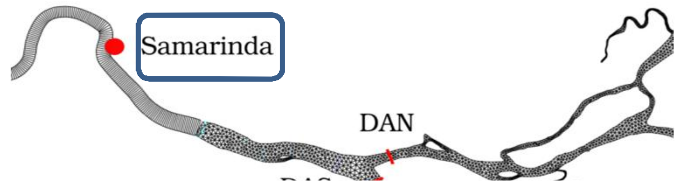
c.01= Zyserman and Fredsøe (1994); c.04= Smith and McLean (1977)

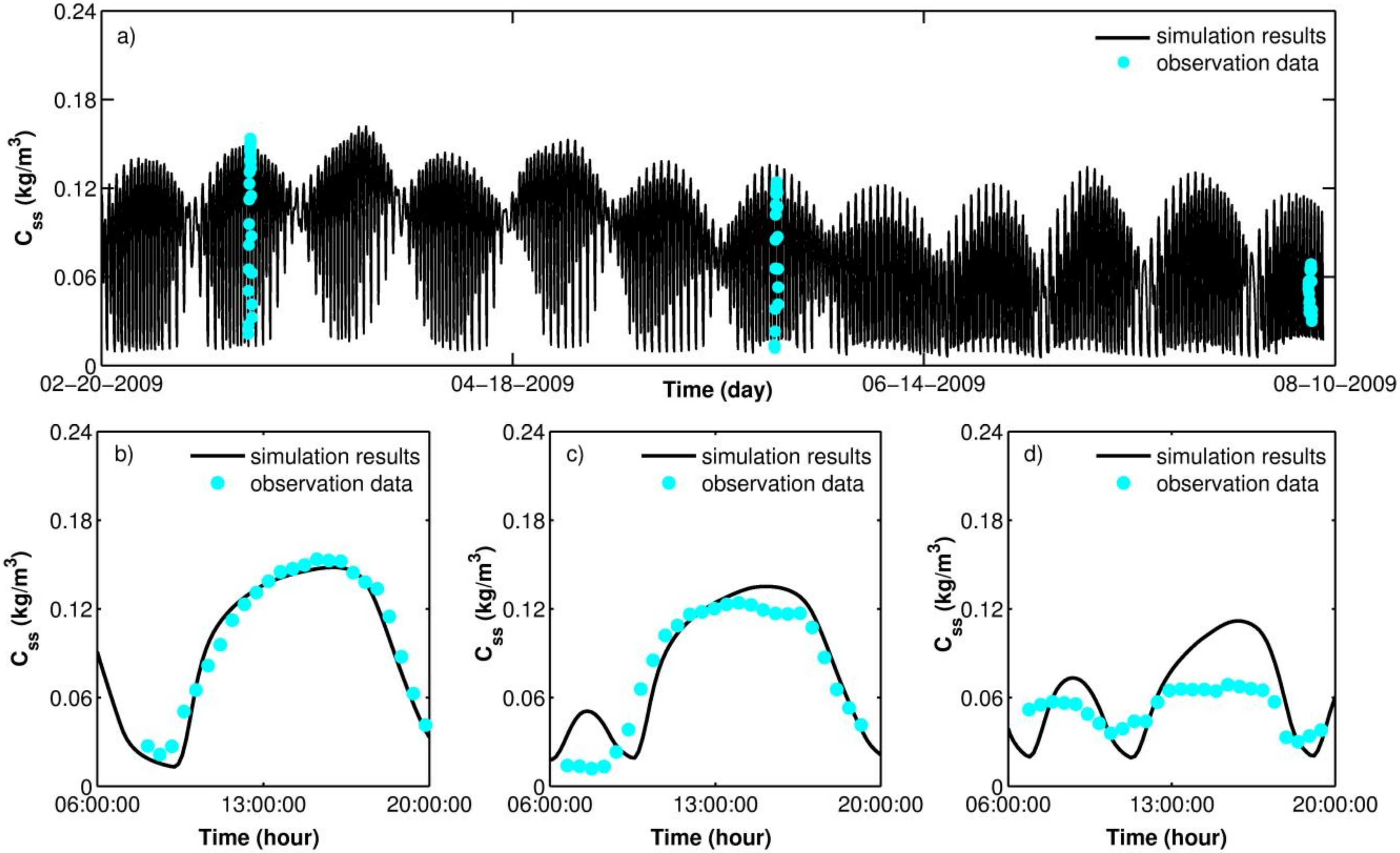
Calibration results | *Optimal set value for the modeling parameters*

Reference	Sim.	d_s (μm)	w_s (mm/s)	Parameters: M (x10^{-5})	Parameters: τ_c^*	Parameters: α	E_t: Samarinda	E_t: DAN	E_t: DAS	E_t: FBN	E_t: FBS
Partheniades [1965]	a.18		**w_{s0}=0.08 β=1.25**	**12**			**0.0608**	**0.1858**	**0.2002**	**0.2034**	**0.1750**
Zyserman and Fredsøe [1994]	b.01	65	w_{s0}=0.08 β=1.25			1.25	0.1930	0.2163	0.2583	0.2874	0.2771
	c.01	10-370	w_{s0}=0.08 β=1.25			4.0	0.3710	0.3717	0.4081	0.4908	0.5006
Smith and McLean [1977]	b.10	65	w_{s0}=0.08 β=1.25		0.03	5.0	0.2353	0.1682	0.2094	0.2181	0.2155
	c.04	10-370	0.05-44.3		0.01	5.0	0.2326	0.2291	0.2507	0.2122	0.2074
van Rijn [1984]	b.31	125	9.7		0.03	1.5	0.5533	0.3783	0.3949	0.3307	0.4911

Validation results

E_t = 0.21, r = 0.92



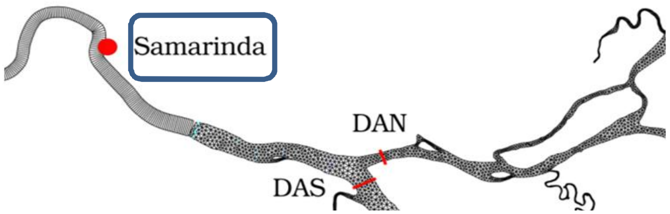


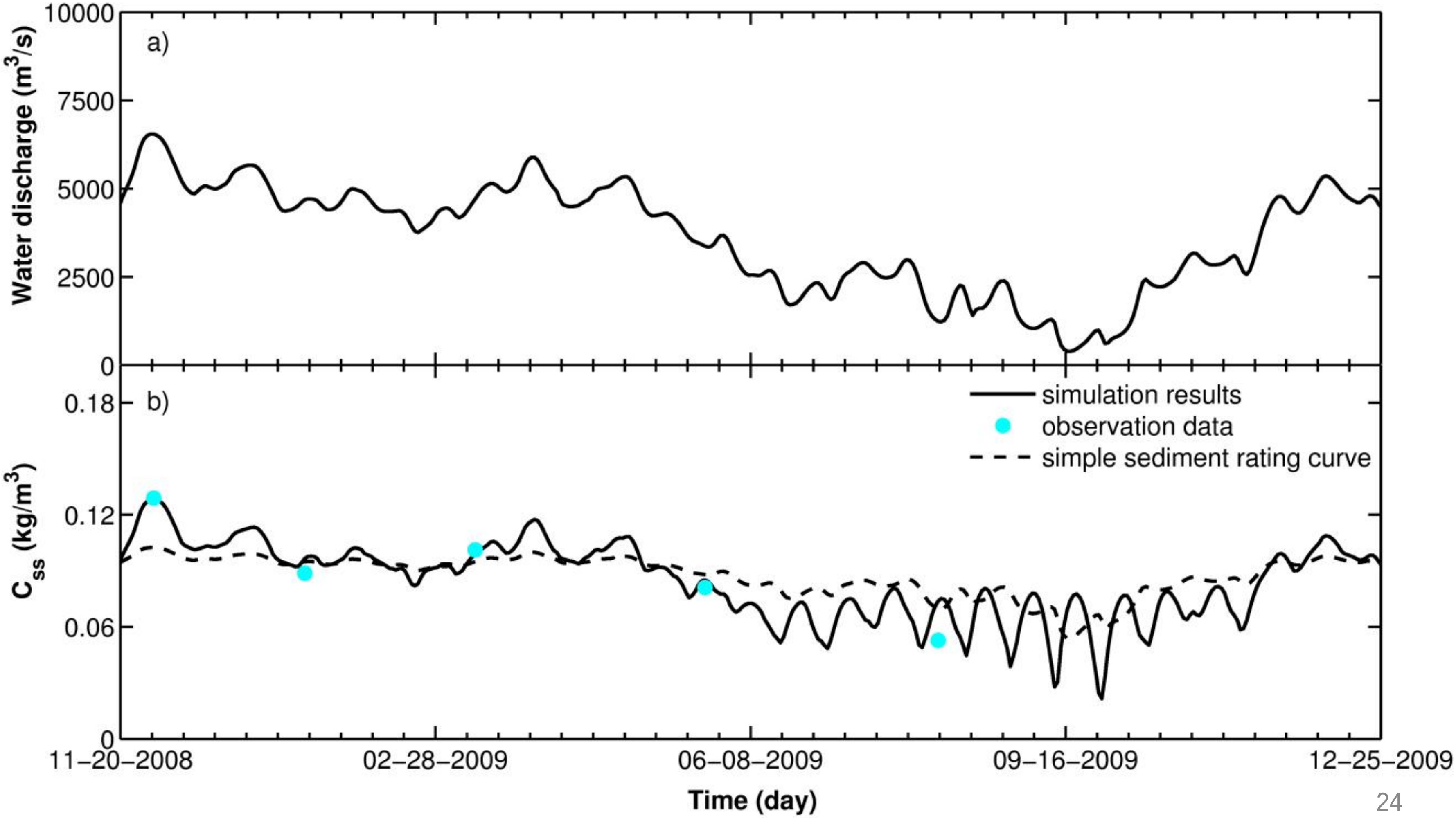
Temporal variation and spatial distribution of SSC

Temporal variation of SSC

- Simple sediment rating curve

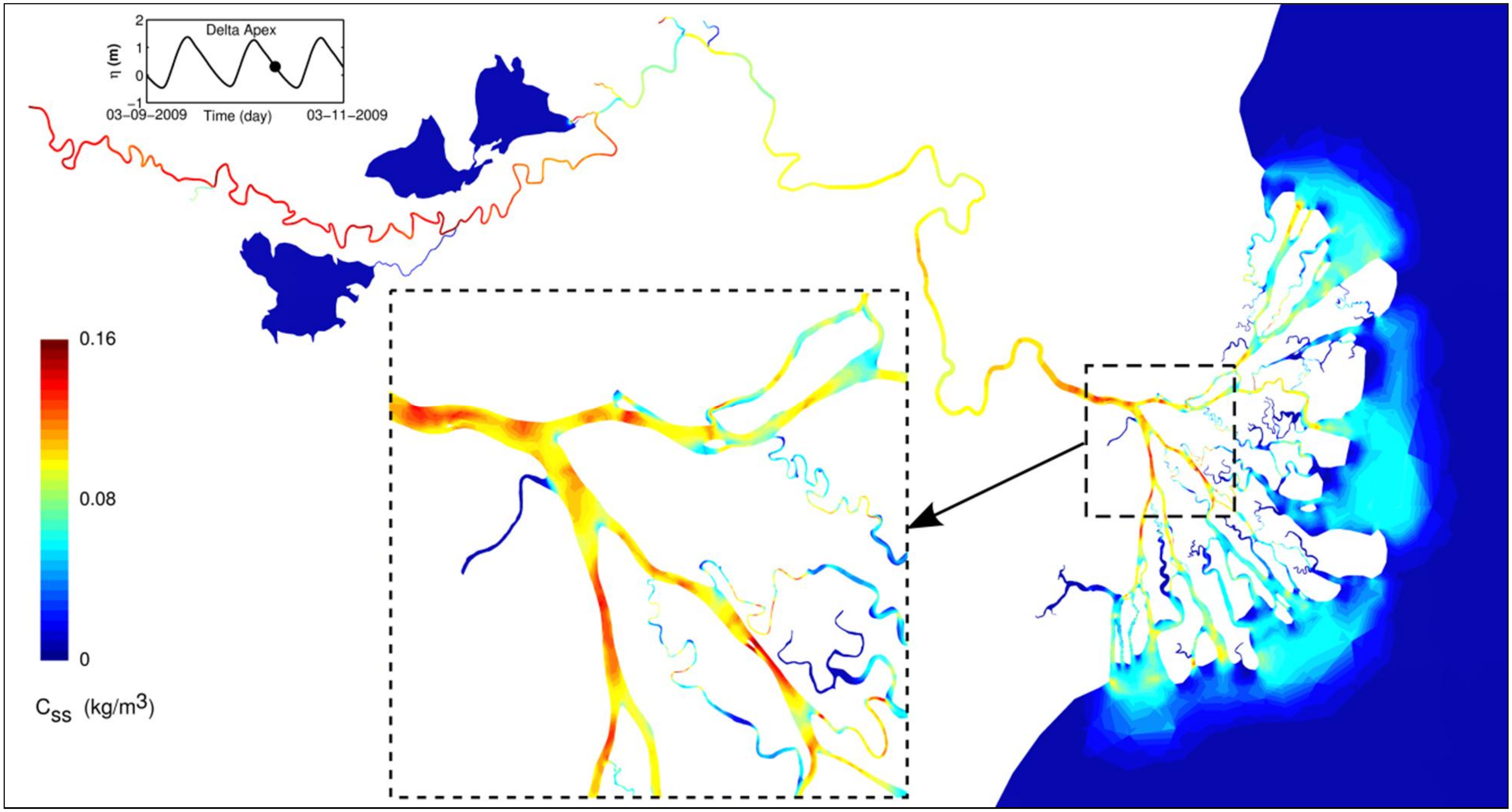
$$C_{ss} = pQ^{q}, with \quad p = 0.0136 \text{ and } q = 0.23$$





Spatial distribution of SSC

At the ebb tidal phase of neap tide, i.e. at 13:50:00 on 10 March 2009



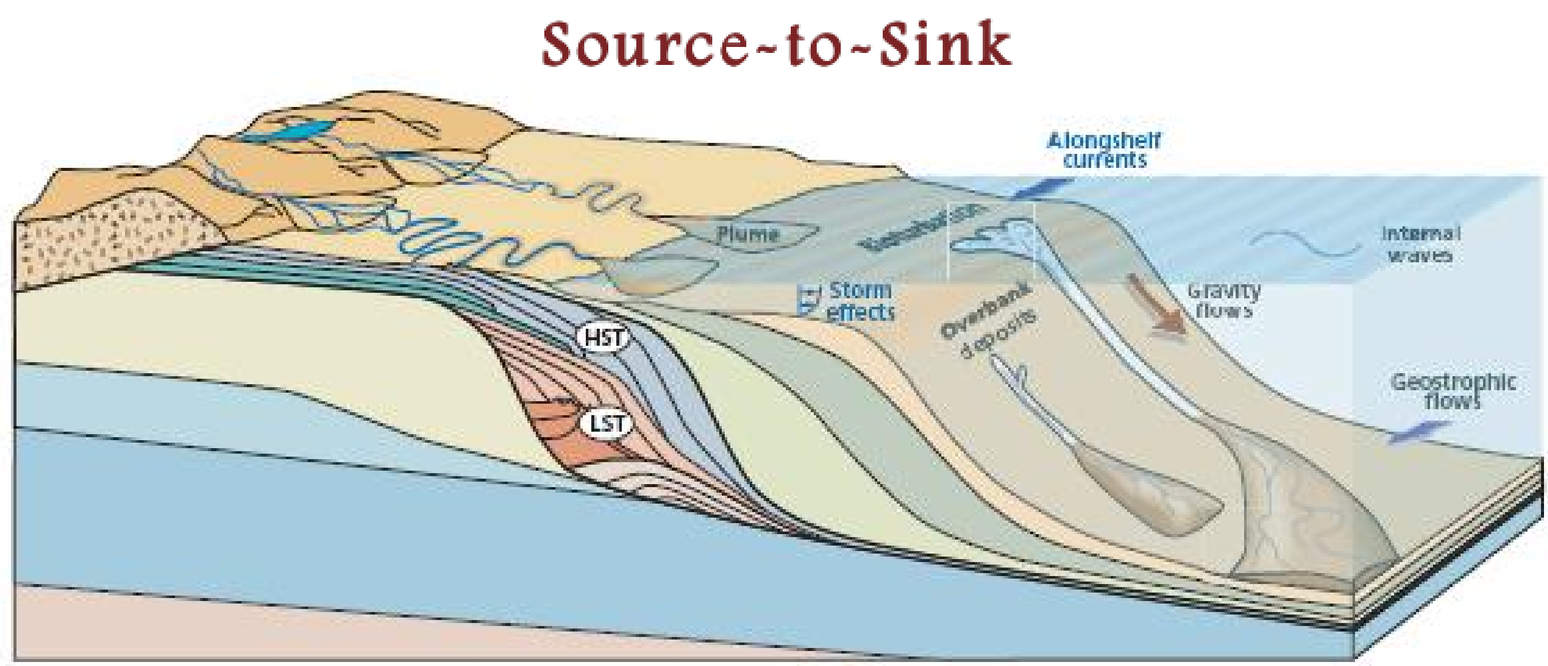
C_{SS} = (0.006 - 0.182) kg/m^3 (Budhiman et al., 2012; Storms et al., 2005)

Conclusions

- Various parameterizations of erosion rate are performed.
- The formulation proposed by Partheniades (1965) to parameterize the erosion rate performs the best among four considered formulations.
- The Partheniades' formulation is not limited only to muddy environments. It can be used for mixture environments of mud and sand.
- The coupled 2D/1D model of the finite-element SLIM successfully reproduces the observed SSC at measurement stations in the system.
- Simulation results over a year in 2008-2009 shows that the model is able to accurately simulate the temporal variation of SSC in response to the variation of the river flow. Comparisons of model results with field observations reported in previous studies for the Mahakam Delta are all favorable.

Conclusions

- The model is not successful to reproduce the observed SSC at measurement stations when the near-bed concentration under equilibrium condition is used to estimate the erosion rate.



THANK YOU

FOR YOUR ATTENTION !

SLIM

http://www.climate.be/slim