Research Topic

Estuarine Dynamics Modeling

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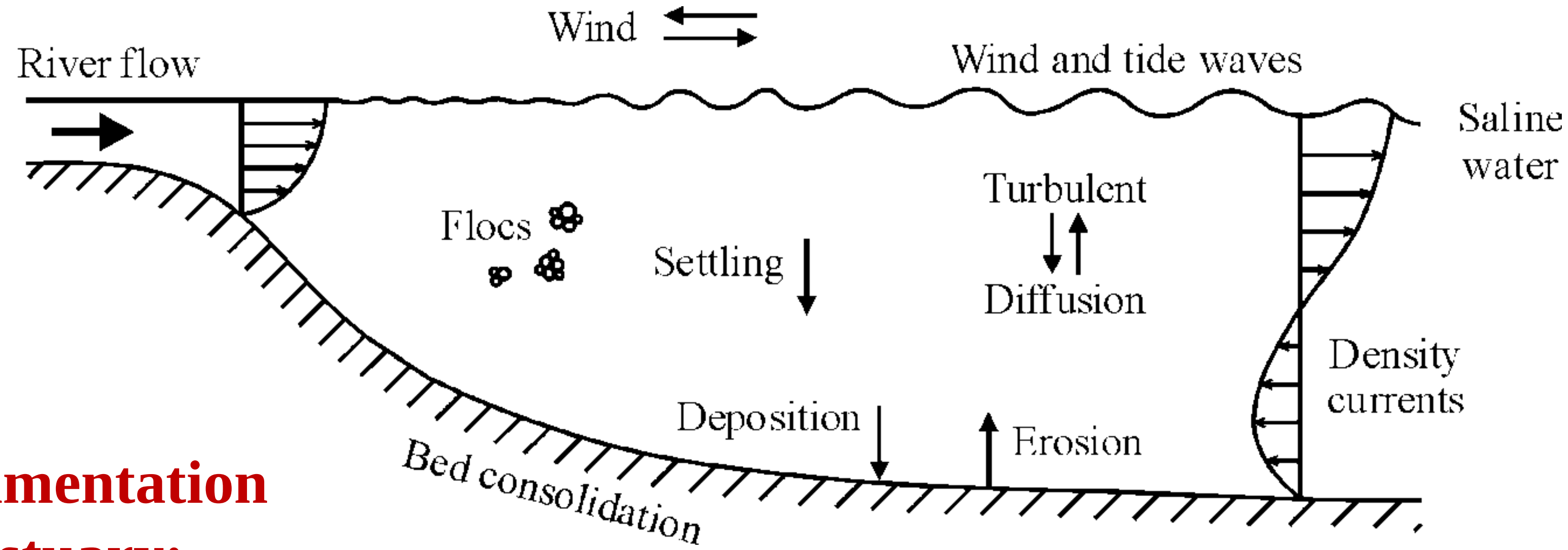
Mixed Cohesive/Non-cohesive Sediments



Sedimentation in Estuary:

- **Flocculation**
- **Deposition**
- **Erosion**
- **Transport**
- **Consolidation**

*: It has been recognized that when the fraction of fine-grained sediments is larger than about 10%, a mixture consisting of cohesive and non-cohesive sediments may exhibit cohesive properties.

Mixed Cohesive/Non-cohesive Sediments

1-D fractional sediment transport equation

$$\frac{\partial}{\partial t}\left(\frac{Q_{tk}}{\beta_{tk}U}\right)+\frac{\partial Q_{tk}}{\partial x}=E_{bk}-D_{bk}+q_{tlk}$$ (k=1, 2, …, N)

Q_{tk}	total-load transport rate of size class k
E_{bk}	erosion rate
D_{bk}	deposition rate
β_{tk}	correction factor
U	flow velocity
q_{tlk}	side inflow of sediment per unit channel length

- **Deposition Rate:**

$$D_{bk}=B\alpha_k\omega_{sf,k}C_k$$

B	channel width
a_k	deposition probability or adaptation coef.
$w_{sf,k}$	settling velocity
C_k	section-averaged sediment concentration

Coefficient α_k

- For non-cohesive sediment, α_k is the adaptation coefficient, calculated by

$$\frac{1}{\alpha_k} = \frac{a}{h} + \left(1 - \frac{a}{h}\right) \exp\left[-1.5 \left(\frac{a}{h}\right)^{-1/6} \frac{\omega_{sf,k}}{u_*}\right]$$

(Armanini and di Silvio, 1988)

- For cohesive sediment, α_k is the deposition probability coefficient, which is related to the bed shear stress as

$$\alpha = \begin{cases} 1 & \tau_b < \tau_{bd,\min} \\ 1 - \left(\tau_b - \tau_{bd,\min}\right) / \left(\tau_{bd,\max} - \tau_{bd,\min}\right) & \tau_{bd,\min} \le \tau_b \le \tau_{bd,\max} \\ 0 & \tau_b > \tau_{bd,\max} \end{cases}$$

Settling Velocity $w_{sf,k}$

- For cohesive sediment, $\omega_{sf,k}$ is calculated by Wu and Wang's (2004) formula, through which the effect of flocculation is considered

$$\frac{\omega_{sf}}{\omega_{sd}} = K_d K_s K_{sa} K_t$$

ω_{sf}	median settling velocity of flocs
ω_{d50}	median settling velocity of dispersed particles

$$K_d = \left(d_r / d_{50}\right)^{n_d}$$

d_{50}	medium diameter
d_r	reference diameter, about 0.0215 mm
n_d	coefficient, approximated to 1.8

$$K_s = \begin{cases} 1 + k_1 C^n & 0 < C \le C_p \\ k\left(1 - k_2 C\right)^r & C > C_p \end{cases}$$

$$K_{sa} = 1.0$$

C	concentration, in kg/m^3
C_p	sediment concentration at the maximum settling
n, r, k_1, k_2	coefficient, ranging from 1 to 2
k	coefficient, equal to $\left(1 + k_1 C_p^n\right) / \left(1 - k_2 C_p\right)^r$

$$K_t = \begin{cases} 1 + k_{t1}\left(\tau_b / \tau_p\right)^{n_{t1}} & 0 < \tau \le \tau_p \\ \left(1 + k_{t1}\right)\left(\tau_b / \tau_p\right)^{-n_{t2}} & \tau > \tau_p \end{cases}$$

k_{t1}, n_{t1}, n_{t2}	empirical coefficient
τ_p	threshold bed shear stress at maximum K_t

Erosion Rate

$$E_{bk} = p_{bk} E_{bk}^{*}$$

p_{bk}	fraction of the k^{th} size class in the surface layer of bed material
E_{bk}^{*}	potential erosion rate of the k^{th} size class

- For non-cohesive sediment

$$E_{bk}^{*} = B \frac{\alpha_k \omega_{sf,k}}{AU_{tk}} Q_{tk}^{*}$$

- For cohesive sediment

$$E_{bk}^{*} = BM \left(\frac{\tau_b}{\tau_{ce}} - 1 \right)^{n}$$

τ_{ce}	critical bed shear stress for surface erosion
M	erodibility coef., related to bed material properties
n	coefficient, equal to 2.5

Critical Bed Shear Stress

- The incipient motion of non-cohesive sediment is affected by the cohesion if non-cohesive and cohesive sediments coexist in the bed material.

$$\tau_{ck} = \begin{cases} \tau_{ck,n} & p_c < p_{c\min} \\ \tau_{ck,n} + \left(\tau_{ce} - \tau_{ck,n}\right)\left(p_c - p_{c\min}\right) / \left(p_{c\max} - p_{c\min}\right) & p_{c\min} \le p_c \le p_{c\max} \\ \tau_{ce} & p_c > p_{c\max} \end{cases}$$

$\tau_{ck,n}$	critical bed shear stress of the size class in the situation where only non-cohesive sediment exists
τ_{ce}	critical bed shear stress for cohesive sediment
p_c	fraction of cohesive sediment
p_{cmin}	minimum fraction of cohesive sediment, below which the critical bed shear stress for non-cohesive sediment is the same as that when no cohesive sediment exists
p_{cmax}	maximum fraction of cohesive sediment, above which the critical bed shear stress of non-cohesive sediment is equal to that of cohesive sediment

$$\tau_{ce} = \tau_{ce0} + k_\tau \left(\rho_d - \rho_{d0}\right)^{n_\tau}$$

(Nicholson and O’Connor, 1986)

τ_{ce0}	initial critical bed shear stress
ρ_{d0}	initial critical dry bed density
ρ_d	dry bed density
k_τ, n_τ	empirical coefficients

Bed Deformation

- The fractional bed mass deformation rate is determined by

$$\frac{\partial M_{bk}}{\partial t} = \rho_s \left(D_{bk} - E_{bk} \right)$$

- Then the total rate of change in bed mass is

$$\frac{\partial M_b}{\partial t} = \sum_{k=1}^{N} \frac{\partial M_{bk}}{\partial t}$$

- which can be converted to the change in bed cross-sectional area:

$$\frac{\partial A_b}{\partial t} = \frac{1}{\rho_s \left(1 - p'_m\right)} \frac{\partial M_b}{\partial t}$$

p'_m bed material porosity

Bed Material Sorting

$$\frac{\partial (M_m p_{bk})}{\partial t} = \frac{\partial M_{bk}}{\partial t} + p^*_{bk} \left(\frac{\partial M_m}{\partial t} - \frac{\partial M_b}{\partial t} \right)$$

Consolidation

- Dry bed density in the first year (Hayter, 1983):

$$\frac{\rho_d}{\rho_{d1}} = 1 - a_\rho e^{-pt}$$

ρ_d	dry bed density
ρ_{d1}	at one-year consolidation time
a_ρ,p	empirical coefficients
t	consolidation time, in hour

- Dry bed density after 1 year (Lane and Koelzer,1953):

$$\rho_d = \rho_{d1} + \beta \log t$$

β	empirical coefficient
t	consolidation time, in year

- Bed Change due to Consolidation:

$$\frac{\partial}{\partial t}\left(\delta_j \rho_{dj}\right) = 0$$

δ_j	thickness of the j^{th} layer of bed material
ρ_{dj}	dry bed density of the j^{th} layer of bed material

$$\Delta z_{b,c} = \sum_{j=1}^{J}\left(\delta_j^{n+1} - \delta_j^n\right) = \sum_{j=1}^{J}\delta_j^n\left(\frac{\rho_{dj}^n}{\rho_{dj}^{n+1}} - 1\right)$$

Lower Fox River

- Mainstream:

  from a dam at De Pere to Green Bay (11 km)

- Tributary:

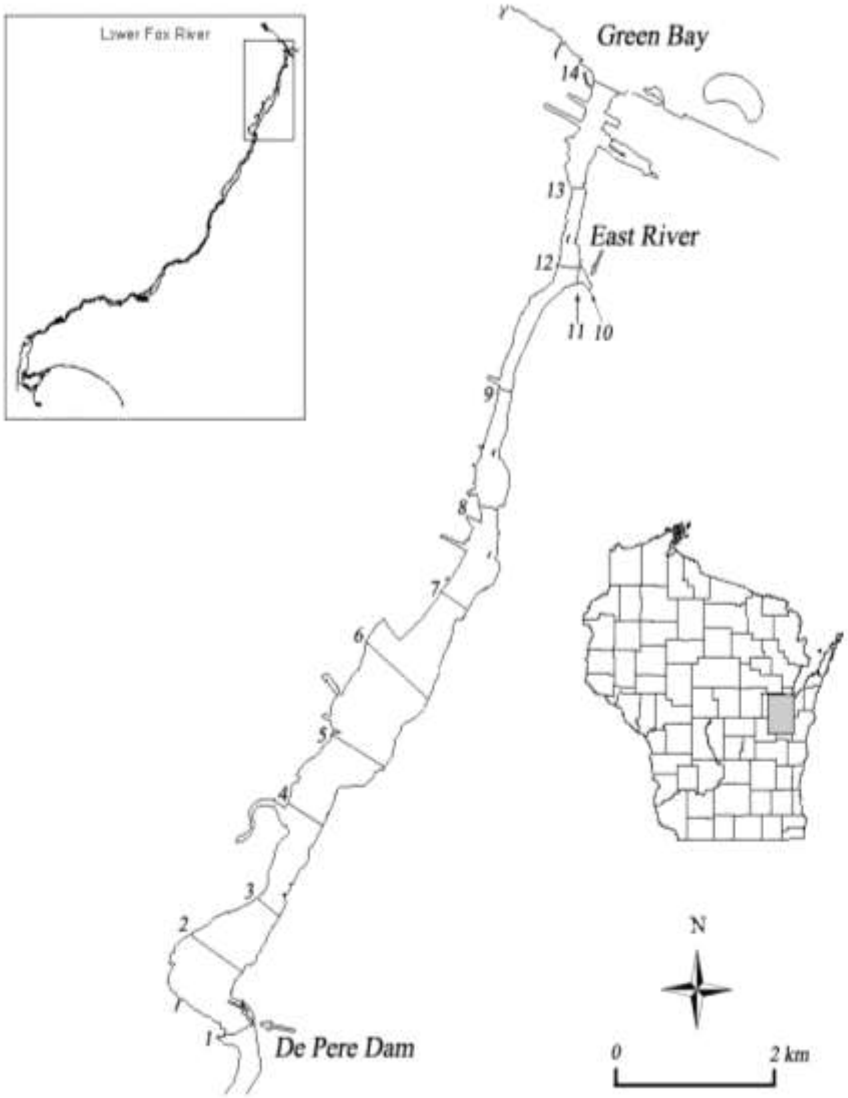
  East River (joins the Fox River approximately 2 km upstream from the river mouth)

- Size Classes:

  Fine ~ 0.00316 mm

  Medium ~ 0.0316 mm

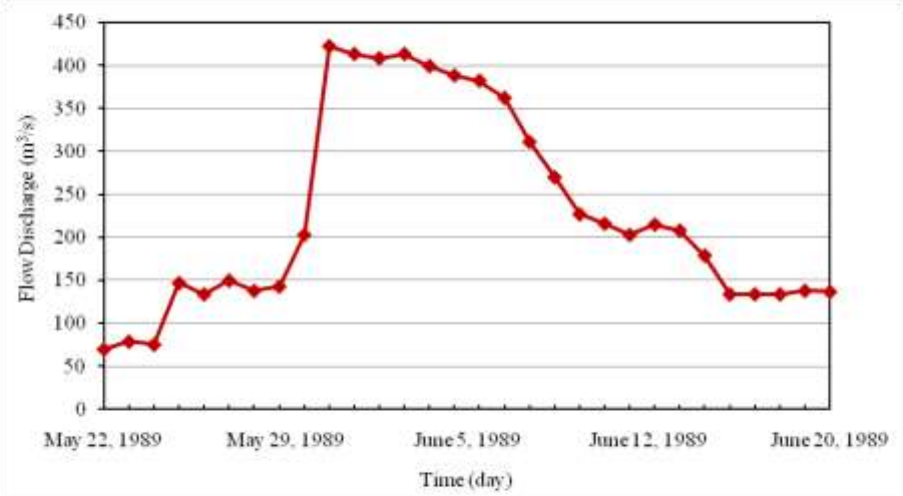
  Coarse ~ 0.447 mm



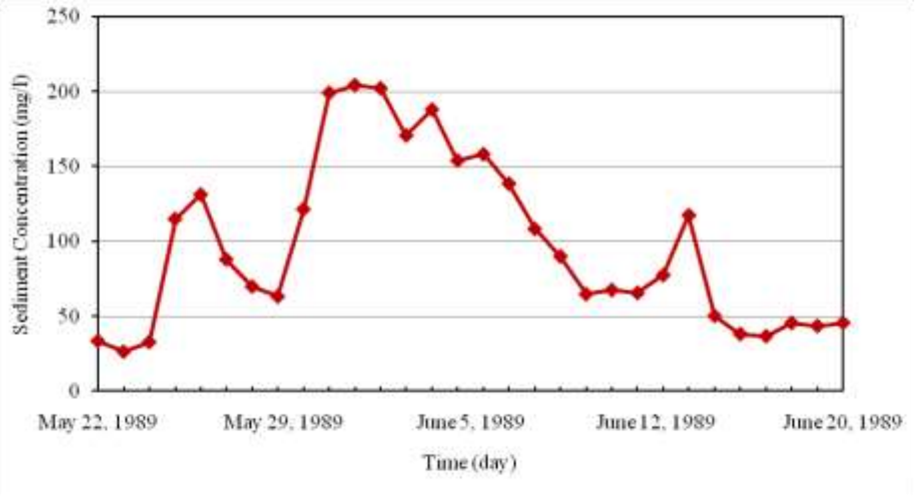
1-D Simulation in Lower Fox River

Clarkson UNIVERSITY defy convention

Flow Discharge at the Dam

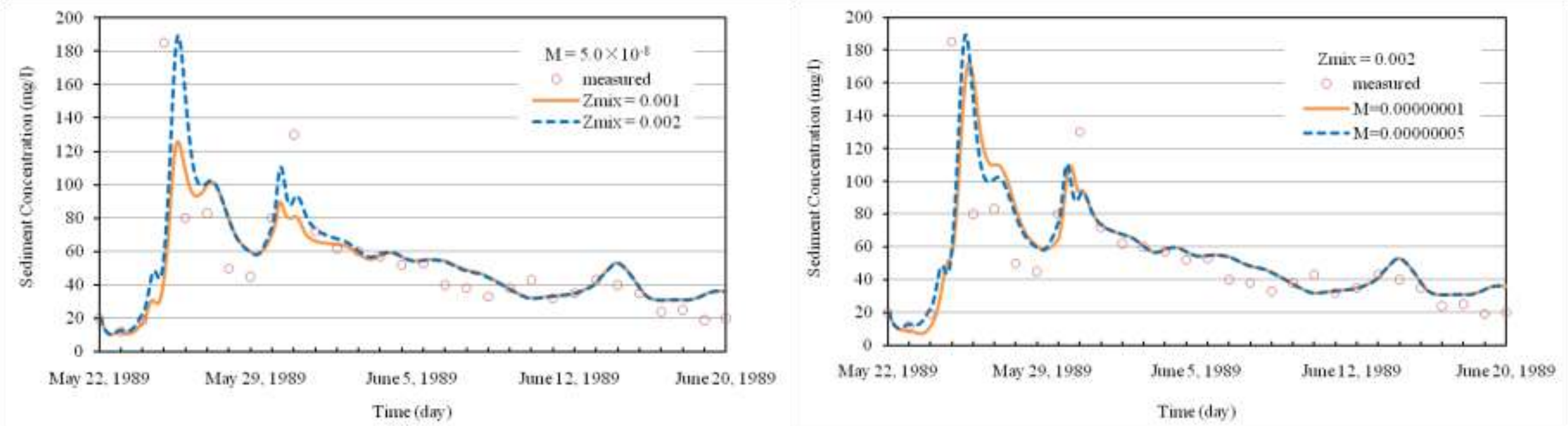


Sediment Concentration at the Dam



Sediment Concentration at the River Mouth

(Lin and Wu, 2013)

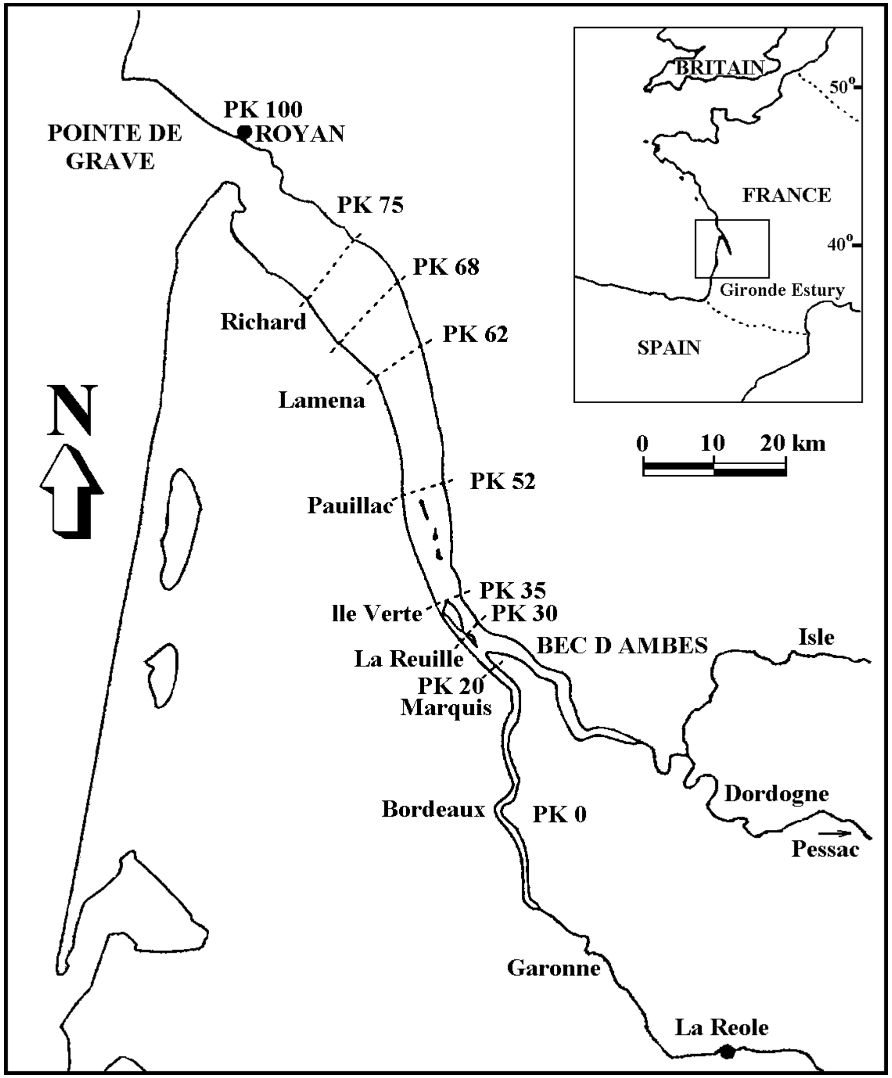


Gironde Estuary, France

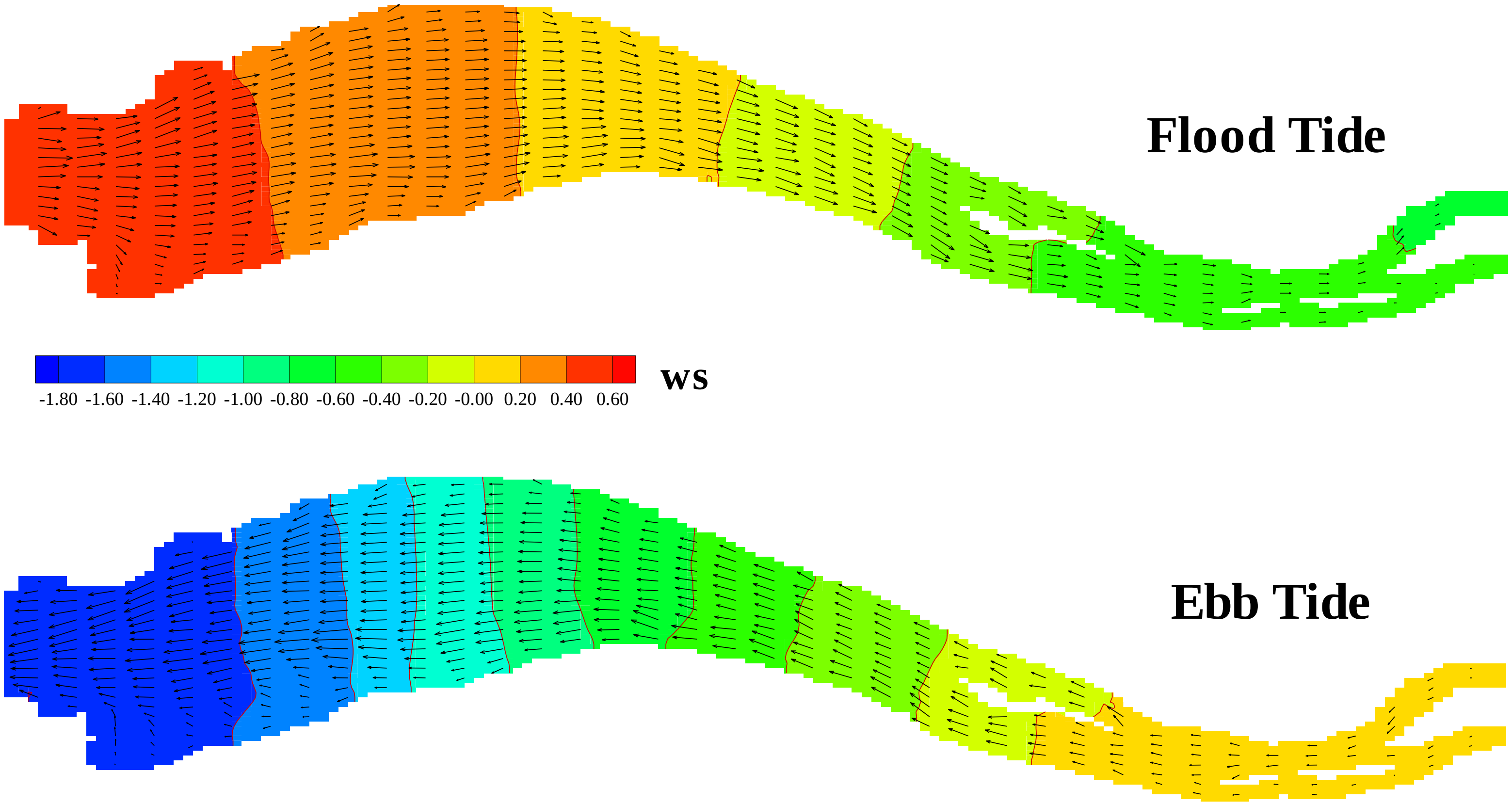
Gironde Estuary, France

2-D simulation using FASTER2D (Wu and Wang, 2004)

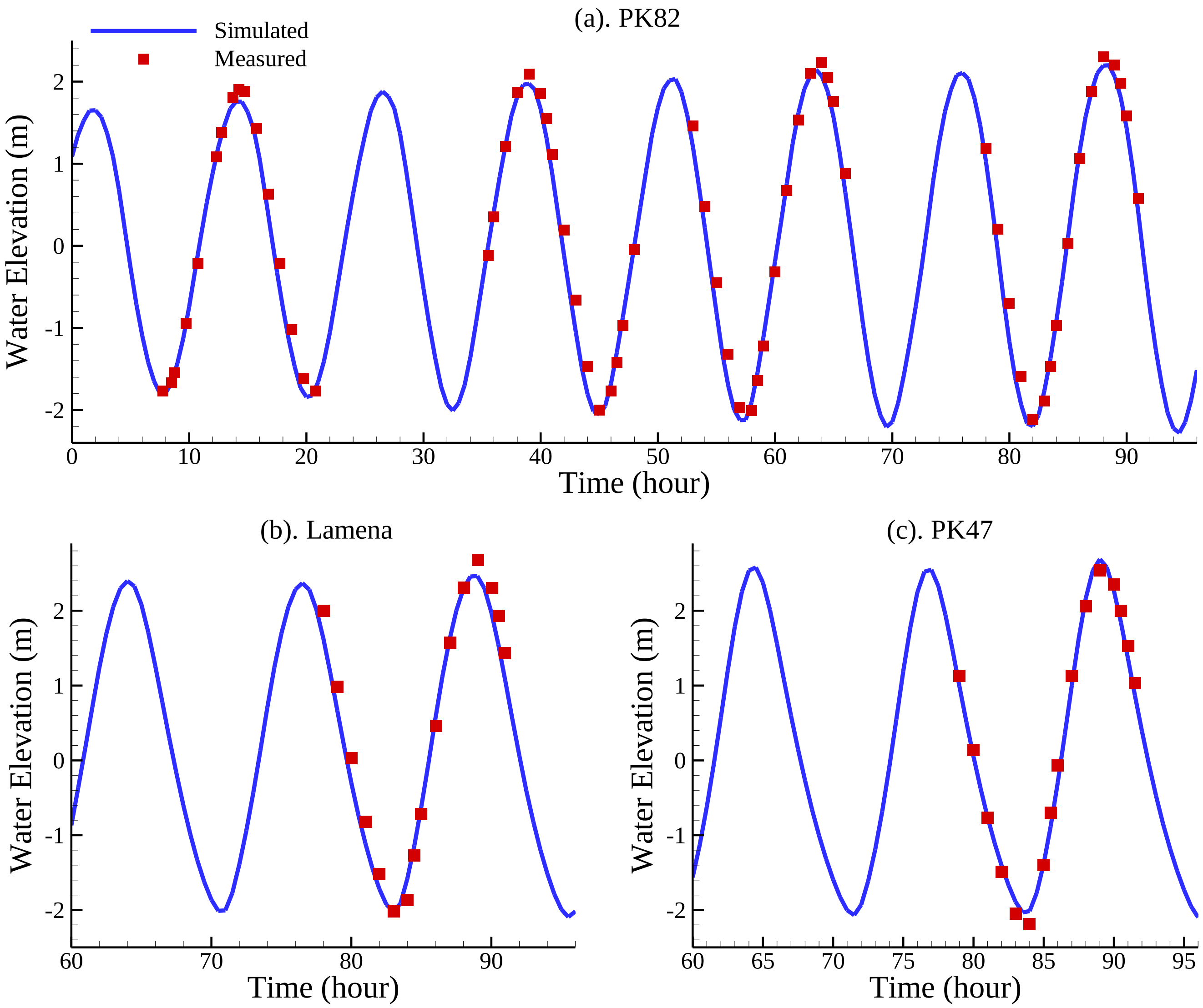
Mesh: 157×69
Δt=30 min
Period: May 19-22, 1974



Tidal Flow in Gironde Estuary, France



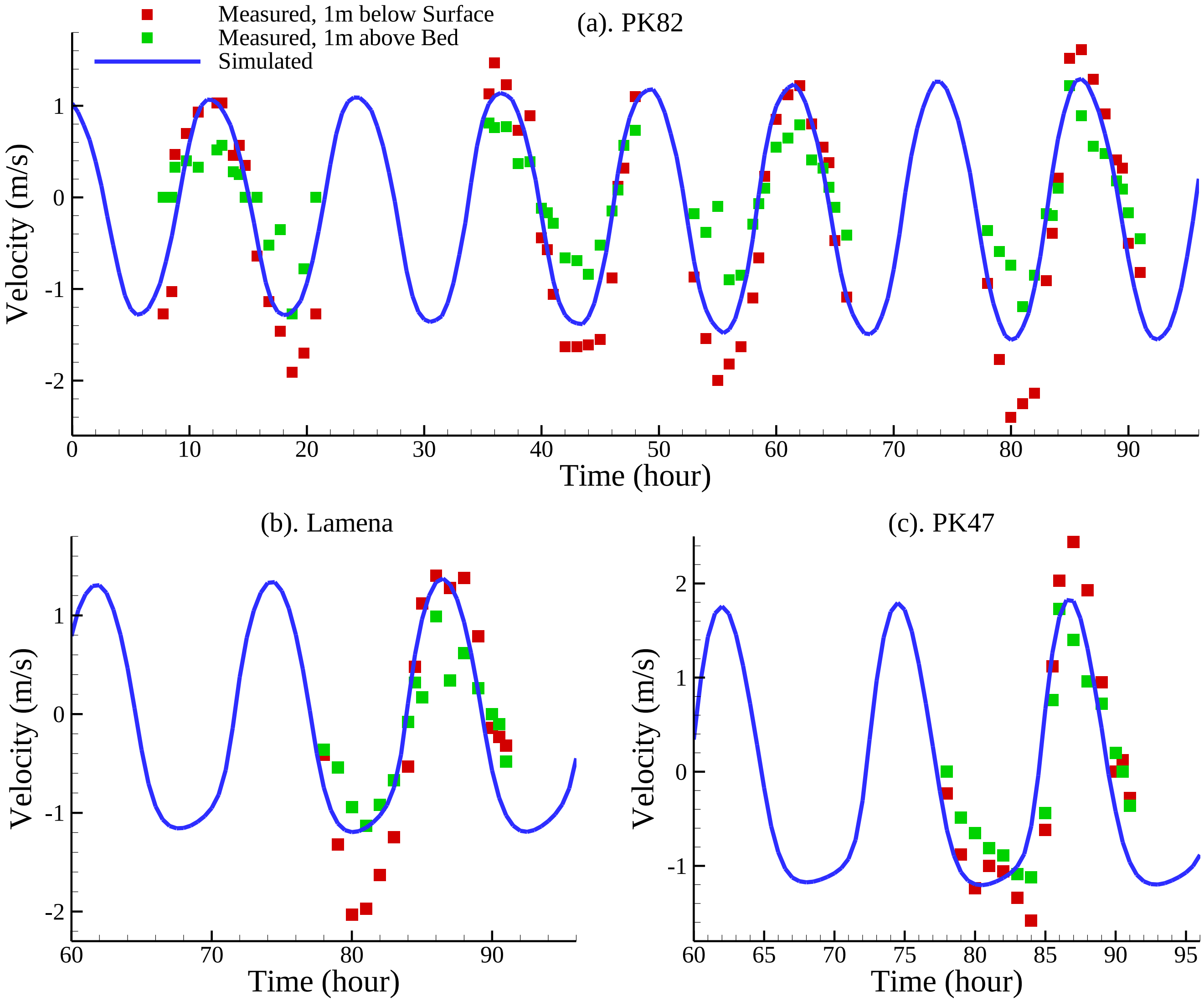
Tidal Level in Gironde Estuary


(a). PK82

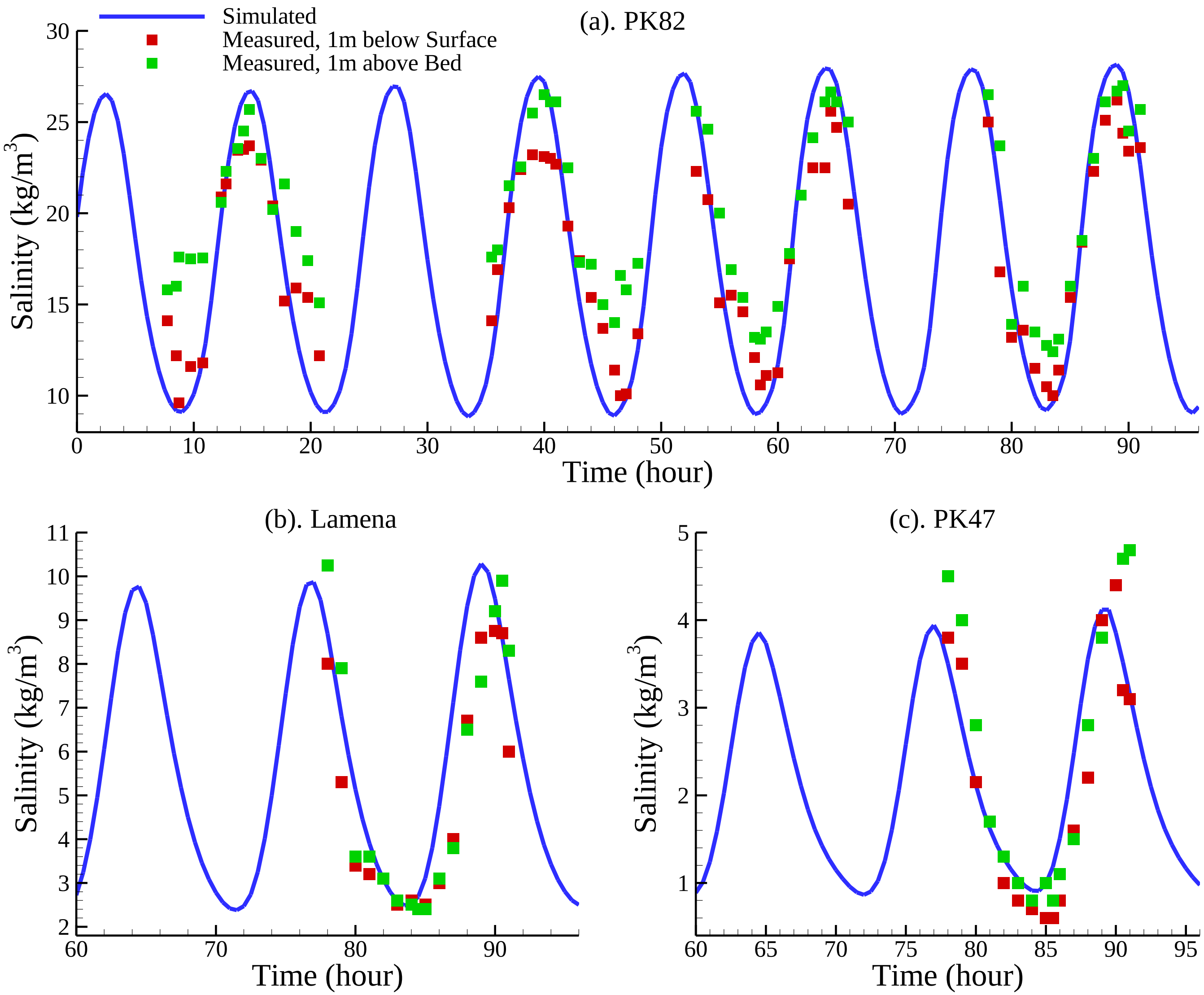
(b). Lamena

(c). PK47

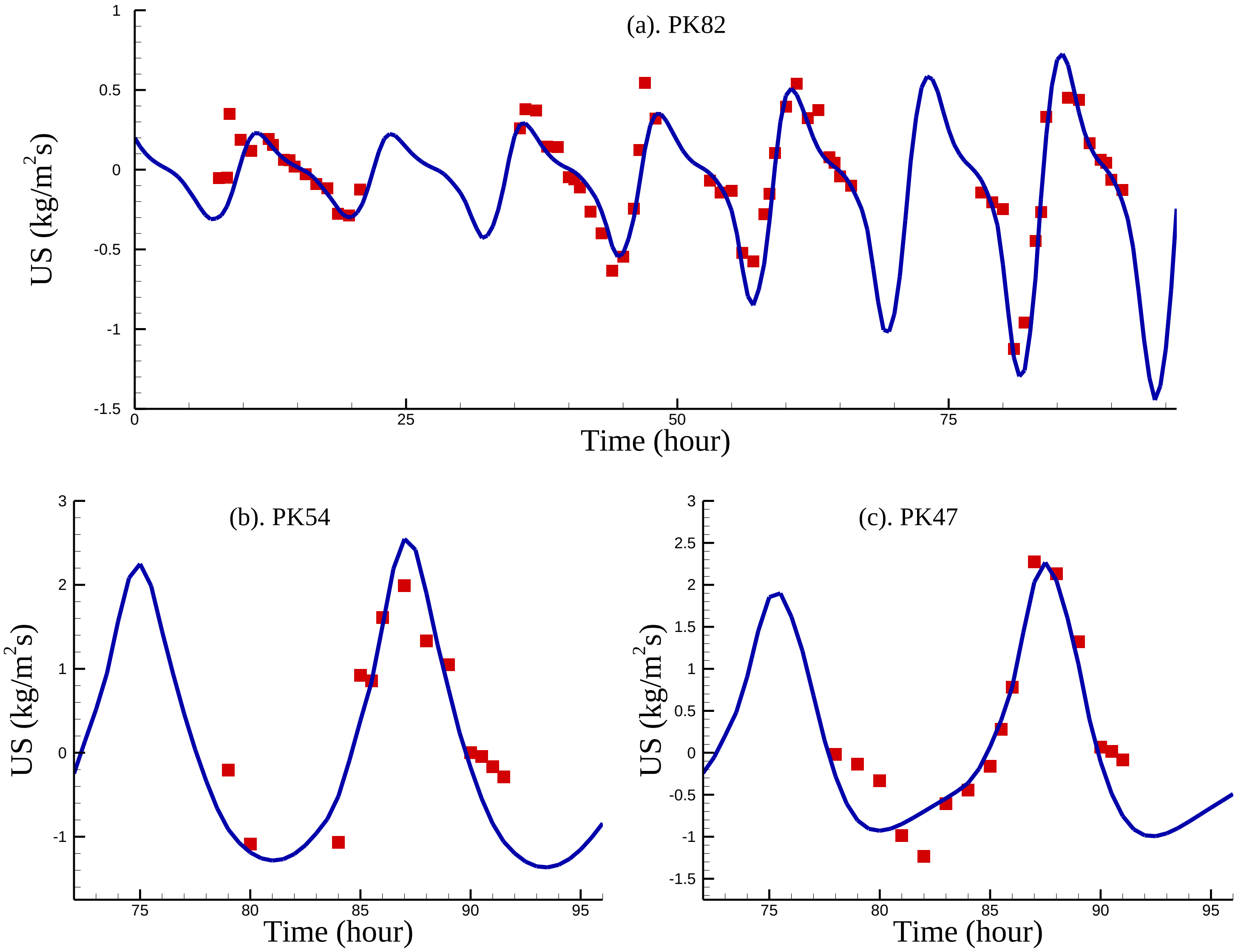
Velocity in Gironde Estuary



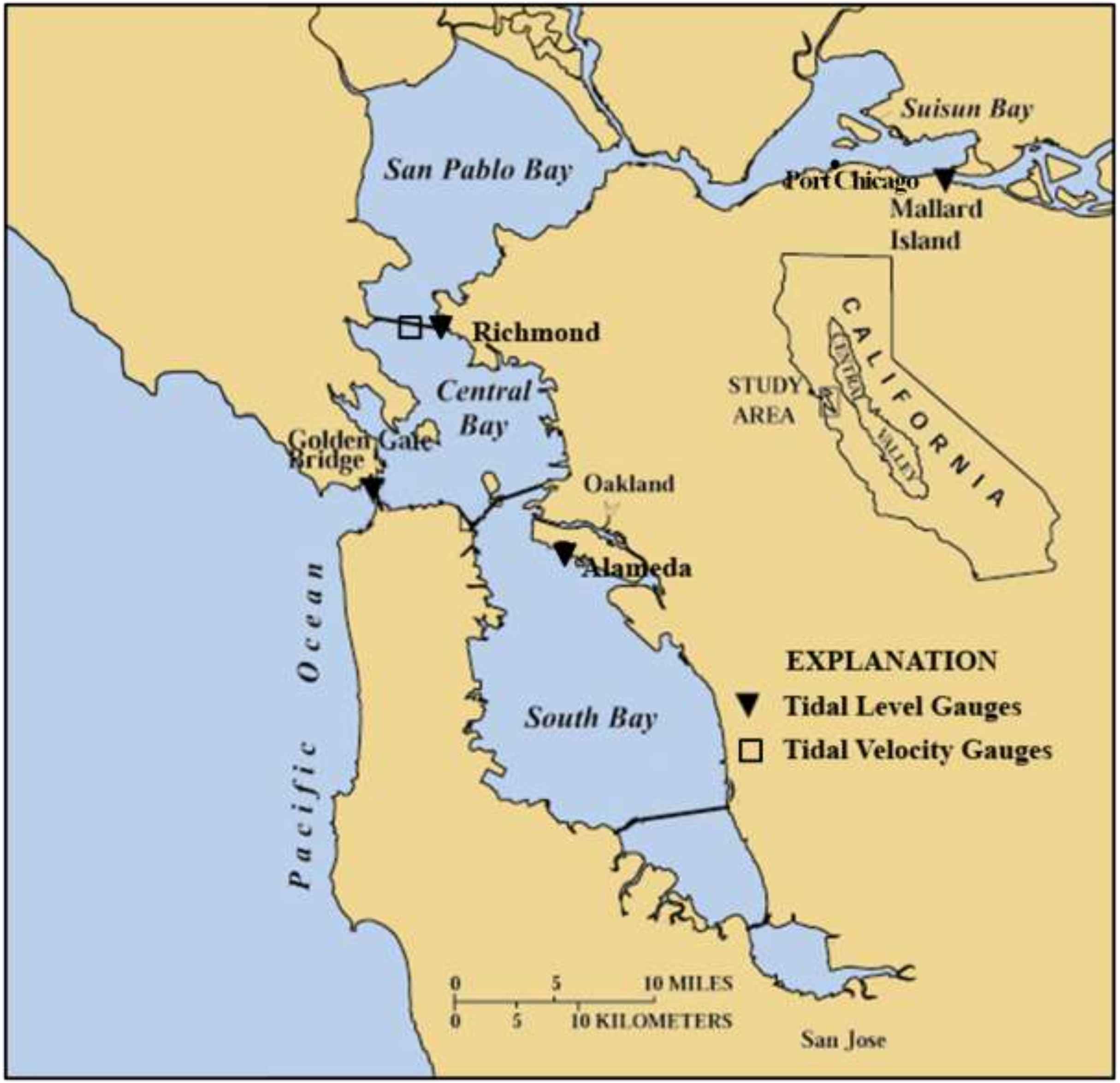
Salinity in Gironde Estuary



Sediment Discharge in Gironde

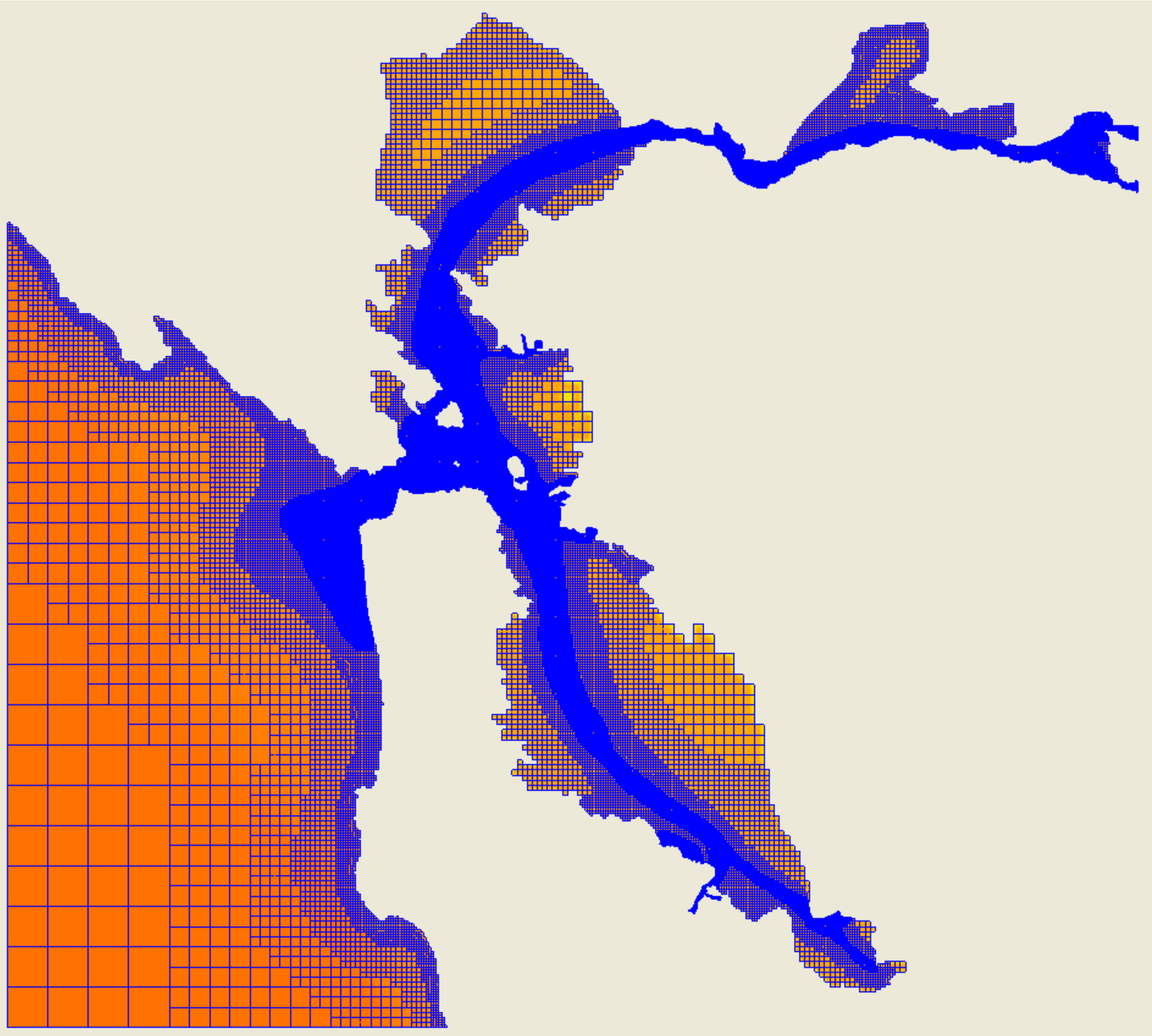


San Francisco Bay

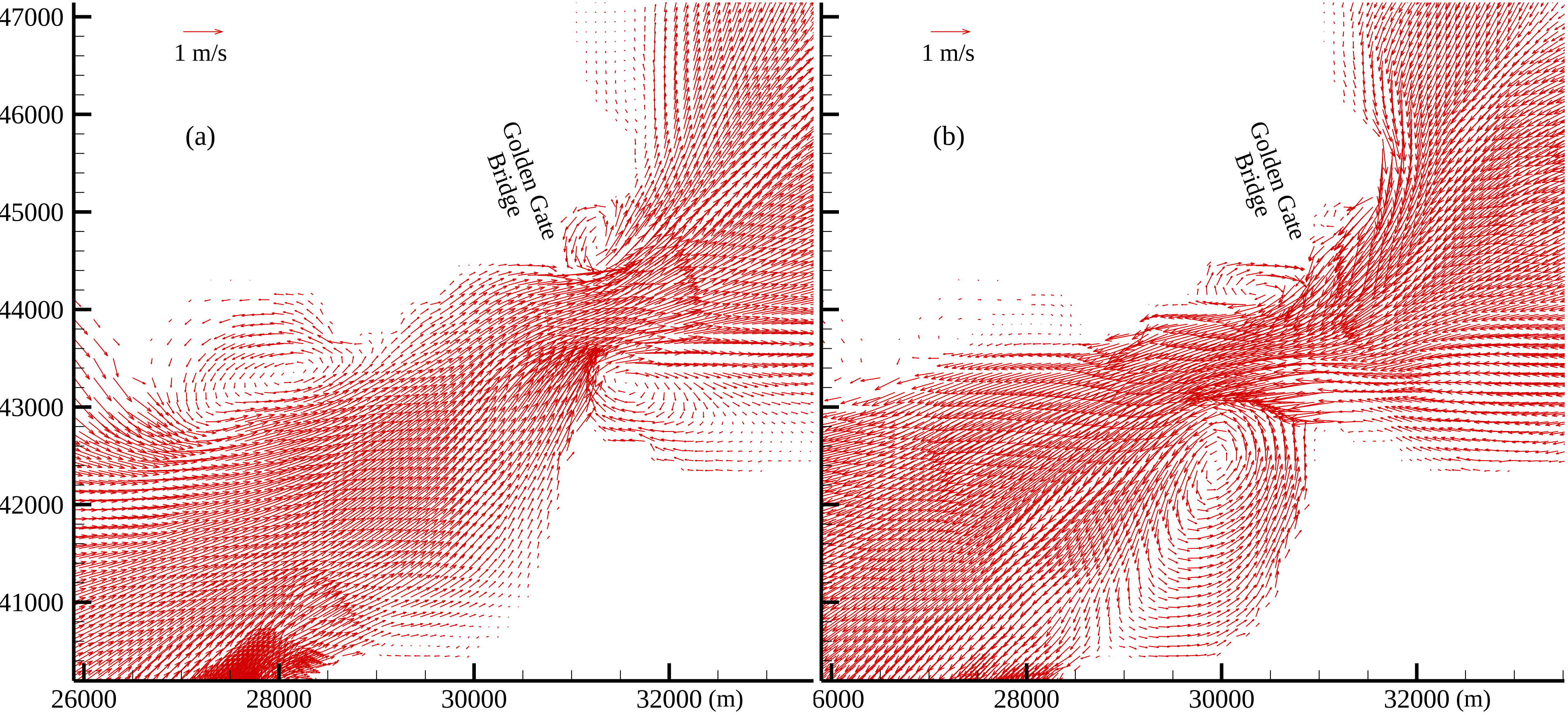


San Francisco Bay –Mesh

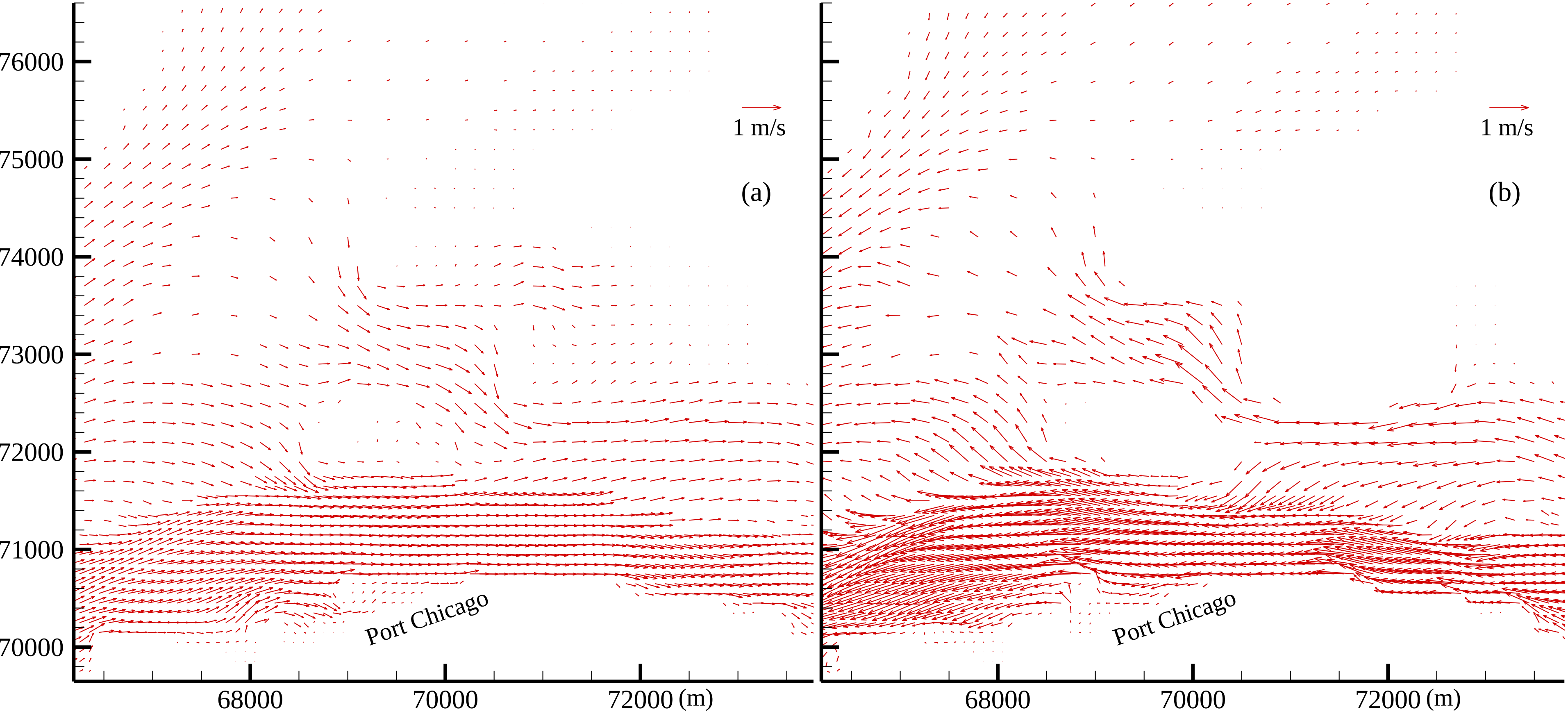
3-D Simulation using CRESTS3D (Wu and Lin, 2011)



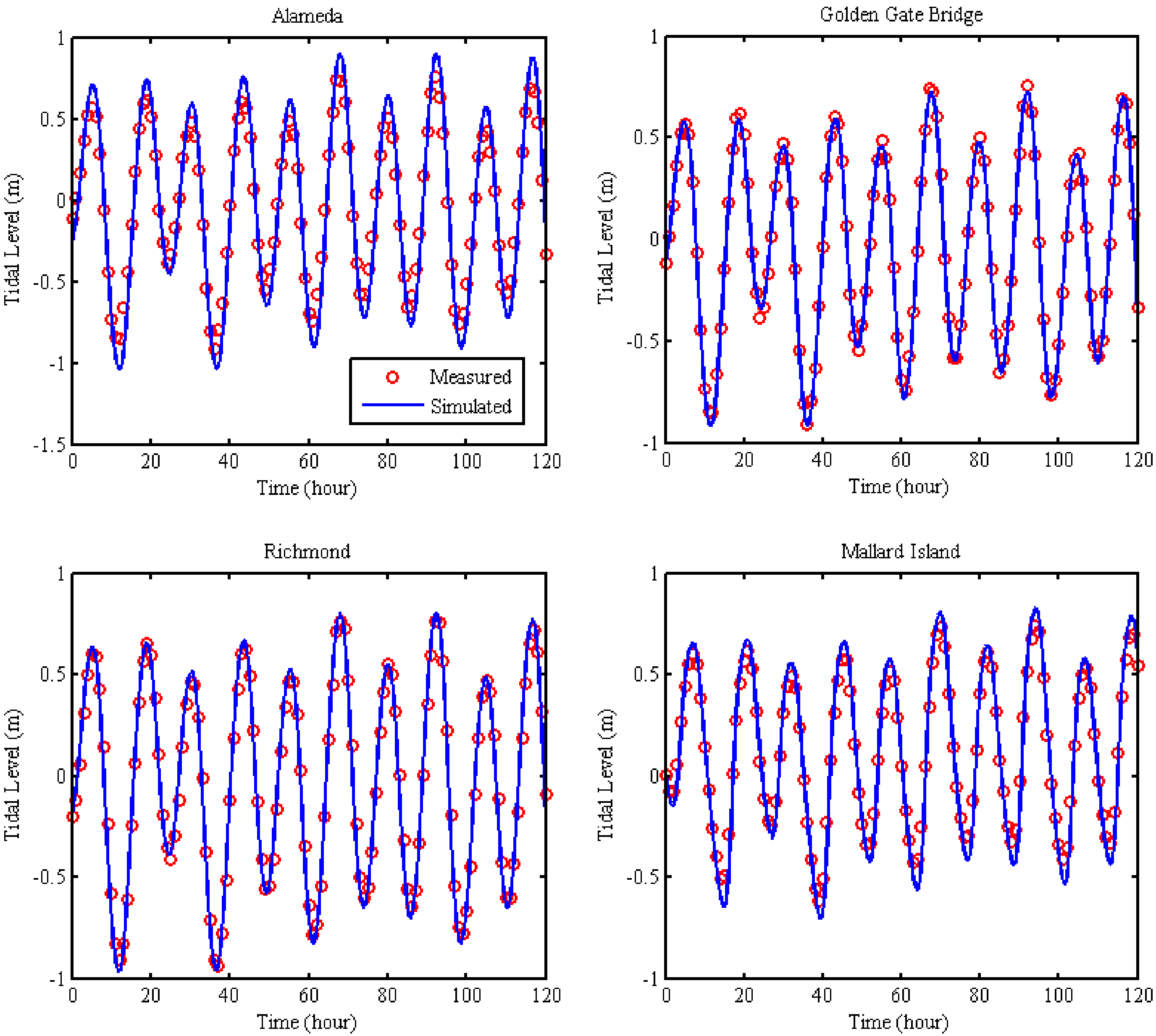
Flow near Golden Gate Bridge



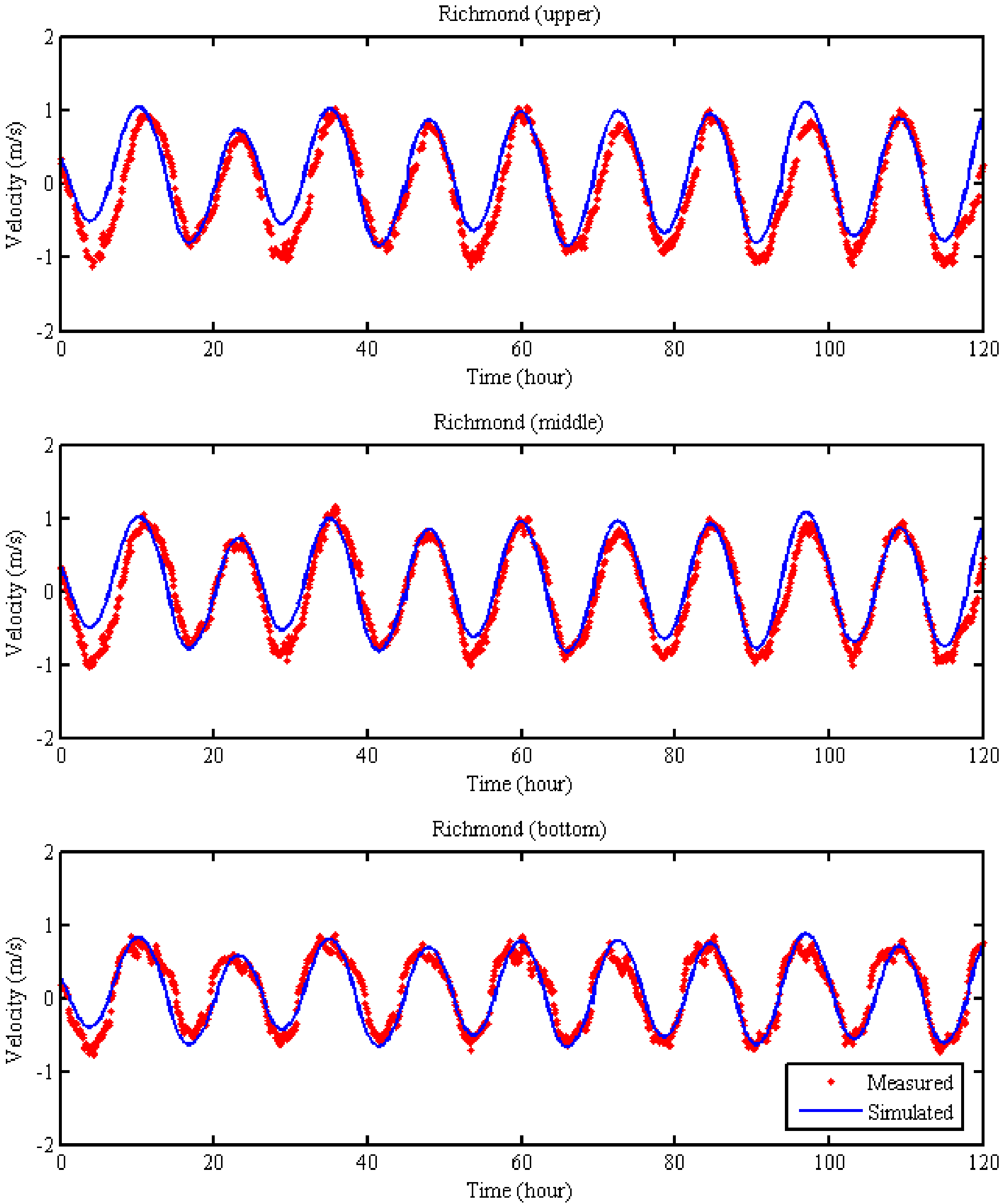
Flow near Port Chicago



Water Level


Alameda
Golden Gate Bridge
Richmond
Mallard Island
Tidal Level (m)
Time (hour)
Measured
Simulated
1
0.5
0
-0.5
-1
-1.5
0
20
40
60
80
100
120

Currents


Richmond (upper)
Richmond (middle)
Richmond (bottom)
Velocity (m/s)
2
1
0
-1
-2
0
20
40
60
80
100
120
Time (hour)
Measured
Simulated

Publications Related

W. Wu and S. S.Y. Wang (2004). “Depth-averaged 2-D calculation of tidal flow, salinity and cohesive sediment transport in estuaries,” Int. J. Sediment Research, 19(3), 172–190.

W. Wu and Q. Lin (2011). “An implicit 3-D finite-volume coastal hydrodynamic model.” Proc., 7th Int. Symposium on River, Coastal and Estuarine Morphodynamics, September 6-8, Beijing, China.

Q. Lin and W. Wu (2013). “A one-dimensional model of mixed cohesive and non-cohesive sediment transport in open channels.” Journal of Hydraulic Research, IAHR, 51(5), 506–517, DOI: 10.1080/00221686.2013.812046.