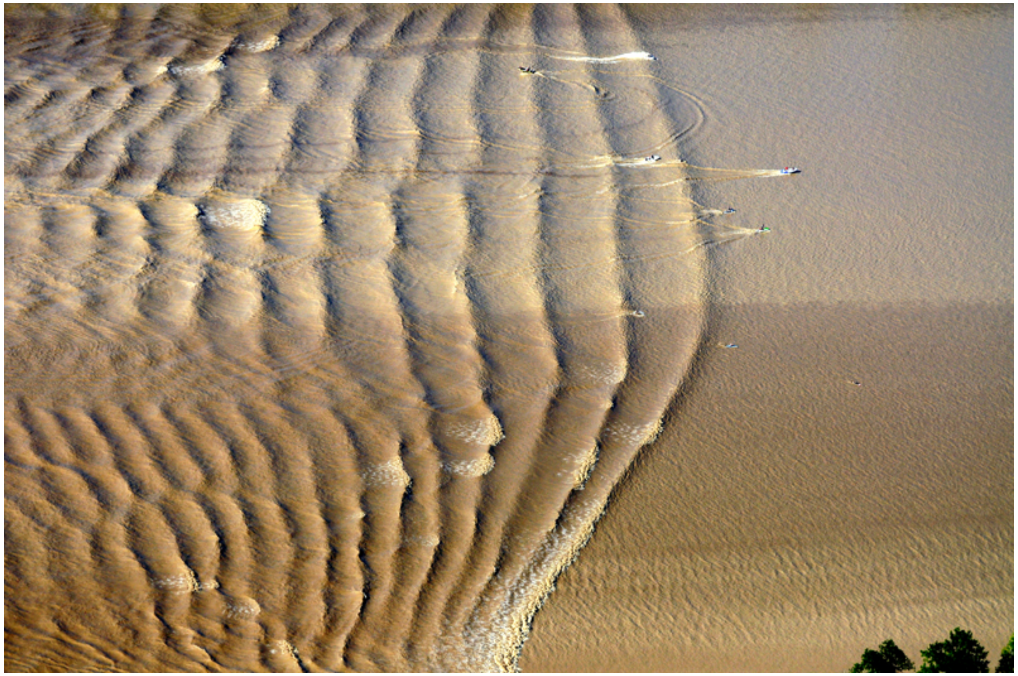
UNIVERSITÉ DE BORDEAUX

Tsunami-like bore formation in coastal and estuarine environments

Philippe Bonneton

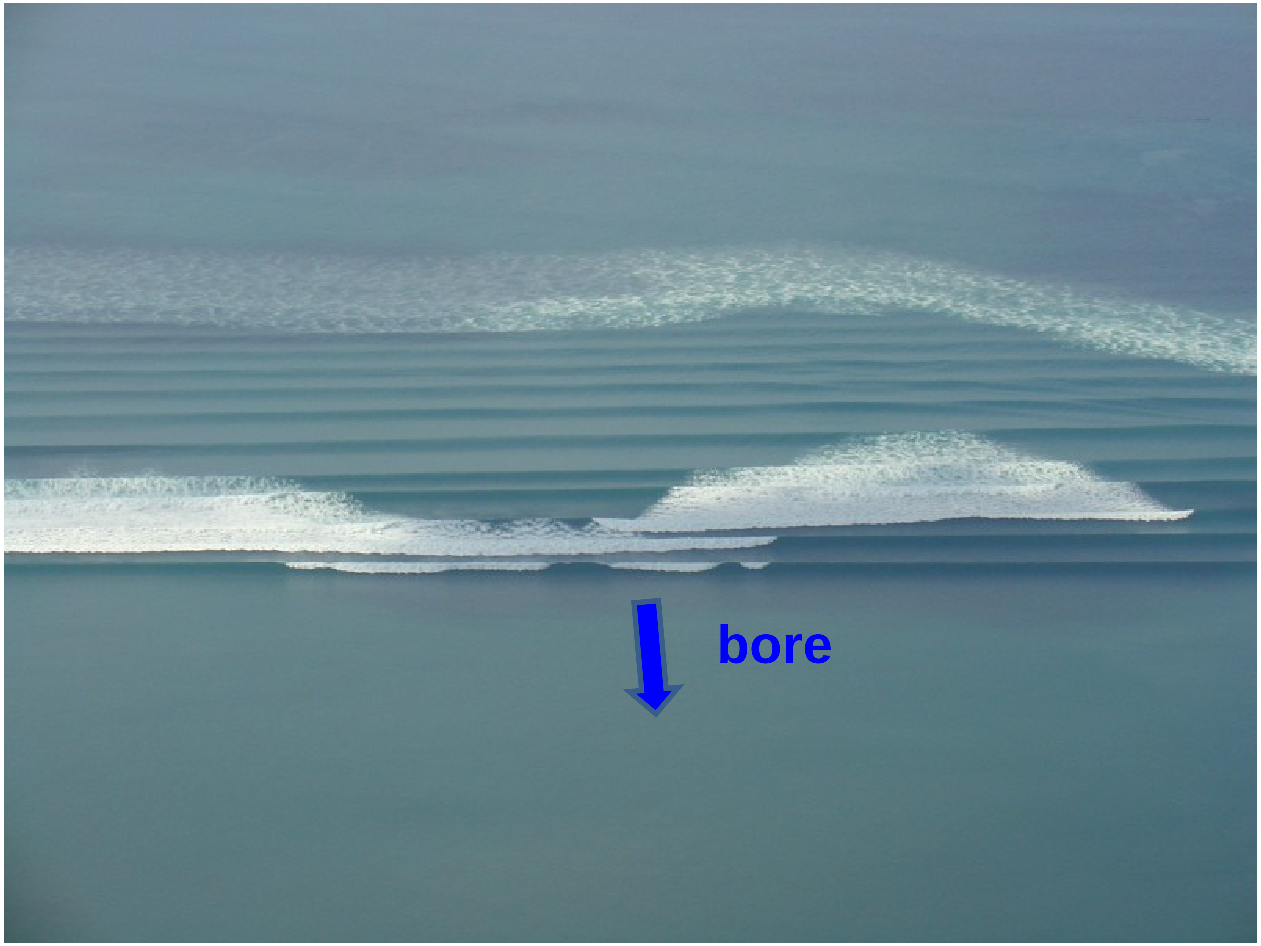
EPOC/METHYS, CNRS, Bordeaux Univ.



Tidal bore – Gironde – Lavigne Y.

Long waves

Tsunamis, tides, infragravity waves, meteorological tsunamis, …



Sumatra 2004 tsunami reaching the coast of Thailand

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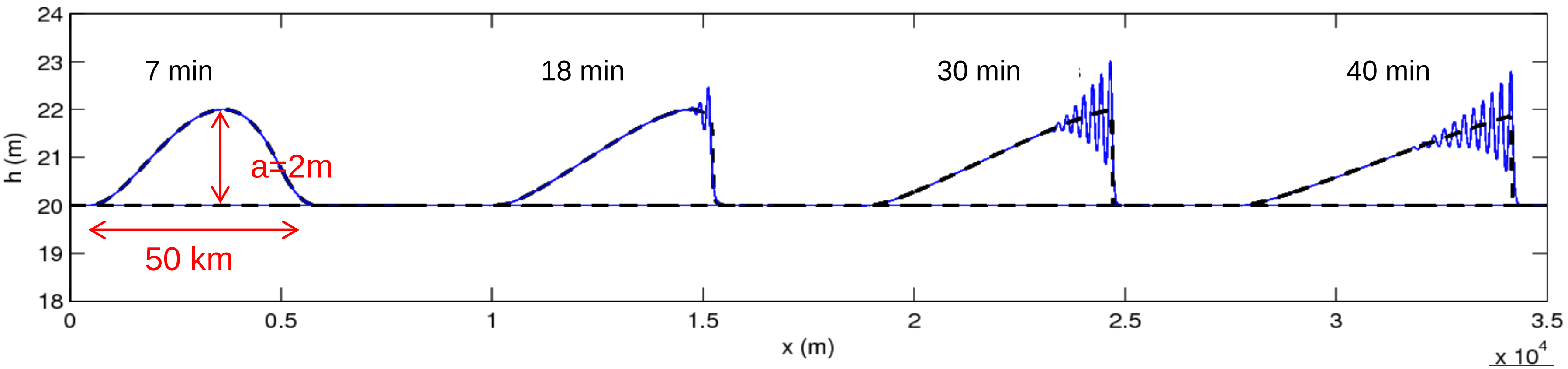


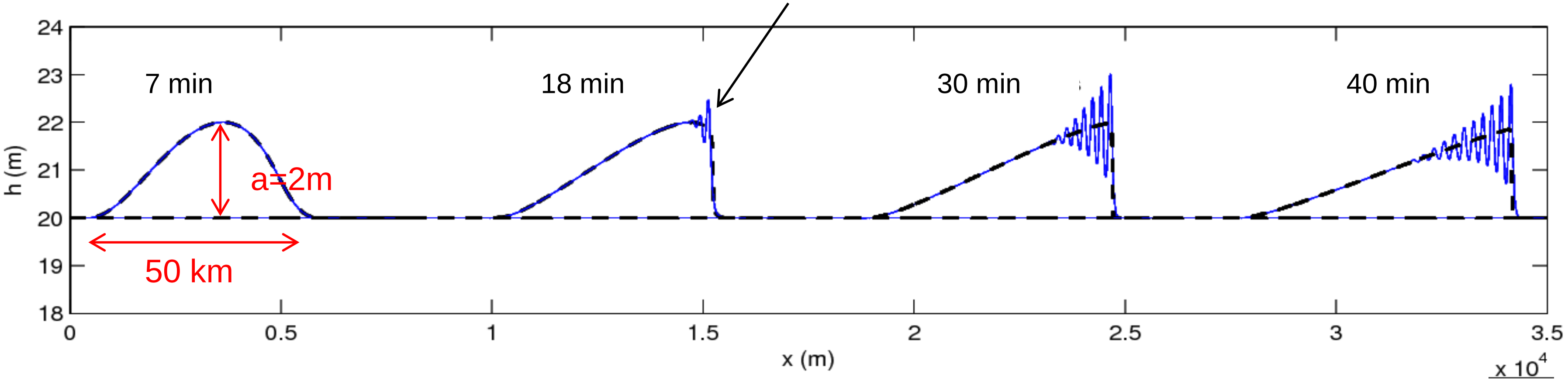
Serre Green Naghdi model

Tissier , Bonneton et al., JCR2011

Long waves

Tsunamis, tides, infragravity waves, meteorological tsunamis, …

dispersive shock inception



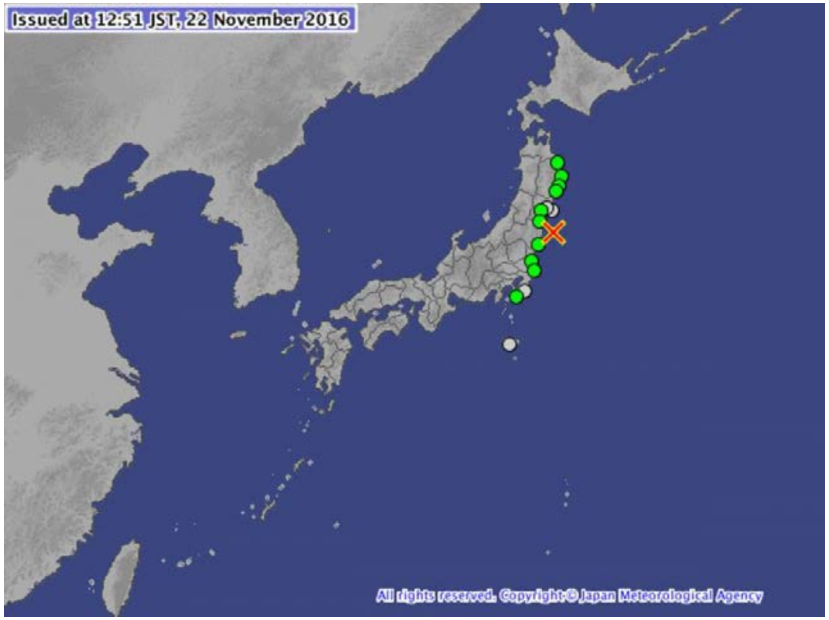
⇒ **bore formation**

Sumatra 2004 tsunami reaching the coast of Thailand

http://www.kohjumonline.com/anders.html

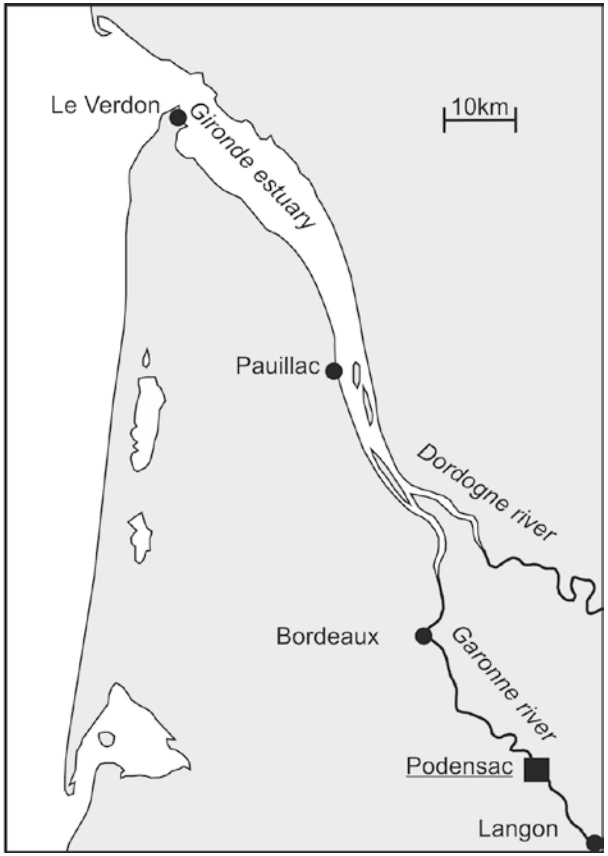
references:

- *Grue et al. 2008*
- *Madsen et al. 2008*

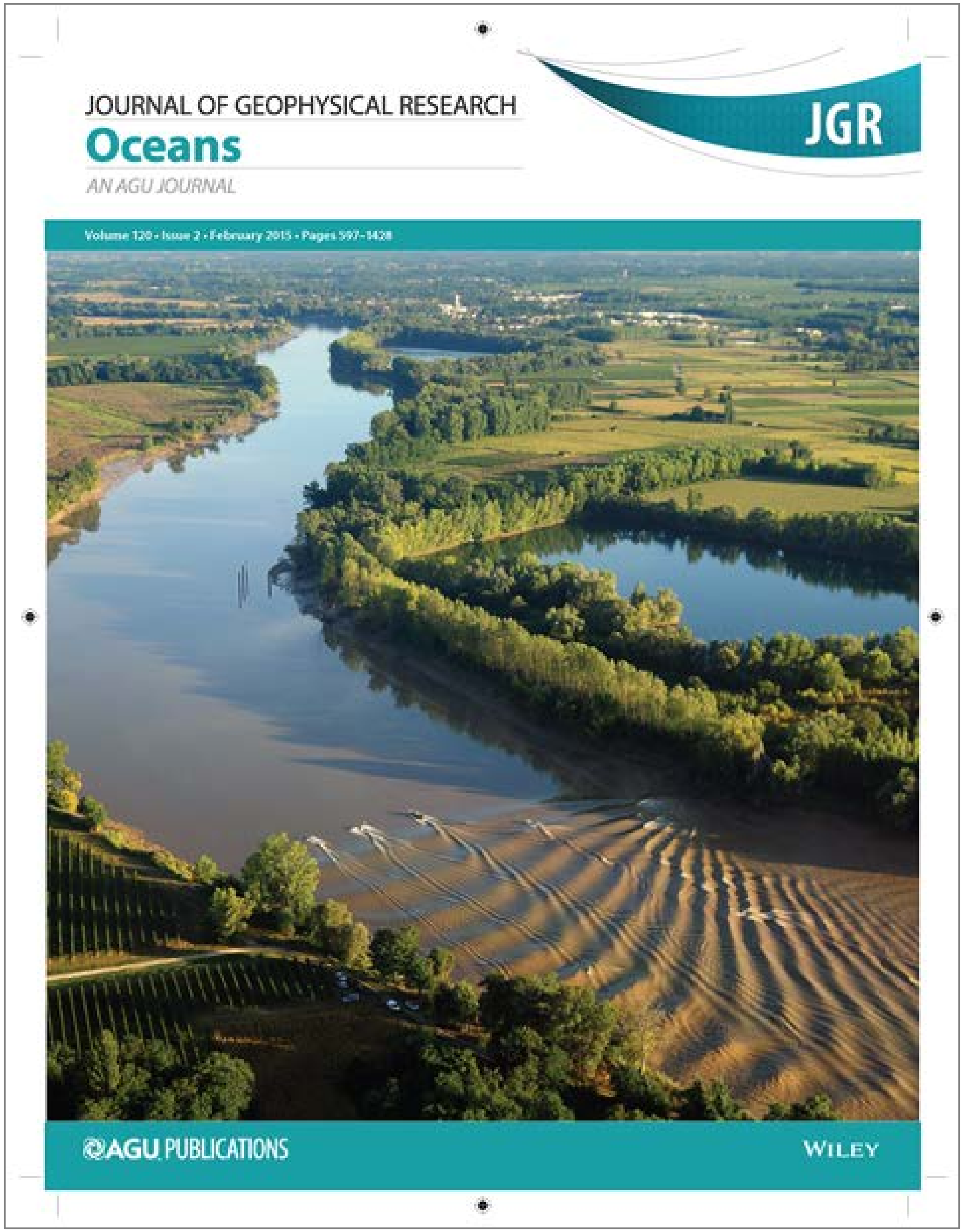


21st November 2016, Sunaoshi River in Tagajo city, Japan (earthquake 7.4)

Tidal bore



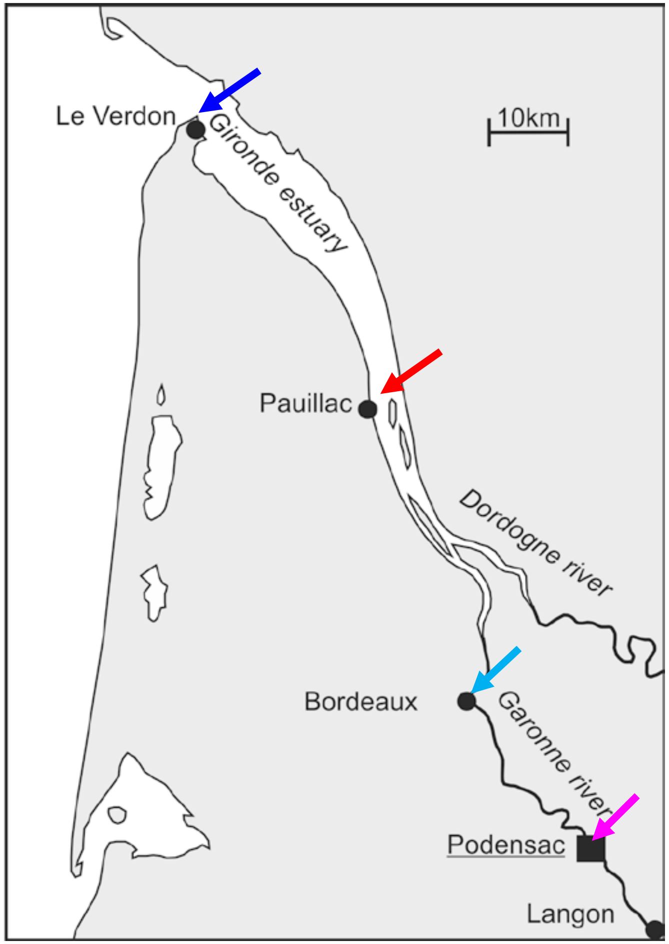
Bonneton et al. JGR 2015



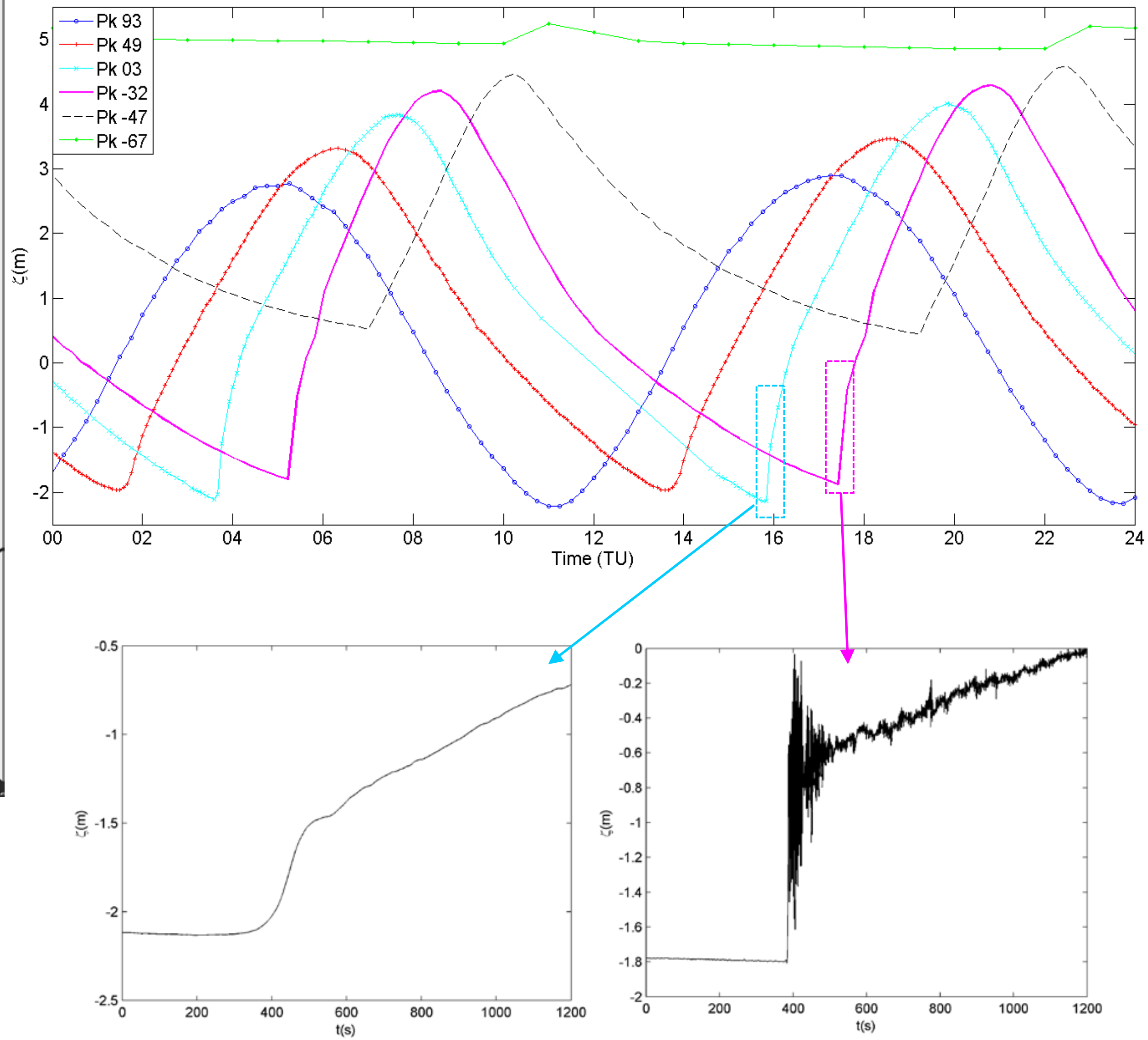
Gironde estuary, Saint Pardon, Dordogne

https://vimeo.com/106090912, Jean-Marc Chauvet, Septembre 2014

Introduction | Tidal bore



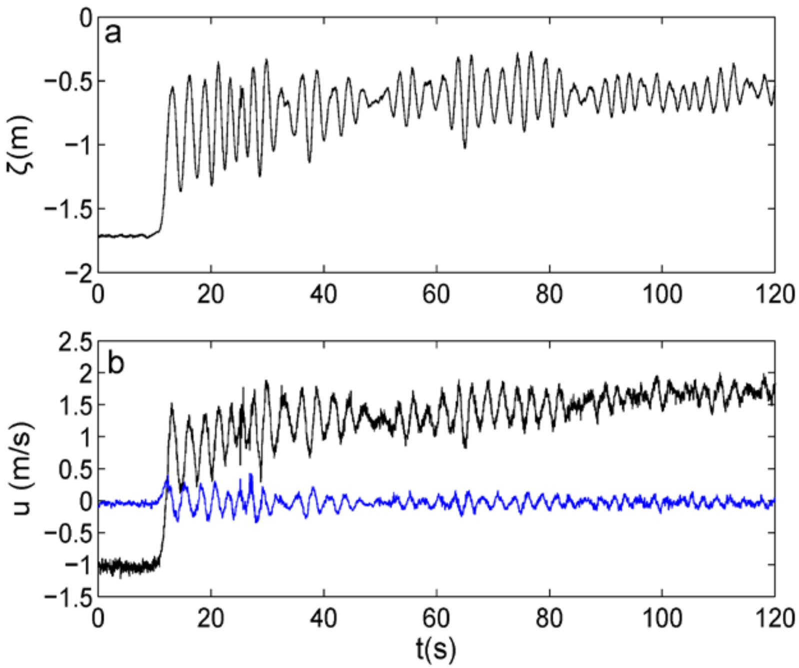
Large amplitude spring tide – 10th September 2010



Bonneton et al. JGR 2015

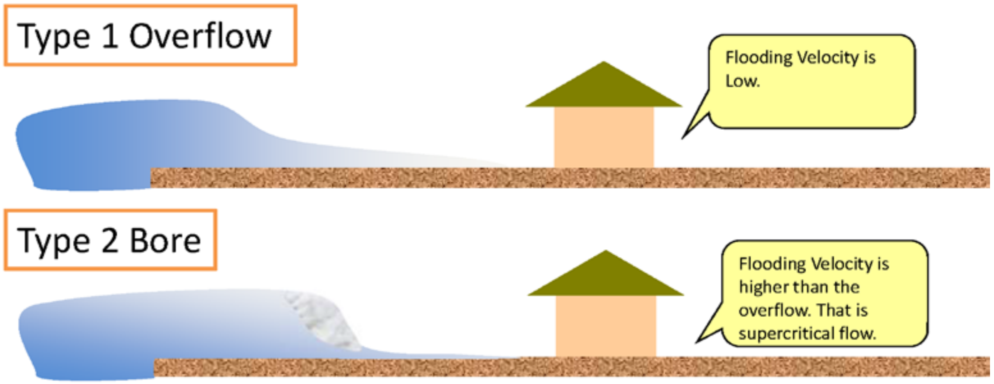
⇒ **Strong impact on coastal and estuarine environments**

❑ Sediment transport and erosion



Tidal Bores, Bonneton et al. 2015

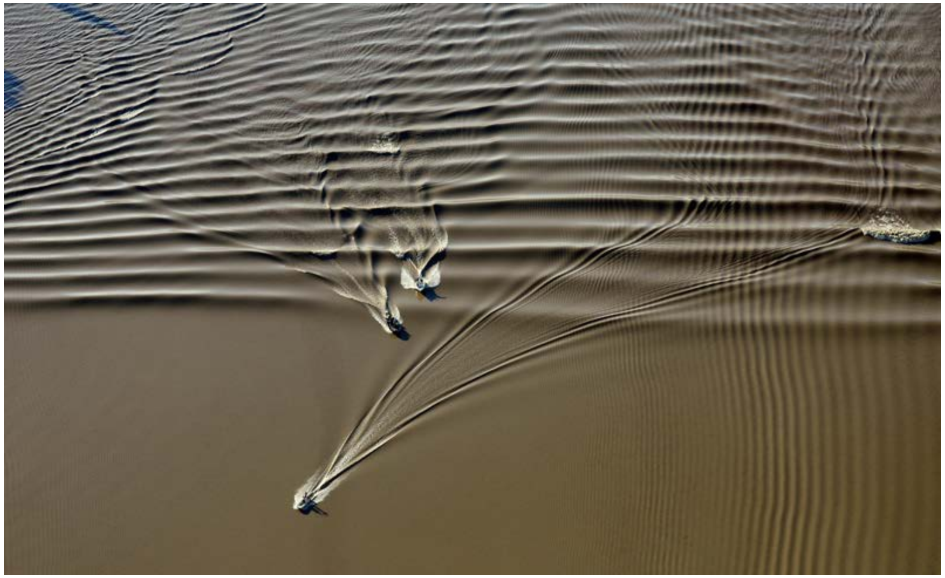
❑ Impact on marine structures and buildings



Tsunamis, Arikawa et al. 2013

Conditions for tsunami-like bore formation in coastal and estuarine environments

tsunami bore



tidal bore

- **field measurements**

→ *Bonneton N., Castelle B., Detandt G., Parisot J-P., Sottolichio A. (EPOC, METHYS team, Bordeaux)*

→ *Frappart F., Roussel N., Darrozes J. (OMP, Toulouse)*

→ *Martins K. (Bath University)*

- **long wave modeling**

→ *Ricchuito M., Arpaia L., Filippini A. (INRIA, Bordeaux)*

→ *Lannes D*. (IMB, Bordeaux)

→ *Marche F. (IMAG, Montpellier),*

→ *Tissier M. (TU Delft, Netherlands)*

Outline

- Introduction
- Basic conditions for bore formation in the coastal zone
- Conditions for tidal bore formation in estuaries
- Conclusion and perspectives

Outline

- ❑ Introduction
- ❑ Basic conditions for bore formation in the coastal zone
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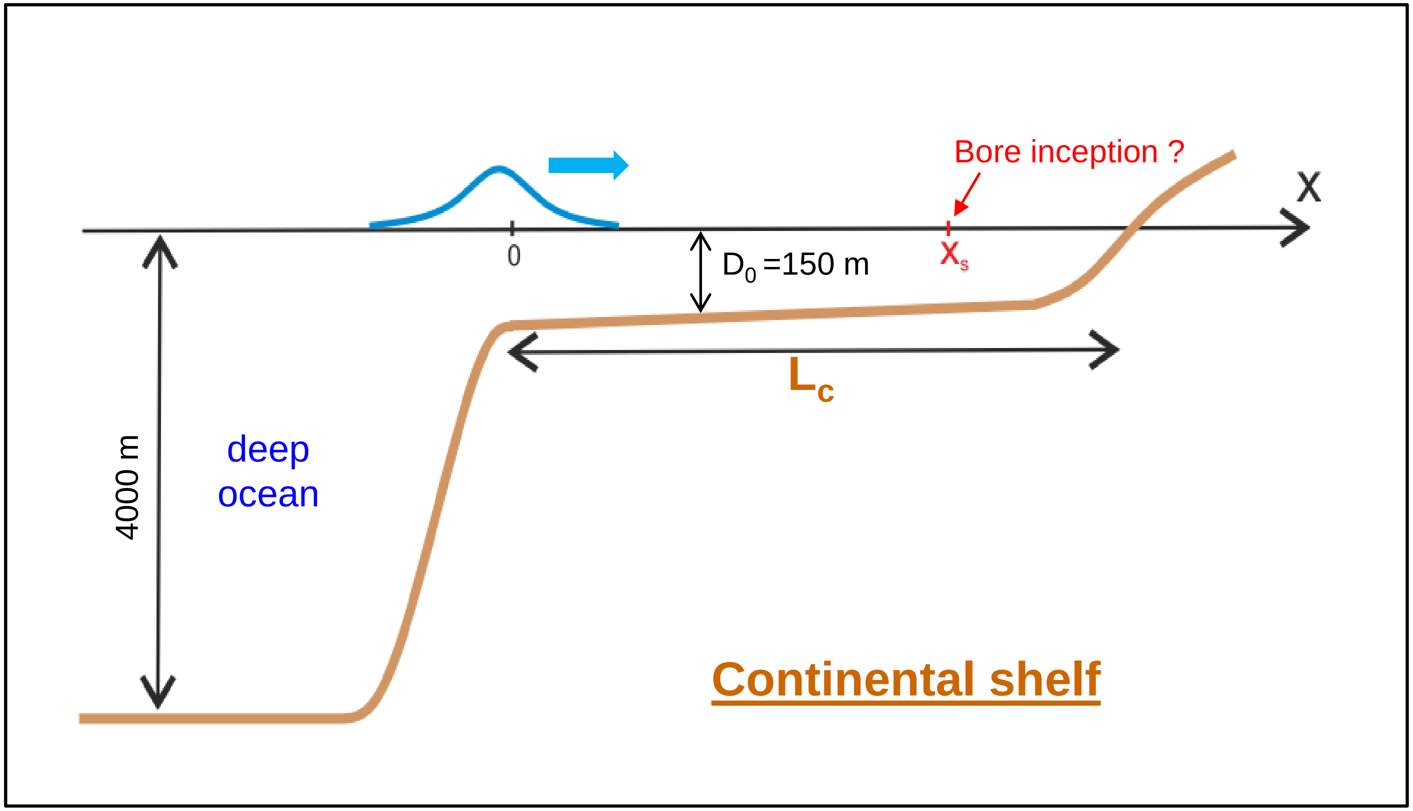
- ❑ Conclusion and perspectives

Basic conditions for bore formation



- the continental shelf is relatively flat

- D_0 , A_0 , $\omega_0 = 2\pi / T_0$

$$L_{w0} = \frac{\sqrt{g D_0}}{\omega_0}$$

$$\epsilon_0 = \frac{A_0}{D_0} \qquad \mu_0 = \frac{D_0^2}{L_{w0}^2}$$

Basic conditions for bore formation

$\mu_0 << 1 \quad \varepsilon_0 = O(1)$

$$\frac{\partial \zeta}{\partial t} + \vec{\nabla}.((1+\epsilon_0 \zeta)\vec{u}) = 0$$
$$\frac{\partial \vec{u}}{\partial t} + \epsilon_0 (\vec{u}.\vec{\nabla})\vec{u} + \vec{\nabla}\zeta = \mu_0 D$$

Serre / Green Naghdi equations

Basic conditions for bore formation

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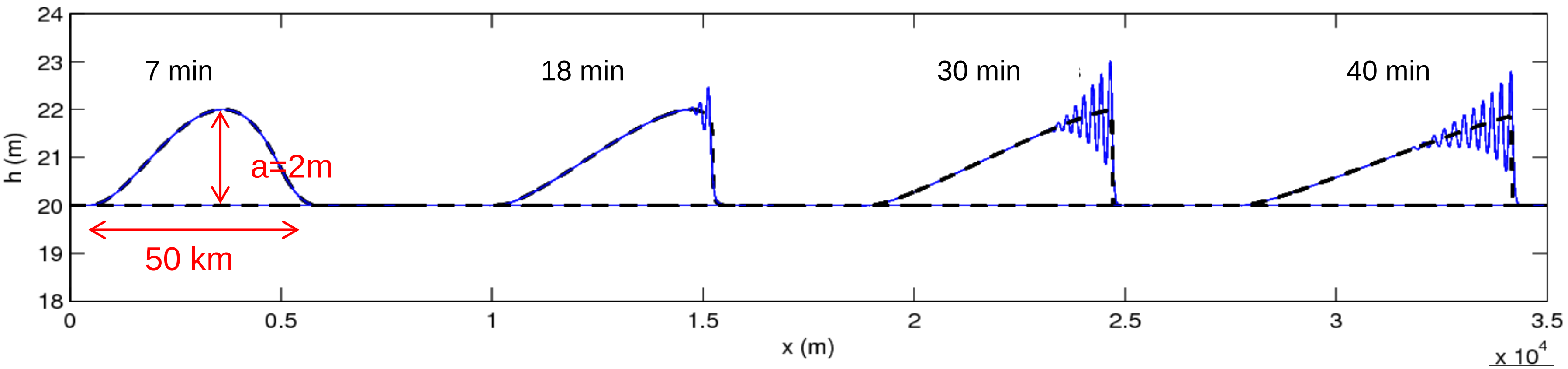

Serre Green Naghdi model

Tissier , Bonneton et al., JCR2011

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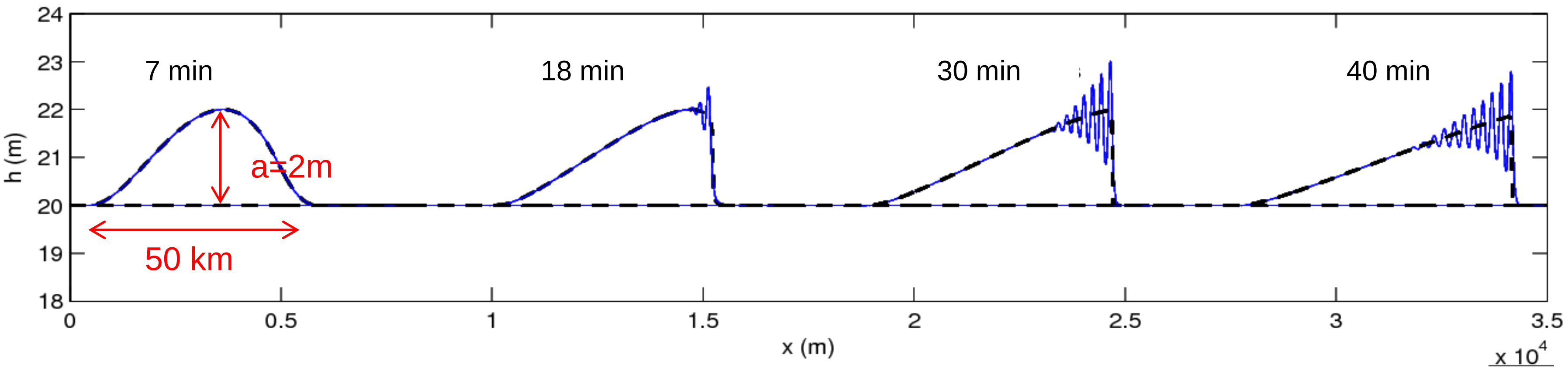


Serre Green Naghdi model

Tissier , Bonneton et al., JCR2011

Basic conditions for bore formation

$$\begin{aligned}\frac{\partial}{\partial t}(u-2c)+(u-c)\frac{\partial}{\partial x}(u-2c) &= 0\\ \frac{\partial}{\partial t}(u+2c)+(u+c)\frac{\partial}{\partial x}(u+2c) &= 0\end{aligned}$$

$$c=(gh)^{1/2} \qquad c_0=(gD_0)^{1/2}$$

$$\text{One way} \quad \Rightarrow \quad u-2c=-2c_0$$

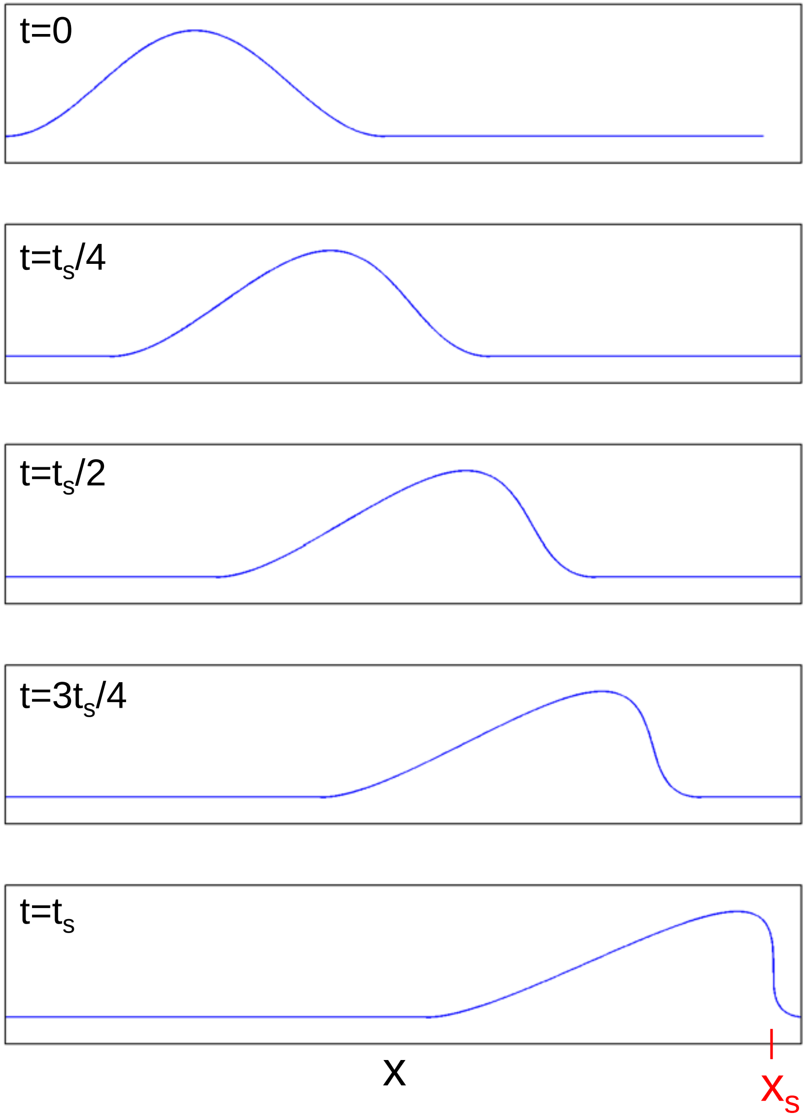
$$\frac{\partial h}{\partial t}+C_h(h)\frac{\partial h}{\partial x}=0 \qquad\qquad C_h=3c-2c_0$$

$$\left\{\begin{aligned} h(x,t) &= h(x_0,t=0) \qquad \text{along}\\ \frac{dx}{dt} &= C_h \qquad \text{or} \qquad x=x_0+C_h(x_0,t=0)t\end{aligned}\right.$$

$$h(x,t)=h_0(x-C_h(x_0)t)$$

Basic conditions for bore formation

$$h(x,t) = h_0(x - C_h(x_0)t)$$

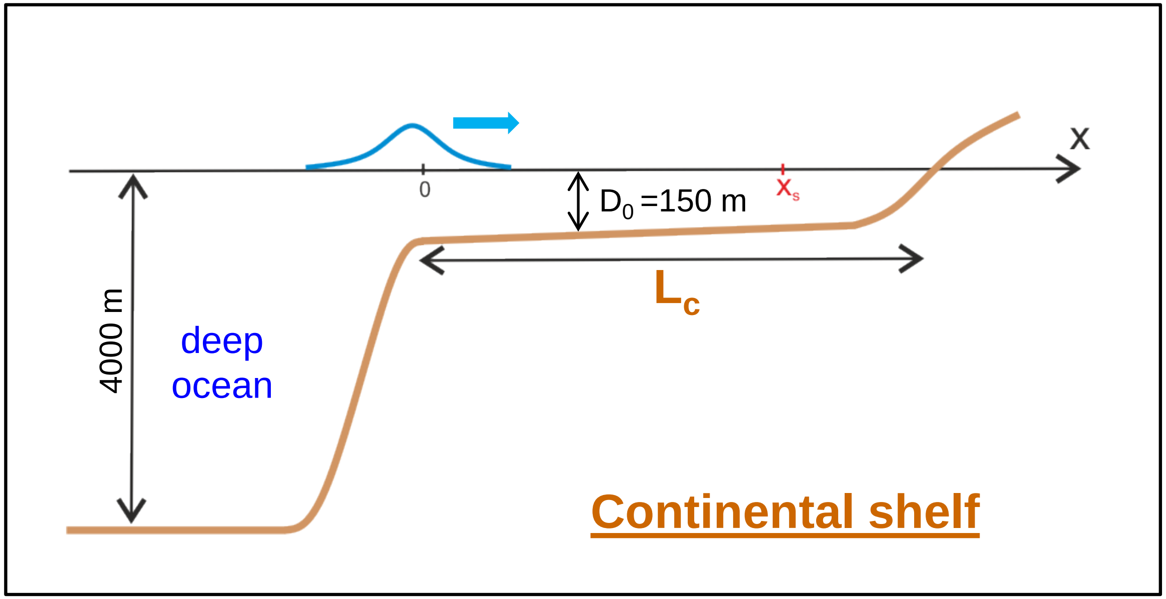


$$\frac{\partial h}{\partial x} = \frac{\frac{\partial h_0}{\partial x_0}}{1 + \frac{\partial C_h}{\partial x_0} t} = \frac{\frac{\partial h_0}{\partial x_0}}{1 + \frac{3c_0}{2\sqrt{D_0 h_0}} \frac{\partial h_0}{\partial x_0} t}$$

$$t_s = -\frac{2}{3} \frac{D_0}{c_0 \frac{\partial h_0}{\partial x_0})_s} \quad \Rightarrow \quad x_s = -\frac{2}{3} \frac{D_0 C_{h_s}}{c_0 \frac{\partial h_0}{\partial x_0})_s}$$

$$x_s \simeq -\frac{2}{3} \frac{D_0}{\frac{\partial h_0}{\partial x_0})_s}$$

Basic conditions for bore formation

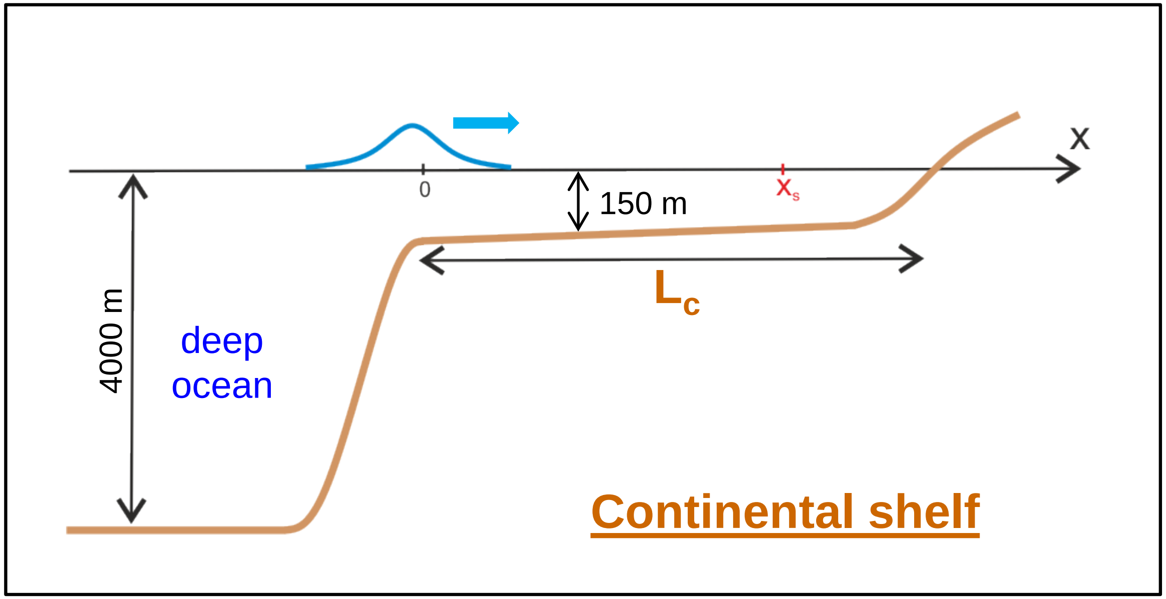


$$h(x_0, t=0) = D_0 + A_0(1 + \sin \frac{x_0}{L_{w0}})$$

$$x_s = \frac{2}{3} \frac{L_{w0}}{\epsilon_0}$$

see Madsen et al 2008

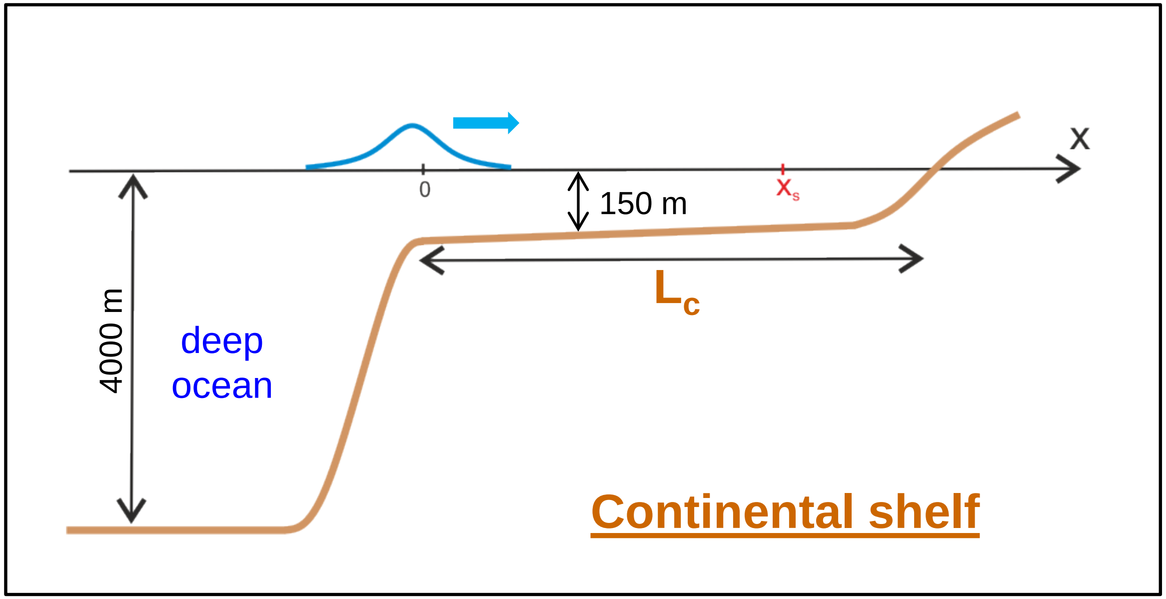
Basic conditions for bore formation



$$h(x_0, t=0) = D_0 + A_0(1 + \sin\frac{x_0}{L_{w0}})$$

$$x_s = \frac{2}{3}\frac{L_{w0}}{\epsilon_0} < L_c$$

Basic conditions for bore formation



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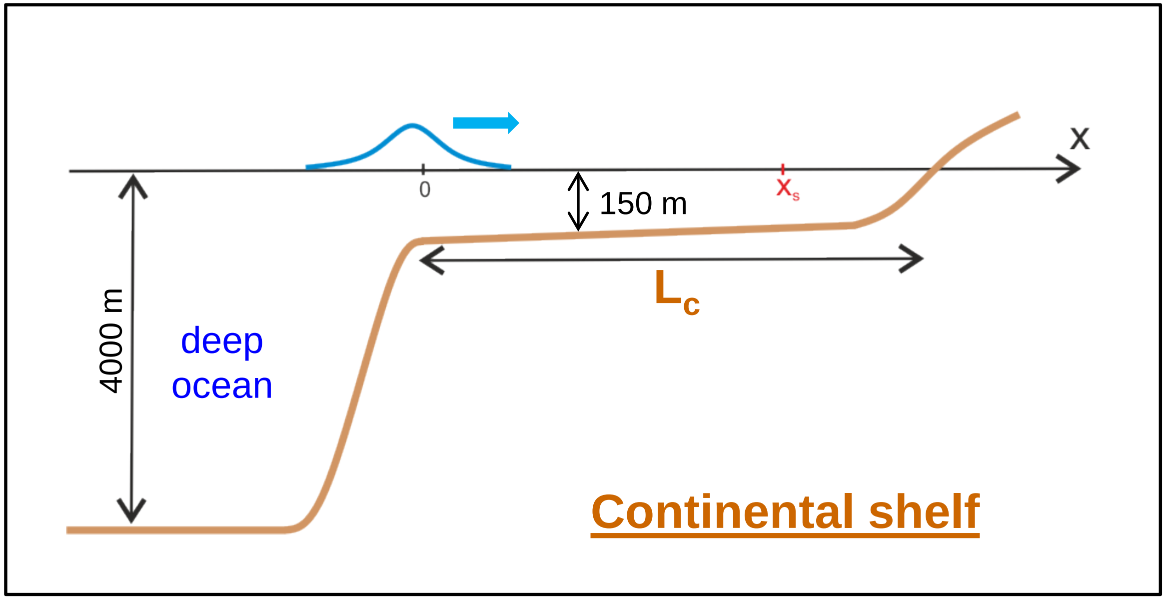
Basic conditions for bore formation



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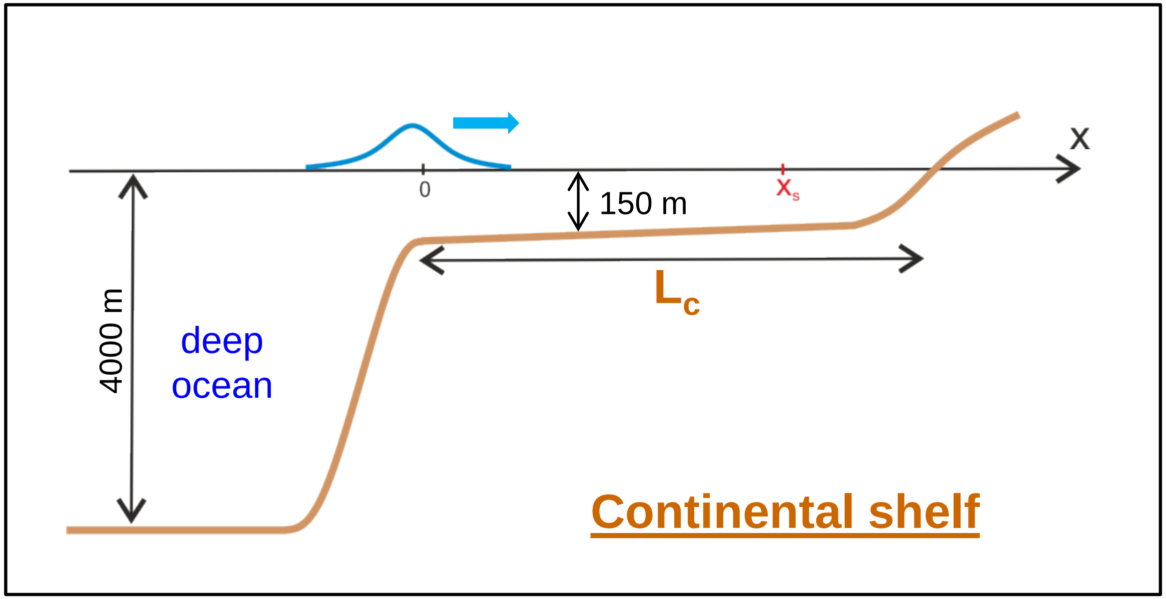
Continental shelves $D_0 \approx 150$ m

- tsunamis: $A_0 \approx 2$ m, $T_0 \approx 25$ min $\Rightarrow$ $x_s = 460$ km
- tides: $T_0 \approx 744$ min $\Rightarrow$ $x_s >> L_c$ $\rightarrow$ no tidal bore in open continental shelf water

Basic conditions for bore formation



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- tsunamis: bores may occur in large and shallow (few tens of m) coastal environments:

  marine coastal plains (e.g.: deltas, alluvial estuaries) or

  carbonate platforms (e.g.: coral reef systems)

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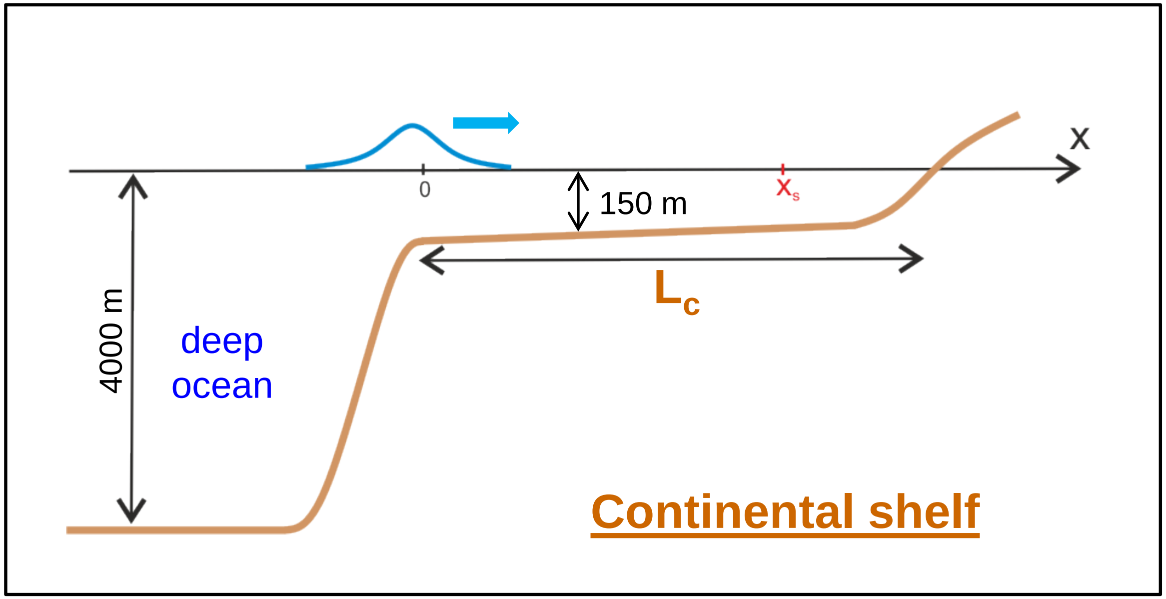

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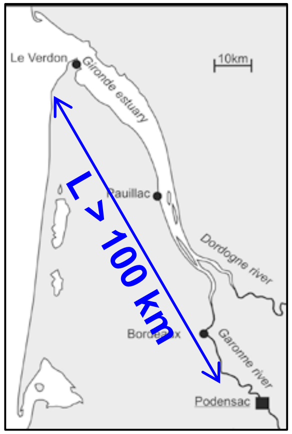
- tides: bores can occur in **long shallow alluvial estuaries**

  $L \approx 100$ km $D_0 \approx 10$ m



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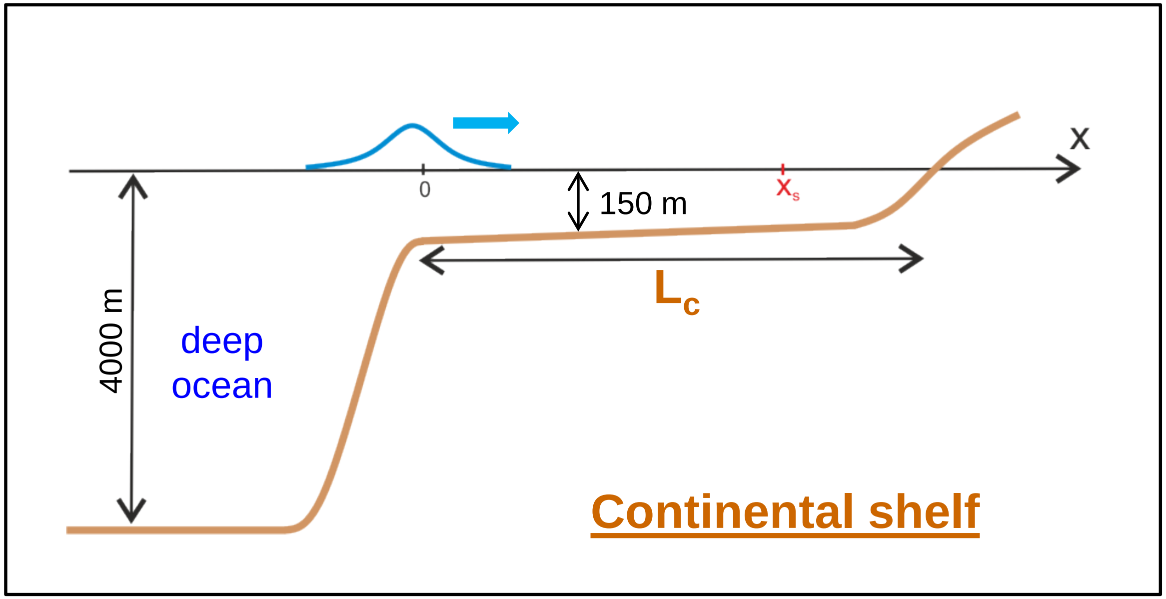

$$h(x_0, t=0) = D_0 + A_0(1 + \sin\frac{x_0}{L_{w0}})$$

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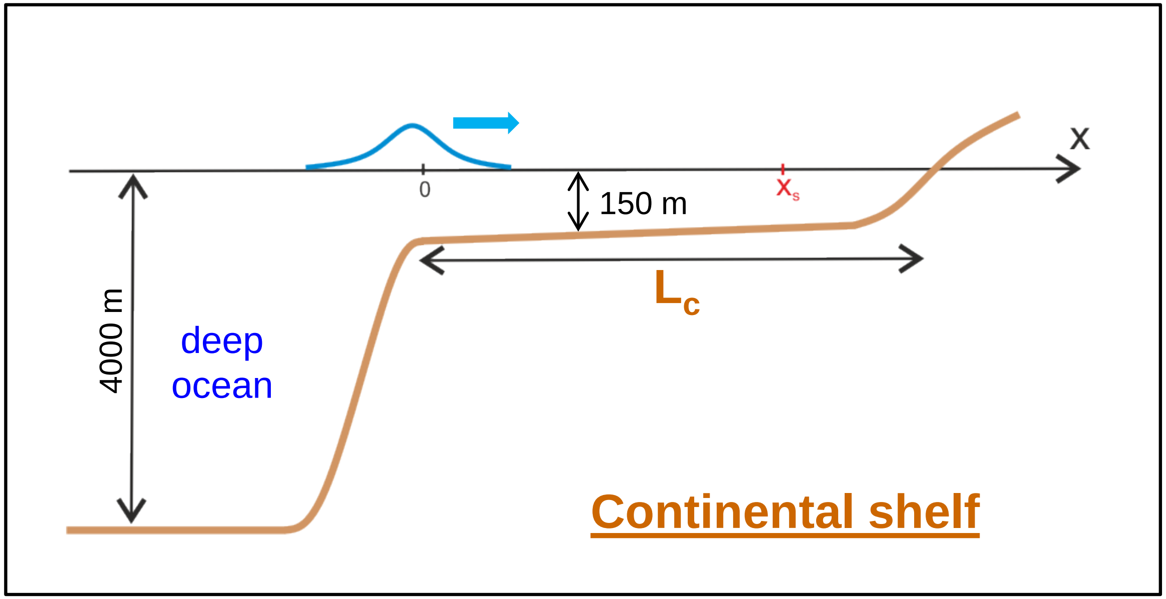
- <u>tides:</u> bores can occur in **long shallow alluvial estuaries**

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + C_{f0}\frac{|u|u}{D} = 0$$

$$\mathcal{D}_i \sim \frac{C_{f0}\frac{|u|u}{D}}{\frac{\partial u}{\partial t}} \sim C_{f0}\varepsilon_0\frac{L_{w0}}{D_0}$$

Basic conditions for bore formation



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- tides: bores can occur in **long shallow alluvial estuaries**

in such shallow environments friction plays a significant role

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  in the coastal zone
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  in estuaries
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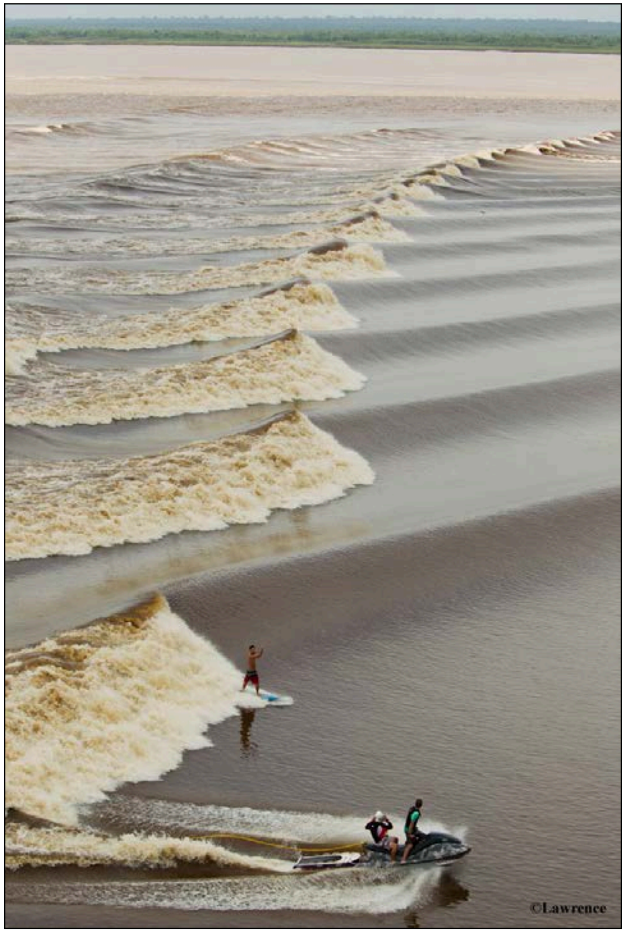
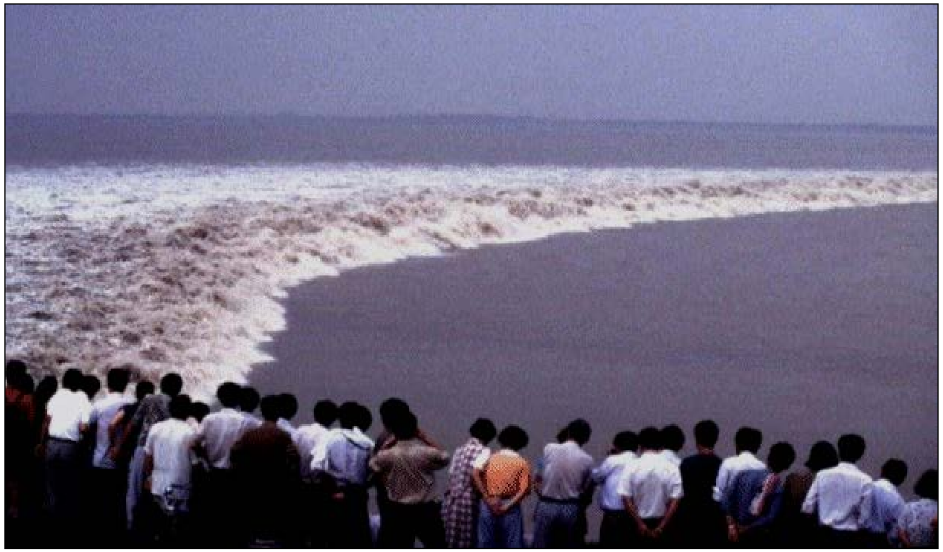
Severn River - England

Amazon River – Brazil (Pororoca)



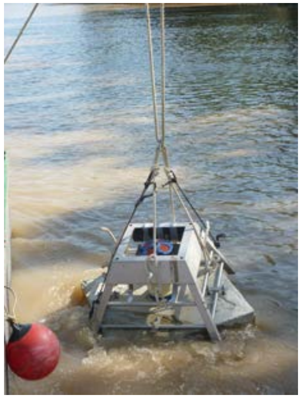
Kampar River – Sumatra (Bono)



Qiantang River – China

Gironde/Garonne/Dordogne estuary – France

3 field campaigns : a unique long-term high-frequency database



Bonneton et al. JGR 2015

Gironde/Garonne/Dordogne estuary – France

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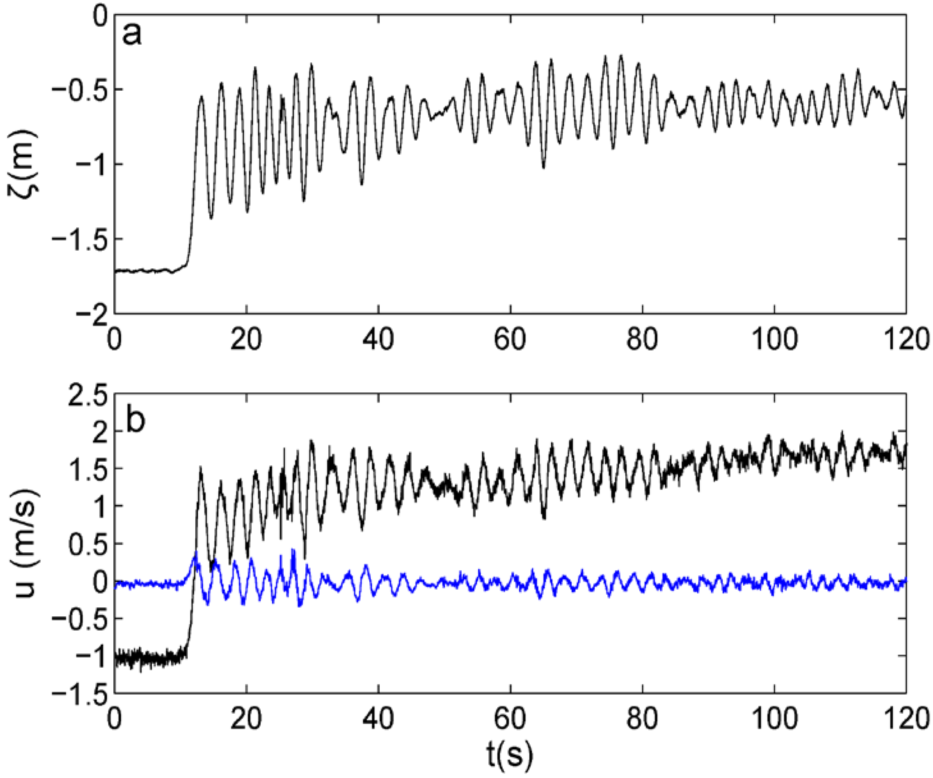


Bonneton et al. JGR 2015

- **Large tidal range** ($Tr_0=2A_0$) $\rightarrow$ Chanson (2012) : ~~$Tr_0 > 4.5\text{-}6$ m~~
- **Small water depth**
- **Large-scale funnel-shaped estuaries**

} coastal plain alluvial estuaries

$\Rightarrow$ Scaling analysis

- Tide propagation in convergent estuaries :

  Parker 1991, Lanzoni and Seminara 1998, Toffolon et al. 2006

- **First scaling analysis of the tidal bore problem**

- ❑ **Large tidal range**
- ❑ **Small water depth**
- ❑ **Large-scale funnel-shaped estuaries**

} coastal plain alluvial estuaries

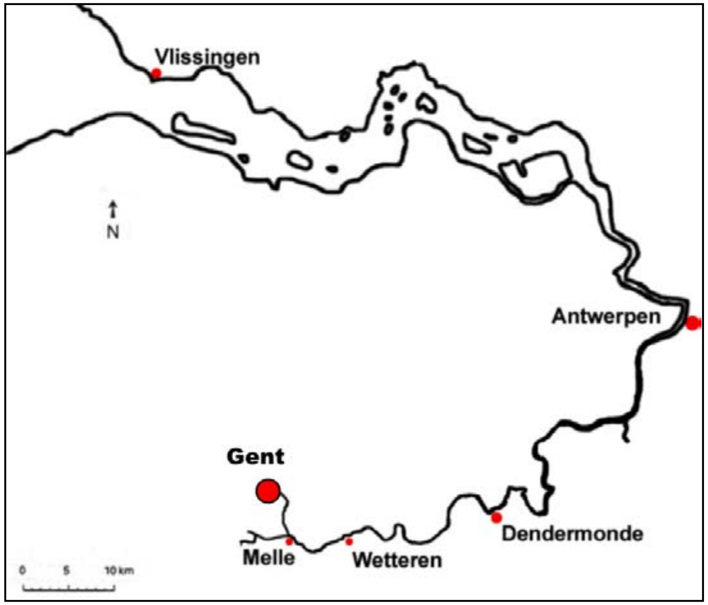
⇒ Scaling analysis

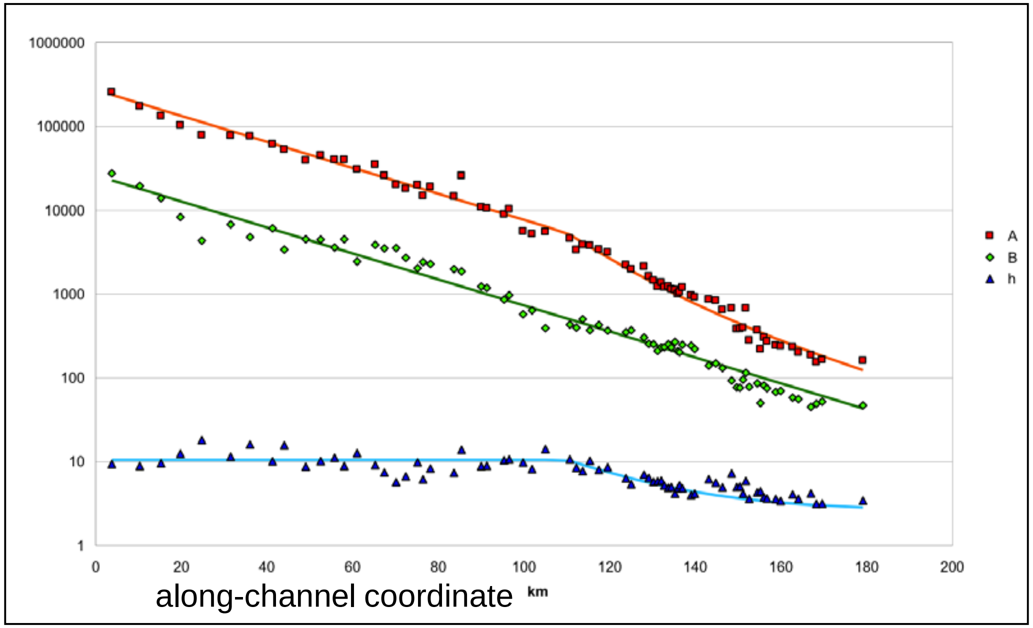
Identify the characteristic scales of the problem:

- **morphology of alluvial estuaries**
- **tidal wave forcing**

Tide-dominated alluvial estuaries show many morphological similarities all over the world

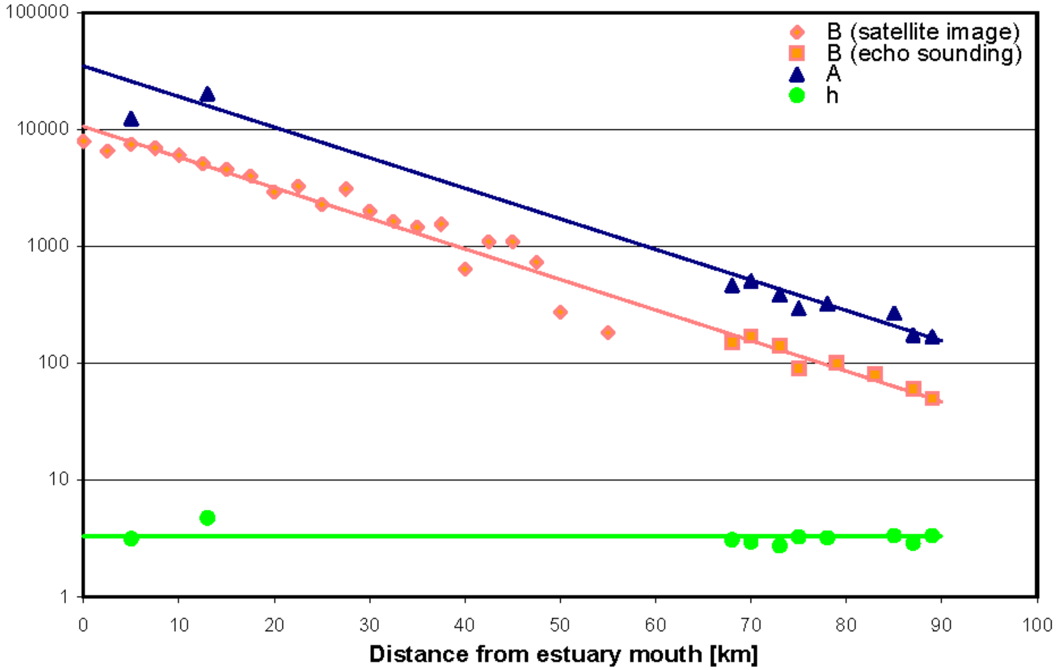
Scheldt estuary





Savenije 2012

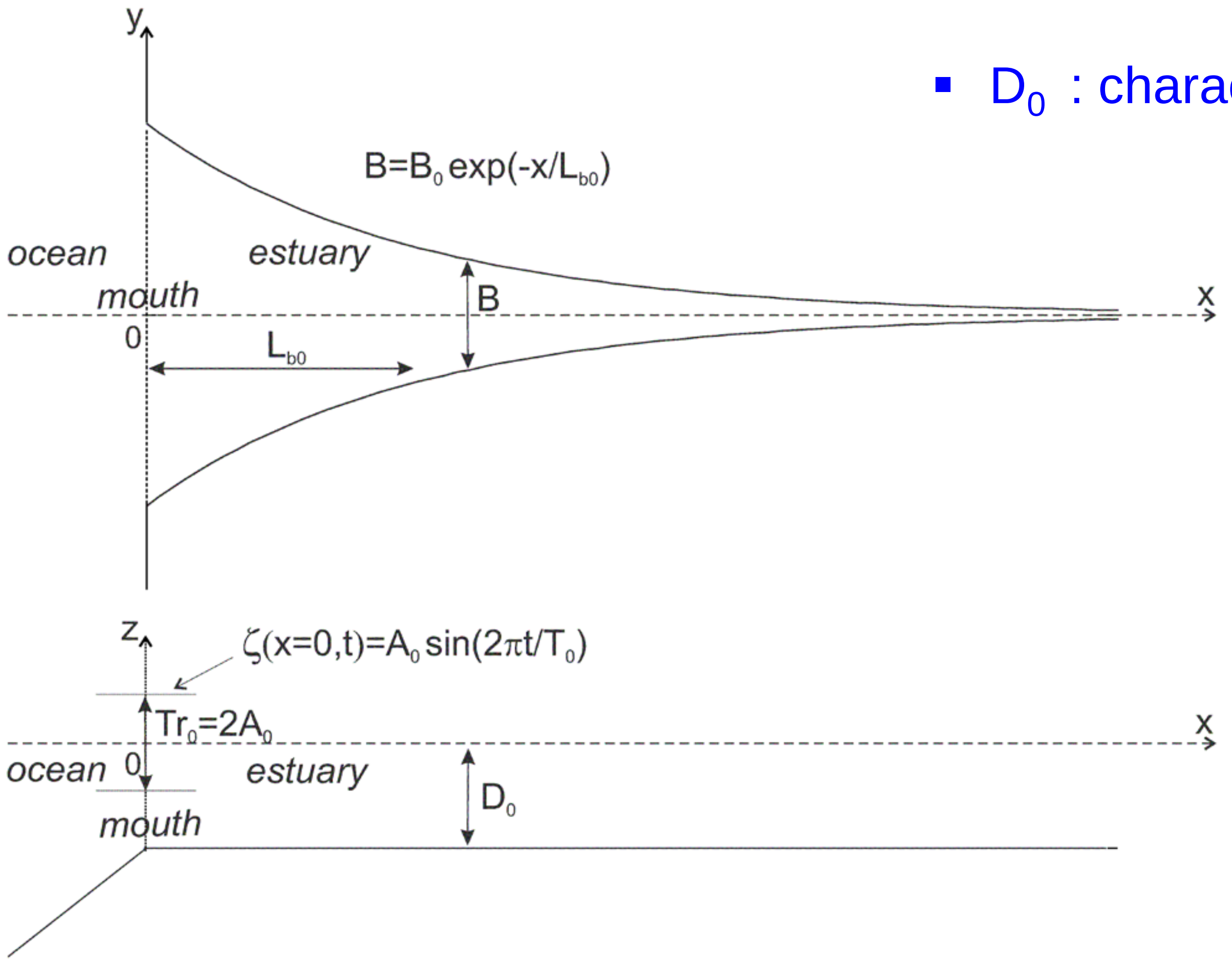
Pungue estuary



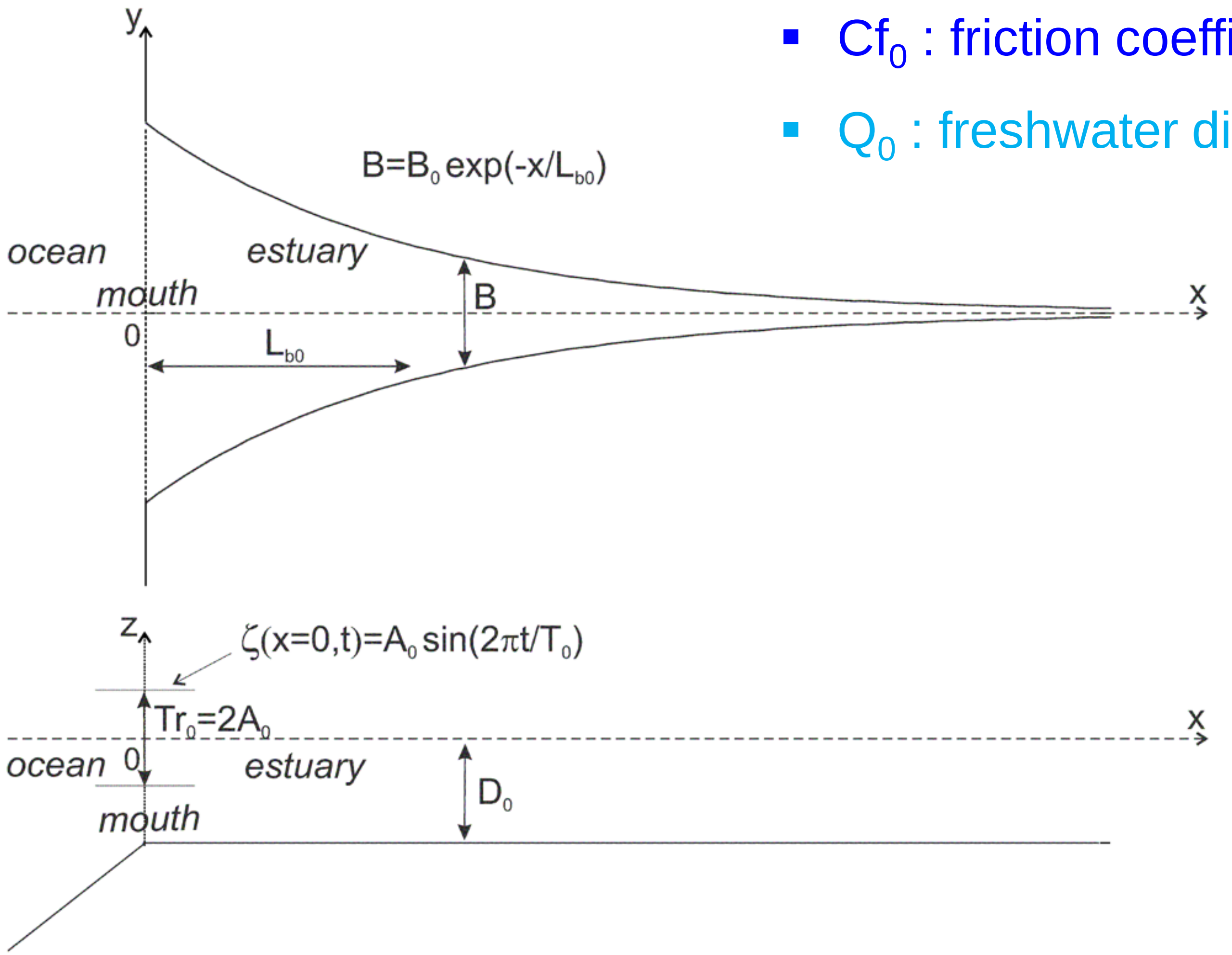
Graas et al. 2008

$$B = B_0 e^{-x/L_{B0}}$$

- L_{b0} : convergence length
- D_0 : characteristic water depth



- $A_0 = Tr_0/2$ (mean spring tidal amplitude)
- $T_0 = 12.4$ h $\rightarrow$ $L_{w0} = \sqrt{gD_0}/\omega_0$
- Cf_0 : friction coefficient
- Q_0 : freshwater discharge



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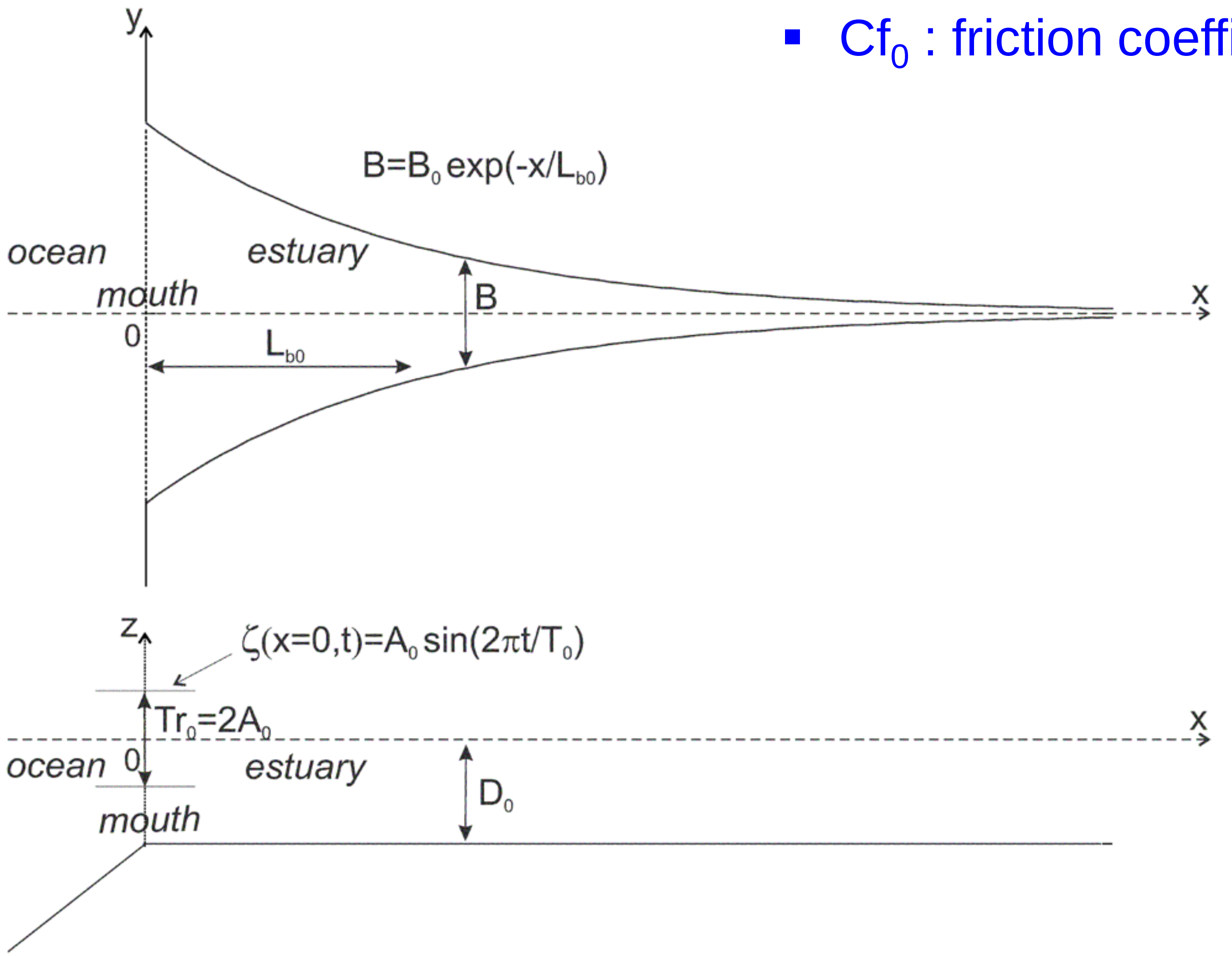
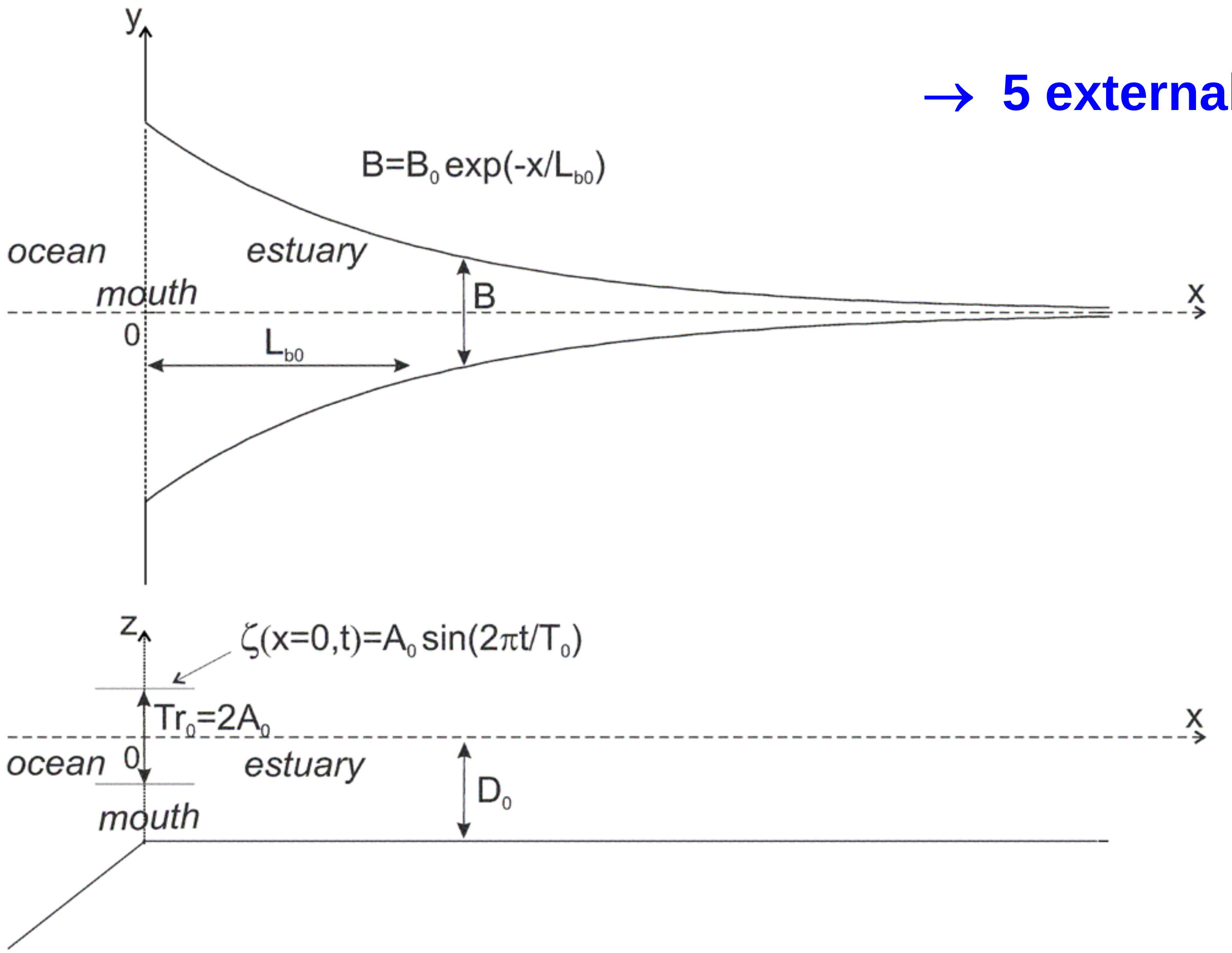


- L_{b0}
- D_0
- A_0
- L_{w0}
- Cf_0

→ **5 external variables**



$$\frac{\partial \zeta}{\partial t} + u\frac{\partial \zeta}{\partial x} + D\frac{\partial u}{\partial x} + \frac{u}{B}\frac{\partial \mathcal{A}}{\partial x})_{z=\zeta} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + C_{f0}\frac{|u|u}{D} = 0$$

$$B = B_0 \exp(-\frac{x}{L_{b0}})$$

$$\frac{1}{B}\frac{\partial \mathcal{A}}{\partial x})_{z=\zeta} = -\frac{D}{L_{b0}}$$

$$
\begin{aligned}
\frac{\partial \zeta}{\partial t} + u\frac{\partial \zeta}{\partial x} + D\frac{\partial u}{\partial x} + \frac{u}{B}\frac{\partial \mathcal{A}}{\partial x})_{z=\zeta} &= 0 \\
\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + C_{f0}\frac{|u|u}{D} &= 0
\end{aligned}
$$

$$B = B_0 \exp(-\frac{x}{L_{b0}}) \qquad \frac{1}{B}\frac{\partial \mathcal{A}}{\partial x})_{z=\zeta} = -\frac{D}{L_{b0}}$$

$$t' = \frac{t}{T_0/2\pi}, \quad D' = \frac{D}{D_0}, \quad \zeta' = \frac{\zeta}{A_0}, \quad x' = \frac{x}{L_0}, \quad u' = \frac{u}{U_0}\,.$$

$$\frac{\partial \zeta}{\partial t} + \mu\lambda\left(\epsilon_0 u \frac{\partial \zeta}{\partial x} + D\frac{\partial u}{\partial x}\right) - \mu\delta_0 uD = 0$$

$$\frac{\partial u}{\partial t} + \mu\lambda\epsilon_0 u \frac{\partial u}{\partial x} + \frac{\lambda}{\mu}\frac{\partial \zeta}{\partial x} + \underbrace{\mu\varepsilon_0\phi_0}_{\mathcal{D}_i}\frac{|u|u}{D} = 0$$

$$\epsilon_0 = \frac{A_0}{D_0} \qquad \delta_0 = \frac{L_{w0}}{L_{b0}} \qquad \phi_0 = \frac{C_{f0}L_{w0}}{D_0}$$

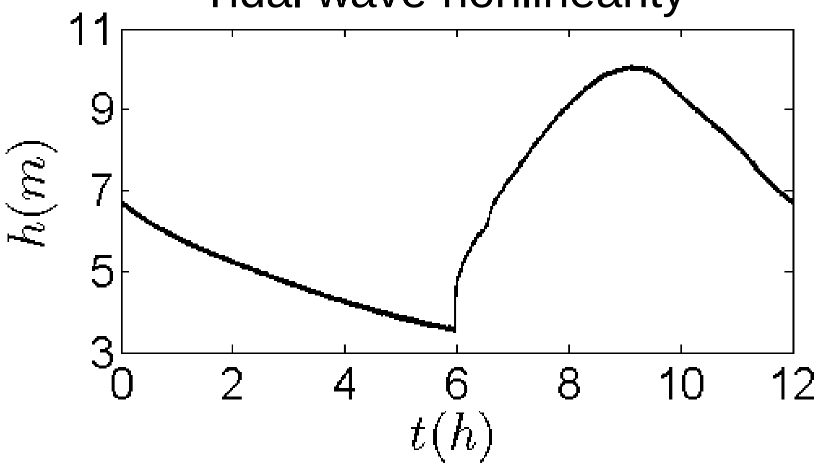
$$L_{w0} = (gD_0)^{1/2}\omega_0^{-1}$$

$$\mu = \frac{U_0}{\varepsilon_0 (gD_0)^{1/2}} \qquad \lambda = \frac{L_{w0}}{L_0}$$

$$\frac{\partial \zeta}{\partial t} + \mu\lambda\left(\epsilon_0 u \frac{\partial \zeta}{\partial x} + D\frac{\partial u}{\partial x}\right) - \mu\delta_0 u D = 0$$

$$\frac{\partial u}{\partial t} + \mu\lambda\epsilon_0 u \frac{\partial u}{\partial x} + \frac{\lambda}{\mu}\frac{\partial \zeta}{\partial x} + \underbrace{\mu\varepsilon_0\phi_0}_{\mathcal{D}_i}\frac{|u|u}{D} = 0$$

Tidal wave nonlinearity



$D_i > 1.5$

Bonneton et al., JGR 2015

→ necessary condition for tidal bore formation by not a sufficient one

$$\frac{\partial \zeta}{\partial t} + \mu\lambda\left(\epsilon_0 u \frac{\partial \zeta}{\partial x} + D\frac{\partial u}{\partial x}\right) - \mu\delta_0 uD = 0$$

$$\frac{\partial u}{\partial t} + \mu\lambda\epsilon_0 u \frac{\partial u}{\partial x} + \frac{\lambda}{\mu}\frac{\partial \zeta}{\partial x} + \underbrace{\mu\varepsilon_0\phi_0}_{\mathcal{D}_i}\frac{|u|u}{D} = 0$$

→ **explore the 3D dimensionless external parameter space: (ε_0 , δ_0 , ϕ_0)**

- Field data: 21 convergent alluvial estuaries

  Bonneton, P., Filippini, A.G., Arpaia, L., Bonneton, N. and Ricchiuto, M 2016.
  Conditions for tidal bore formation in convergent alluvial estuaries. *ECSS,* **172**, 121-127

- Numerical simulations: 225 runs of a Serre/Green Naghdi model

  Filippini, A.G., Arpaia, L., Bonneton, P., and Ricchiuto, M. 2017.
  Modelling analysis of tidal bore formation in convergent estuaries. in press EJM/B Fluids

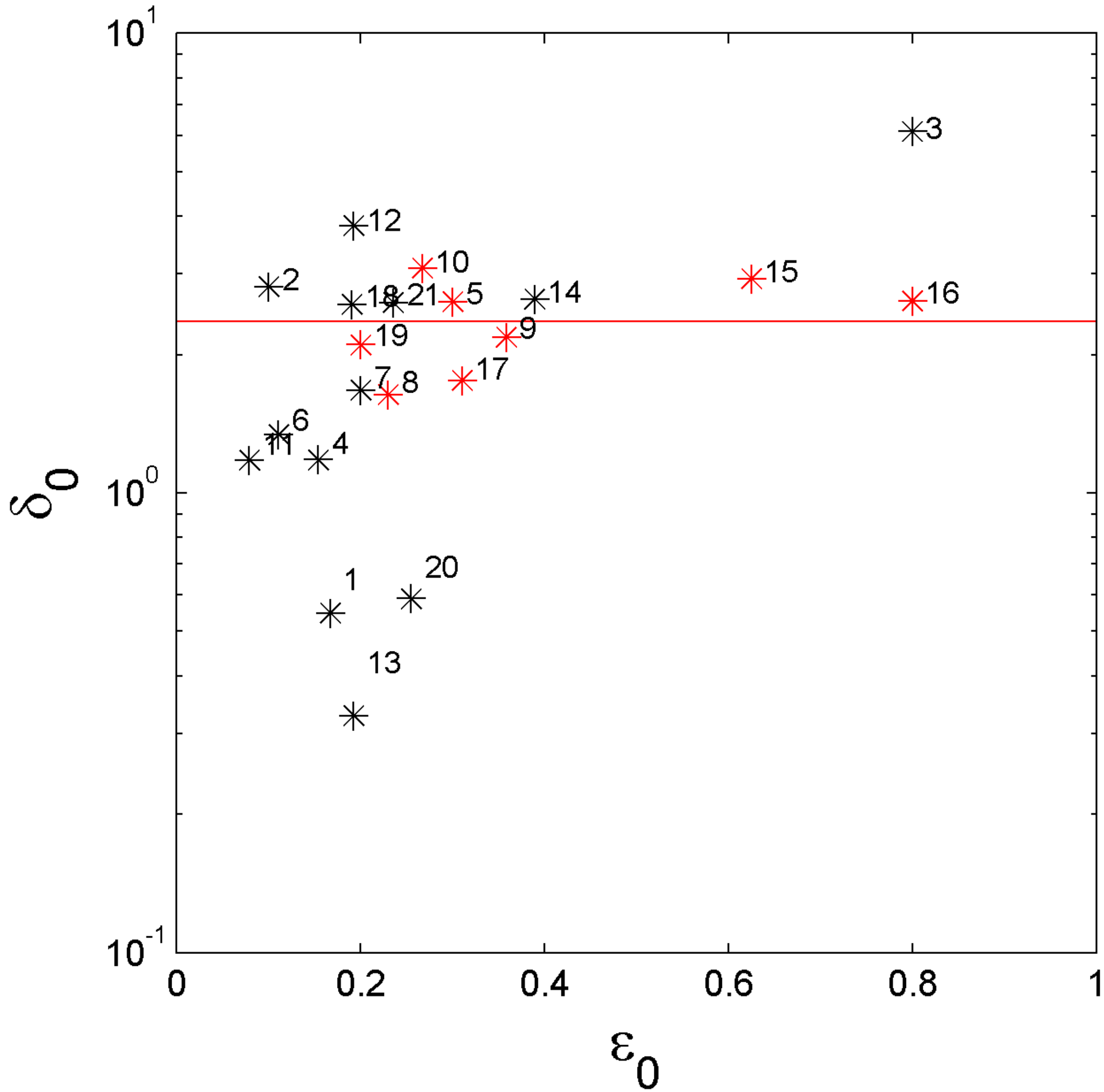
Conditions for tidal bore formation | Field data

1	Chao Phya	Thailand
2	Columbia	USA
3	Conwy	UK
4	Corantijn	USA
5	Daly	Australia
6	Delaware	USA
7	Elbe	Germany
8	Gironde	France
9	Hooghly	India
10	Humber	UK
11	Limpopo	Mozambique
12	Loire	France
13	Mae Klong	Thailand
14	Maputo	Mozambique
15	Ord	Australia
16	Pungue	Mozambique
17	Qiantang	China
18	Scheldt	Netherlands
19	Severn	UK
20	Tha Chin	Thailand
21	Thames	UK

- 21 convergent alluvial estuaries
- 8 tidal bore estuaries

D_0, L_{b0}, $A_0 = Tr_0/2$, Cf_0

Conditions for tidal bore formation | Field data



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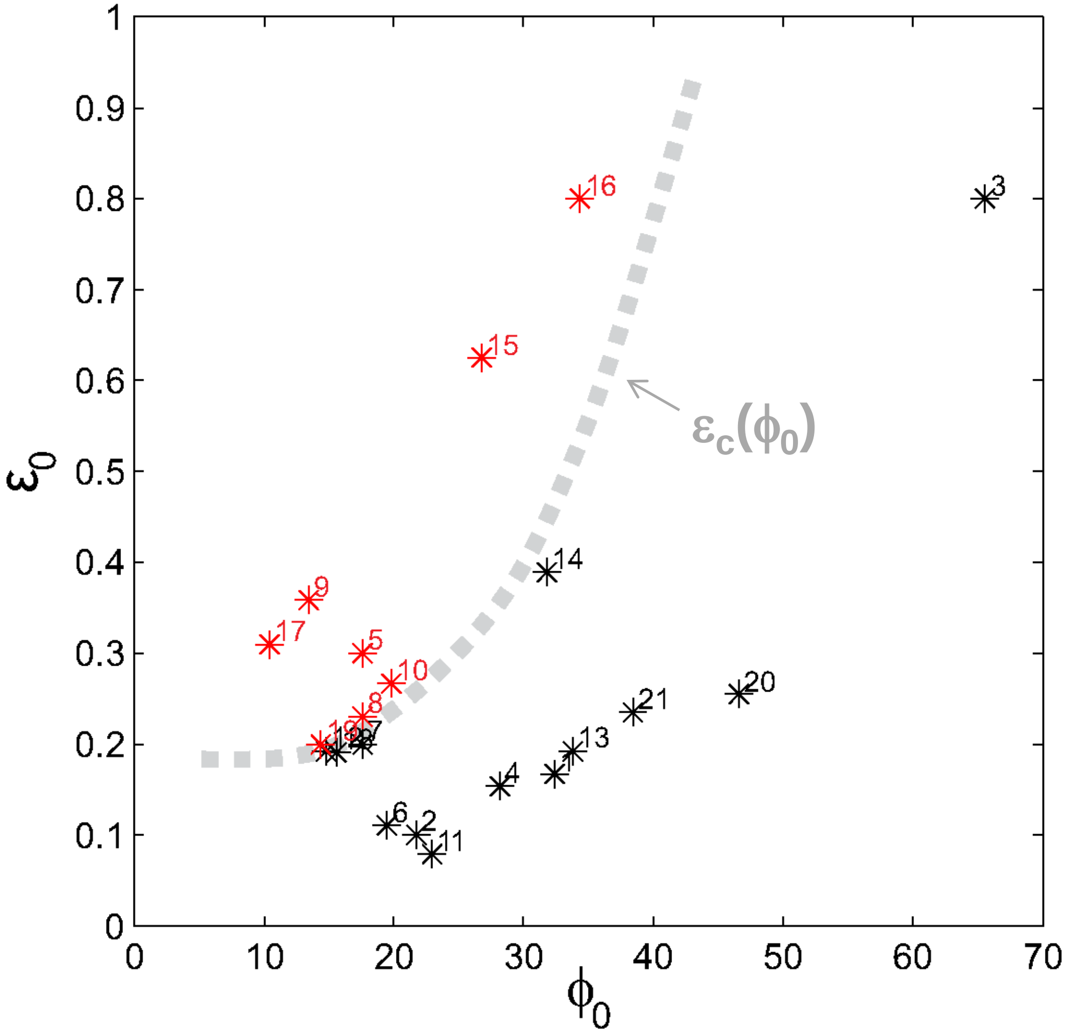
Tidal bore estuaries: $\delta_0 \approx 2.4 \rightarrow$ 2D parameter space (ε_0 , ϕ_0)

Conditions for tidal bore formation — Field data



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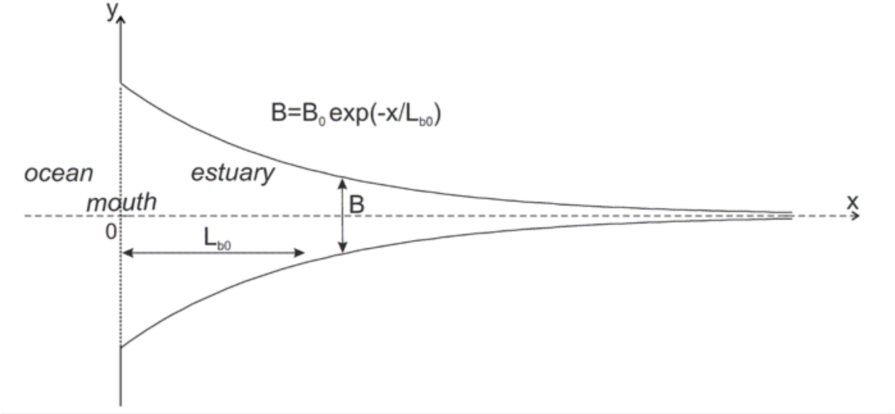
Tidal bores occur when $\varepsilon_0 > \varepsilon_c(\phi_0)$

Numerical investigation of the 2D parameter space (ε_0 , ϕ_0)

Filippini, A.G., Arpaia, L., Bonneton, P., and Ricchiuto, M., EJM-B / Fluids, 2017

- Idealized convergent estuaries



- fully nonlinear weakly dispersive Boussinesq type equations:
  Serre/Green Naghdi equations

$$\partial_t \zeta + \nabla \cdot (h\mathbf{u}) = 0$$

$$\partial_t (h\mathbf{u}) + \nabla \cdot (h\mathbf{u} \otimes \mathbf{u}) + gh\nabla\zeta + C_{f0}\|\mathbf{u}\|\mathbf{u} = \underbrace{(I + \alpha\tau)^{-1}[\tau(gh\nabla\zeta) - Q(\mathbf{u})]}_{\psi}$$

Numerical investigation of the 2D parameter space (ε_0 , ϕ_0)

Filippini, A.G., Arpaia, L., Bonneton, P., and Ricchiuto, M., EJM-B / Fluids, 2017

Hybrid FV/FE scheme

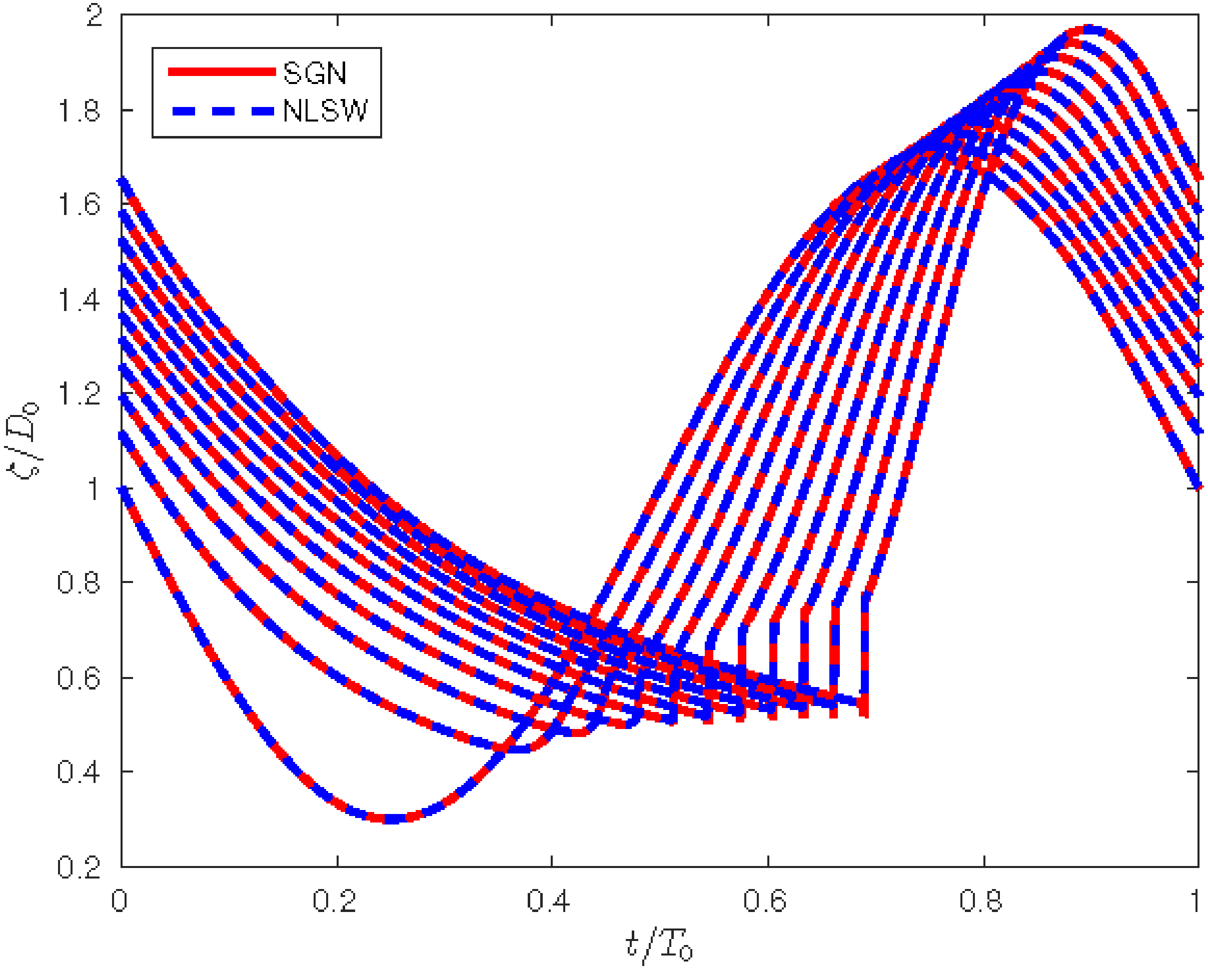
$$
\begin{aligned}
\partial_t \zeta + \nabla \cdot (h\mathbf{u}) &= 0 \\
\partial_t (h\mathbf{u}) + \nabla \cdot (h\mathbf{u} \otimes \mathbf{u}) + gh\nabla\zeta + C_{f0}\|\mathbf{u}\|\mathbf{u} &= \psi
\end{aligned}
$$

→ hyperbolic step
3rd order upwind MUSCL

$$
(I + \alpha\tau)\psi - \tau(gh\nabla\zeta) + Q(\mathbf{u}) = 0
$$

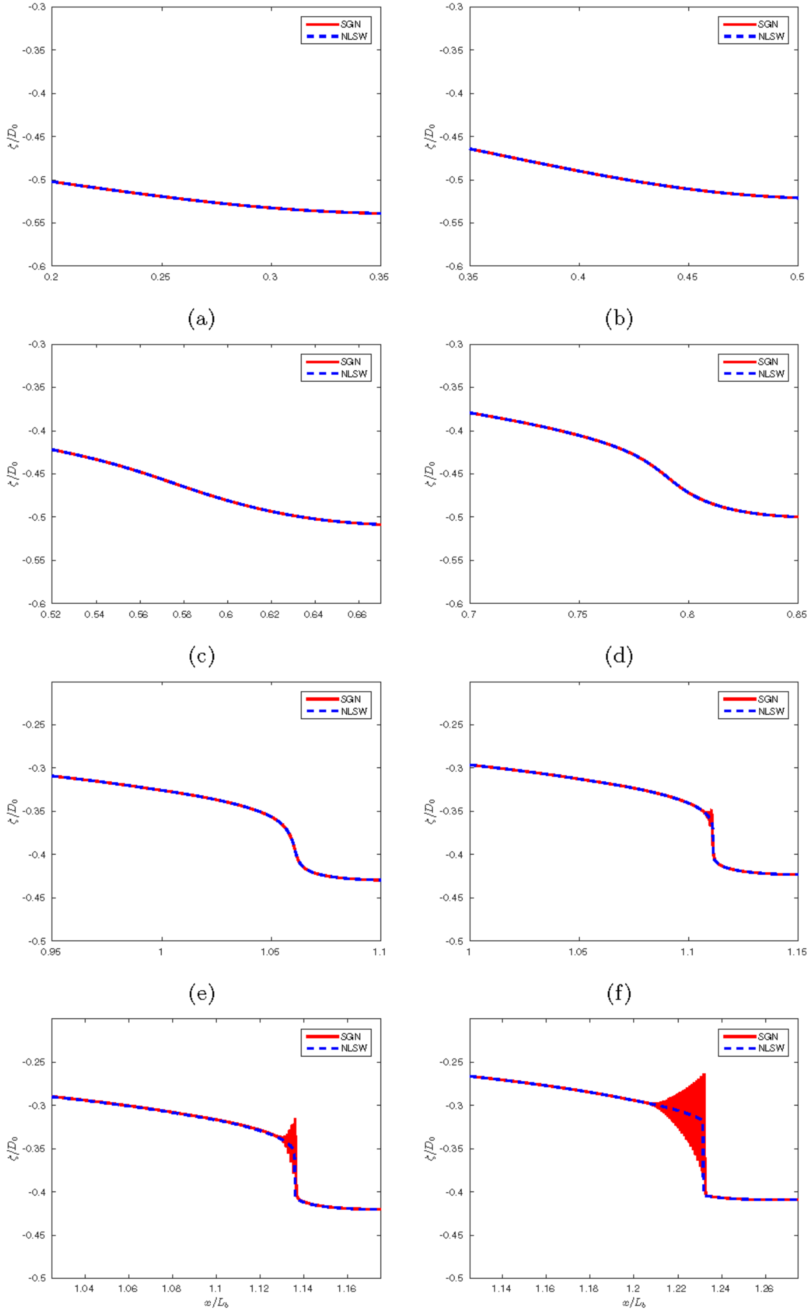
→ elliptic step
2nd order continuous FE

SGN / NLSW

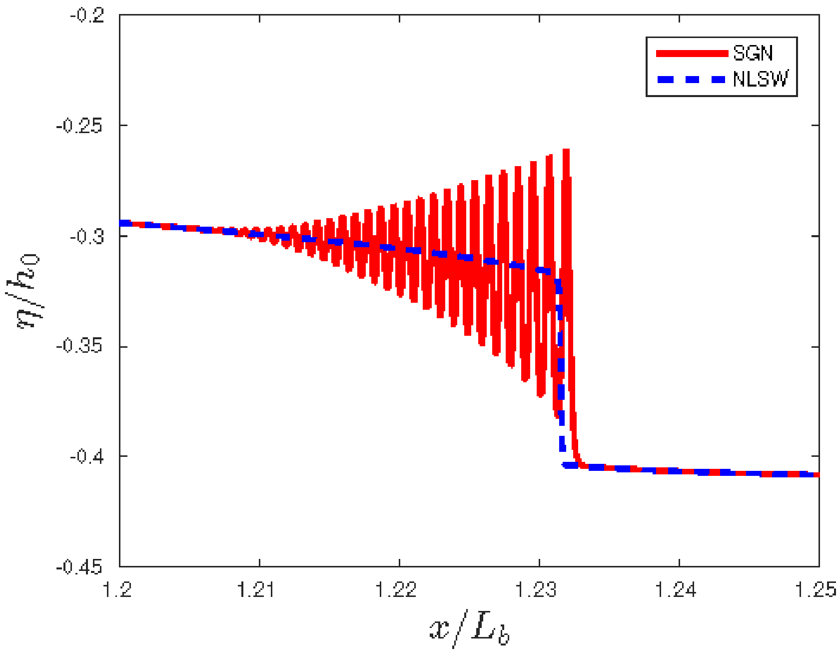


ε_0 =0.7, ϕ_0 = 10

Filippini et al. 2017



SGN / NLSW

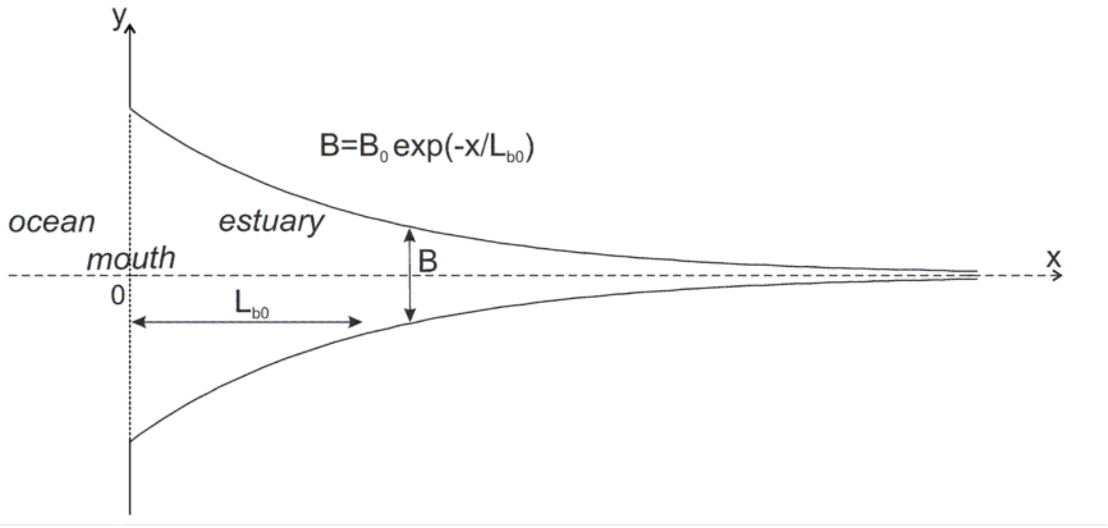


Filippini et al. 2017

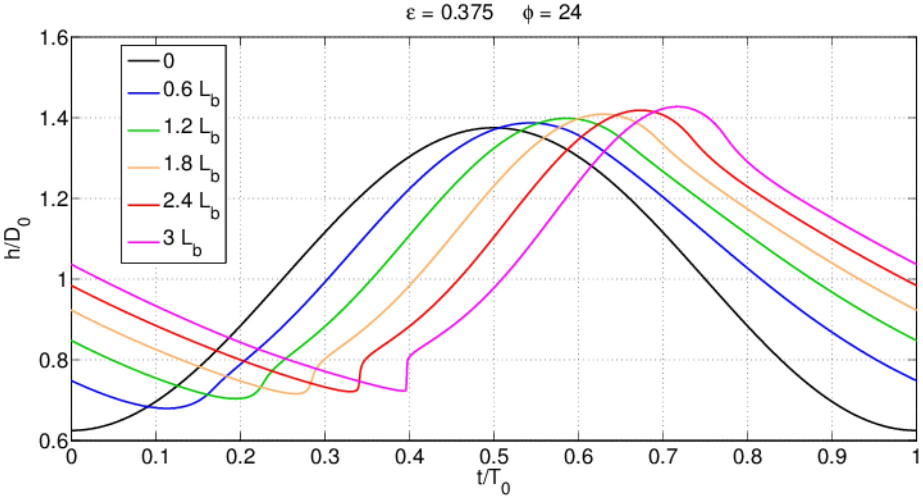
Numerical investigation of the 2D parameter space (ε_0 , ϕ_0)

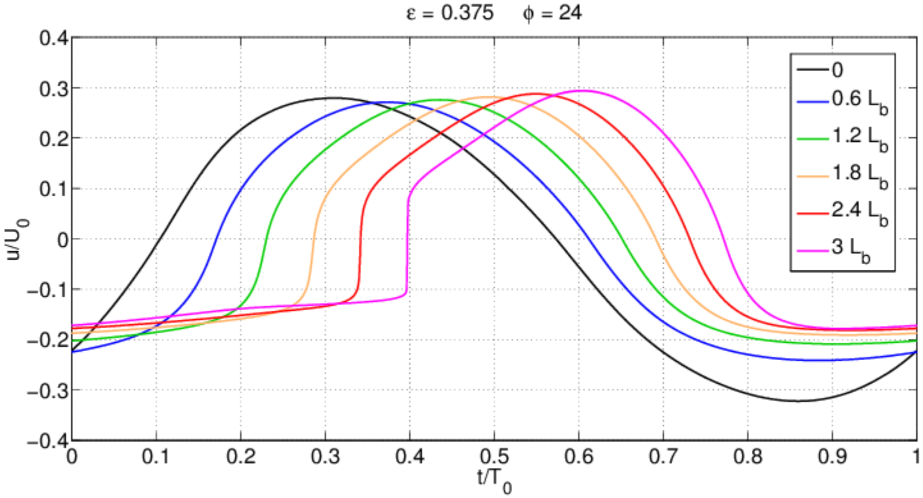
→ **model based on the NLSW equations**

→ **225 runs** with $\delta_0 = 2$



one example on the 225 runs





$$S_{max} = max\left(\frac{\partial \zeta}{\partial x}\right)$$

Filippini et al. 2017

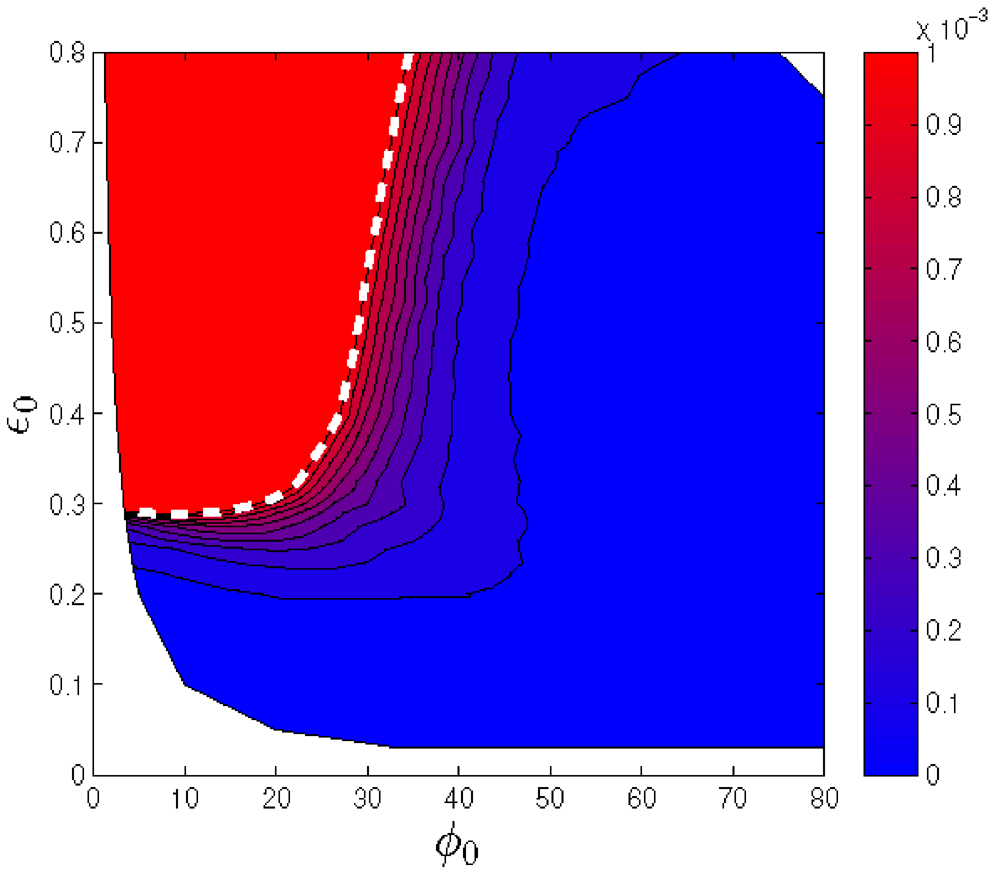
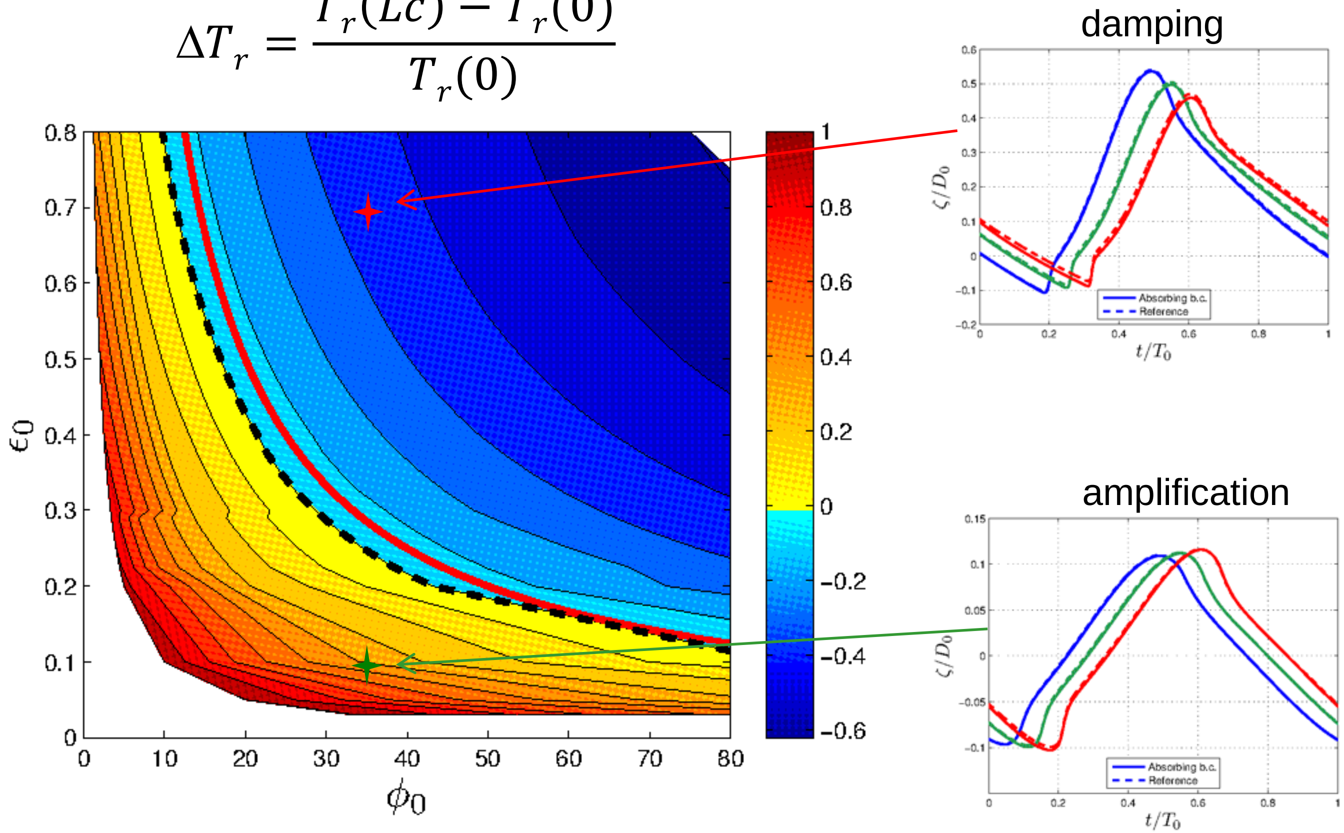


Figure 2: Isocurves of the quantity S_{max} in the plane of the parameters (ϕ_0, ϵ_0), the white dashed line represents the $\epsilon_c(\phi_0)$ curve, namely the limit for tidal bore appearance following the criterion $S_{max} \geq 10^{-3}$.

Filippini et al. 2017

rate of change of the tidal range

$$\Delta T_r = \frac{T_r(Lc) - T_r(0)}{T_r(0)}$$

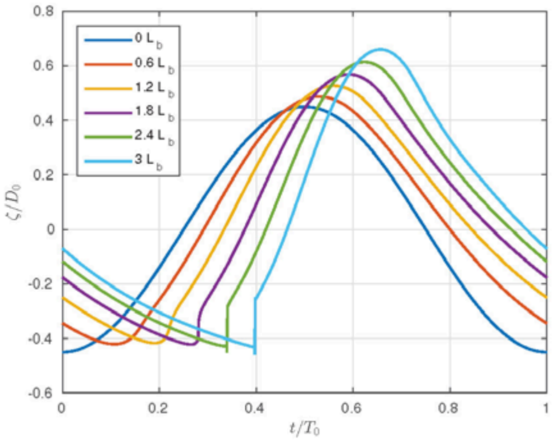


Theoretical zero-amplification curve:

$\varepsilon_0\phi_0 = \delta_0(\delta_0^2 + 1)$ *(Savenije et al. 2008)*

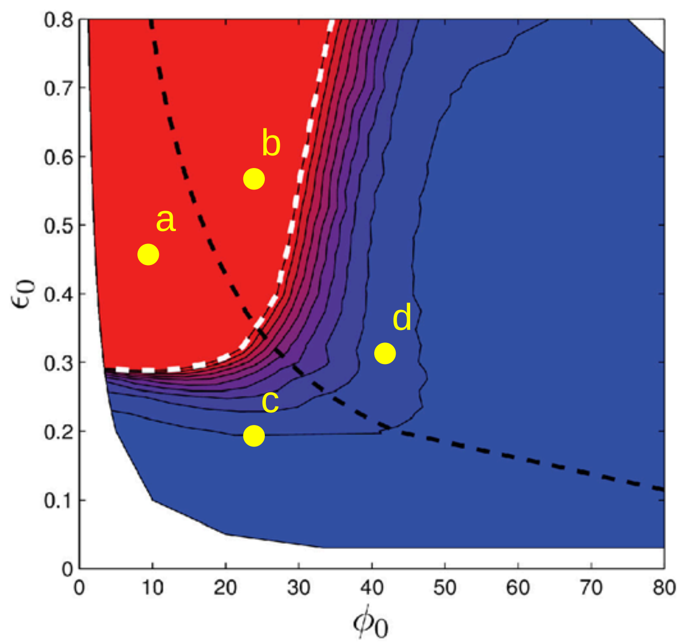
Filippini et al. 2017

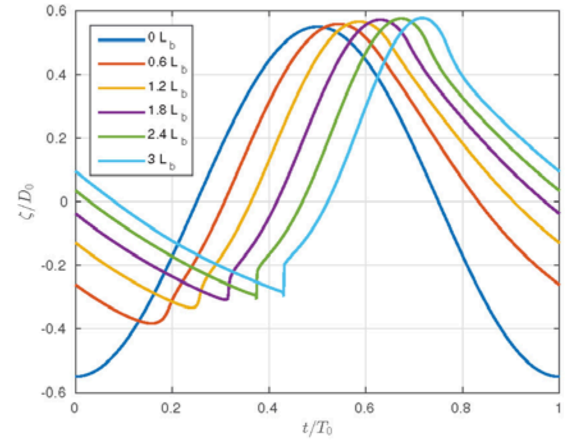
Conditions for tidal bore formation | Estuary classification



a) Tidal Bore + Tidal Range Amplification

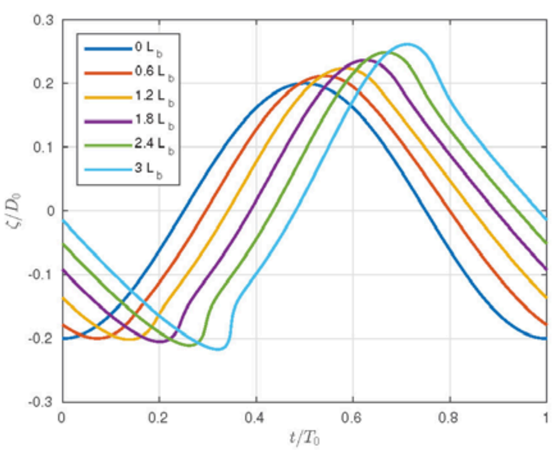
– Marginal Curve for tide amplification



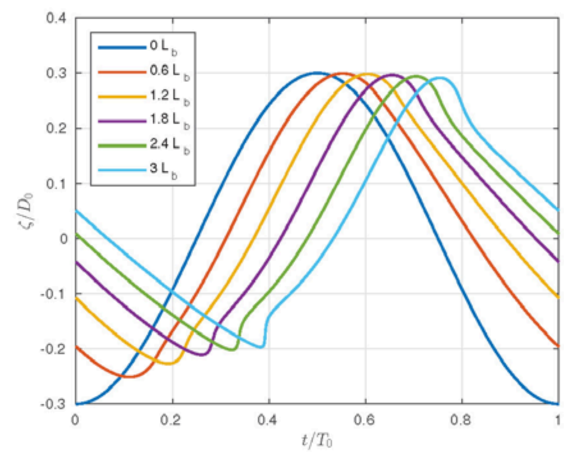


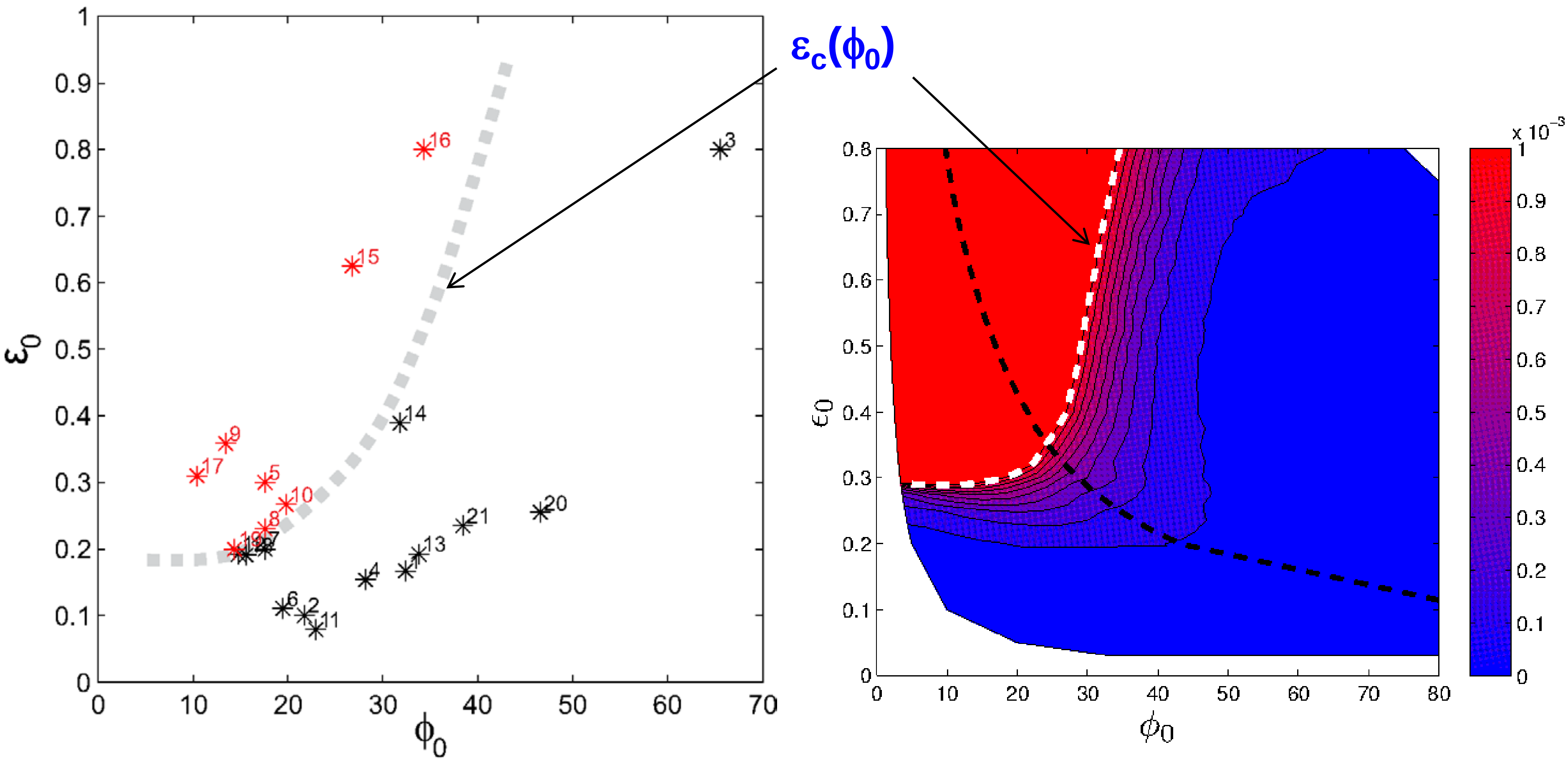
b) Tidal Bore + Tidal Range Damping

c) No Tidal Bore + Tidal Range Amplification



d) No Tidal Bore + Tidal Range Damping





Tidal bores occur when $\varepsilon_0 > \varepsilon_c(\phi_0)$

Conclusion

Criterion for the formation of tsunami-like bore

$$\delta_0 = \frac{L_{w0}}{L_c} < \frac{3}{2}\epsilon_0$$

tsunami bore

tidal bore

- <u>tsunamis:</u> bores may occur in large and shallow coastal environments

  → marine coastal plains with gentle slope (e.g.: deltas, alluvial estuaries)

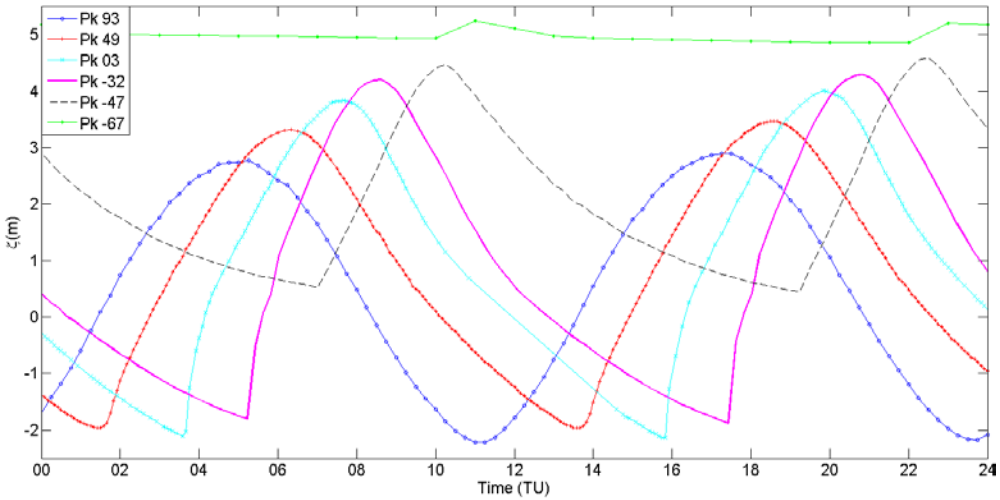
  → carbonate platforms (e.g.: coral reef systems)

- <u>tides:</u> bores may occur in long shallow alluvial estuaries

Conclusion

Conditions for tidal bore formation

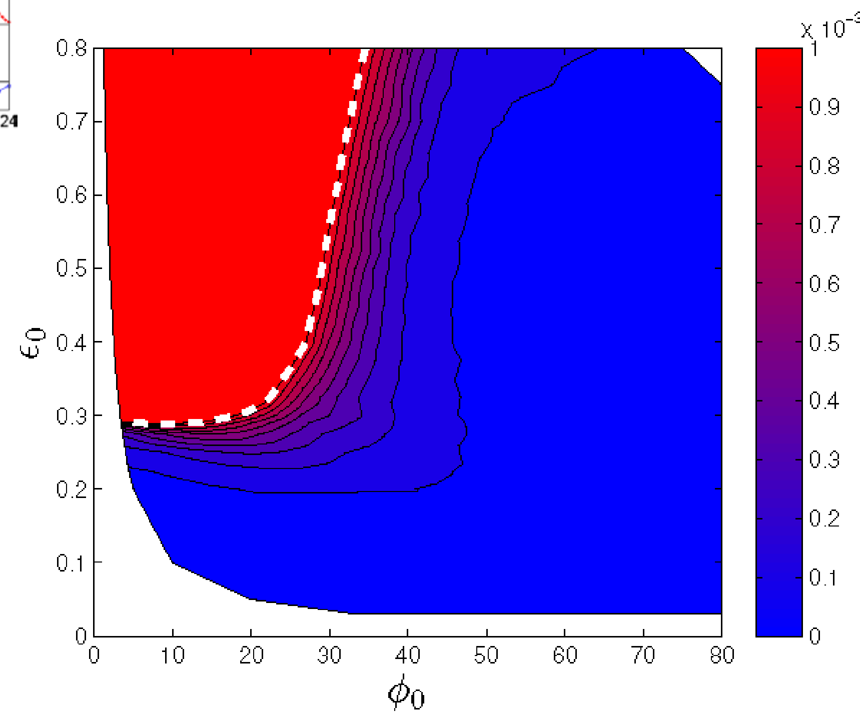
- nonlinear tidal wave transformation is mainly governed by the quadratic friction terms



$$\frac{\partial u}{\partial t} + \mu\lambda\epsilon_0 u\frac{\partial u}{\partial x} + \frac{\lambda}{\mu}\frac{\partial \zeta}{\partial x} + \underbrace{\mu\varepsilon_0\phi_0}_{\mathcal{D}_i}\frac{|u|u}{D} = 0$$

- Tidal bores occur when

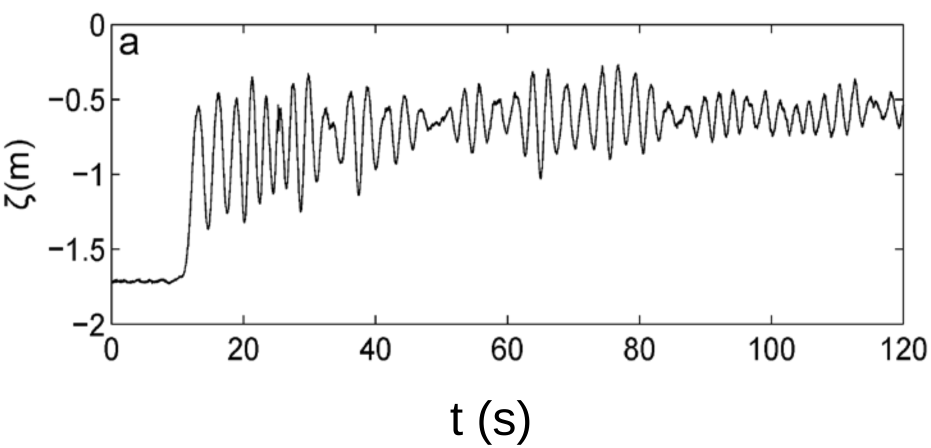
$$\varepsilon_0 > \varepsilon_c(\phi_0)$$

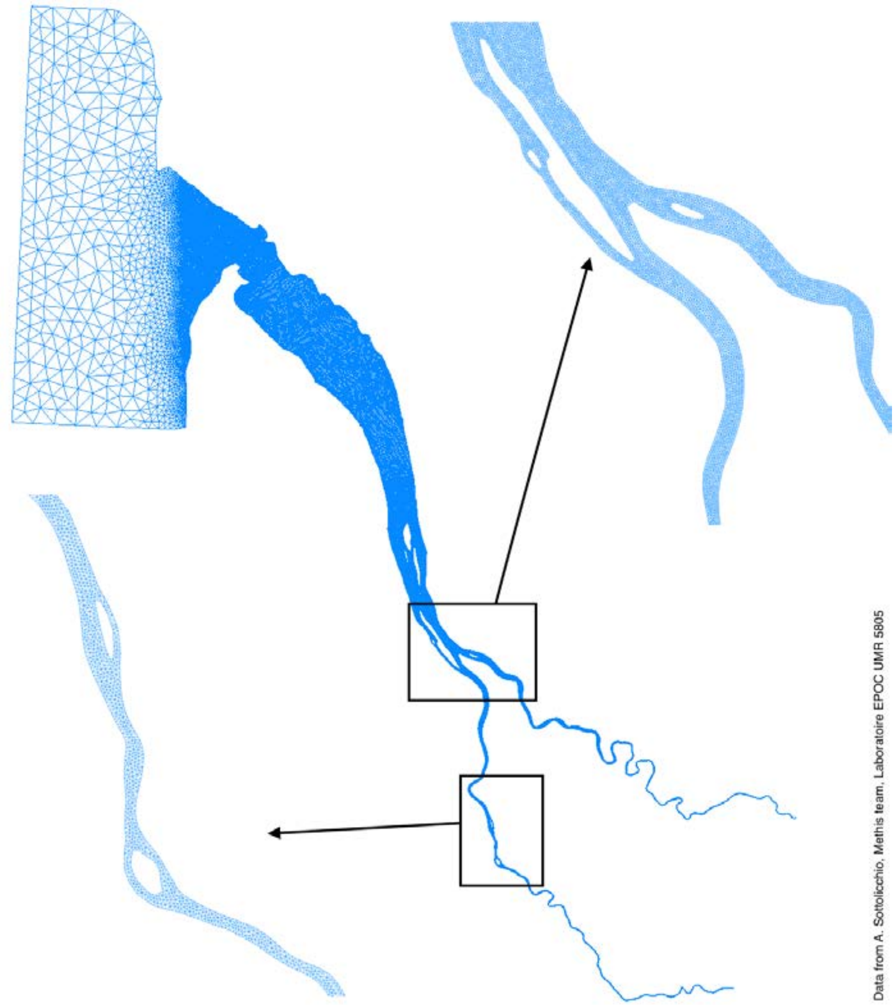


Perspectives

❑ Modelling bore formation from large to small scales using SGN equations

$\rightarrow$ application to tidal bores in the Gironde/Garonne estuary





Data from A. Sottolicchio, Methis team, Laboratoire EPOC UMR 5805

Thank you for your attention