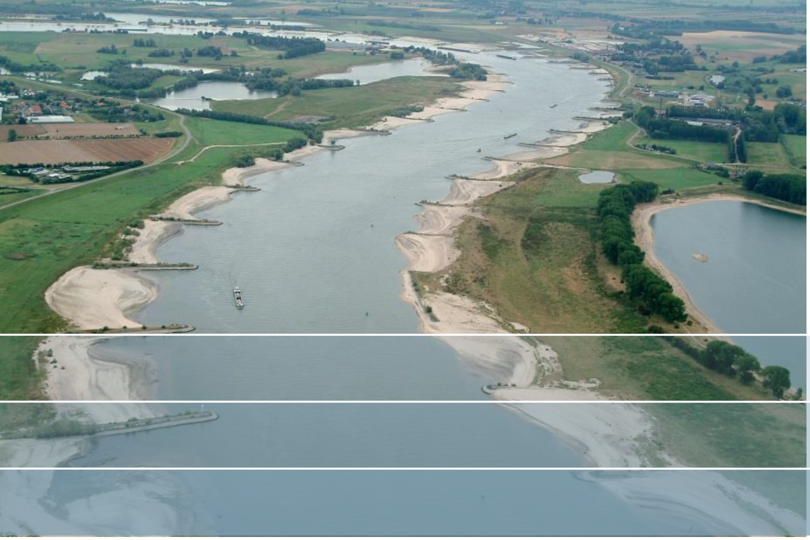

Deltares

Enabling Delta Life

Morphological model of the River Rhine branches in The Netherlands

from the concept to the operational model

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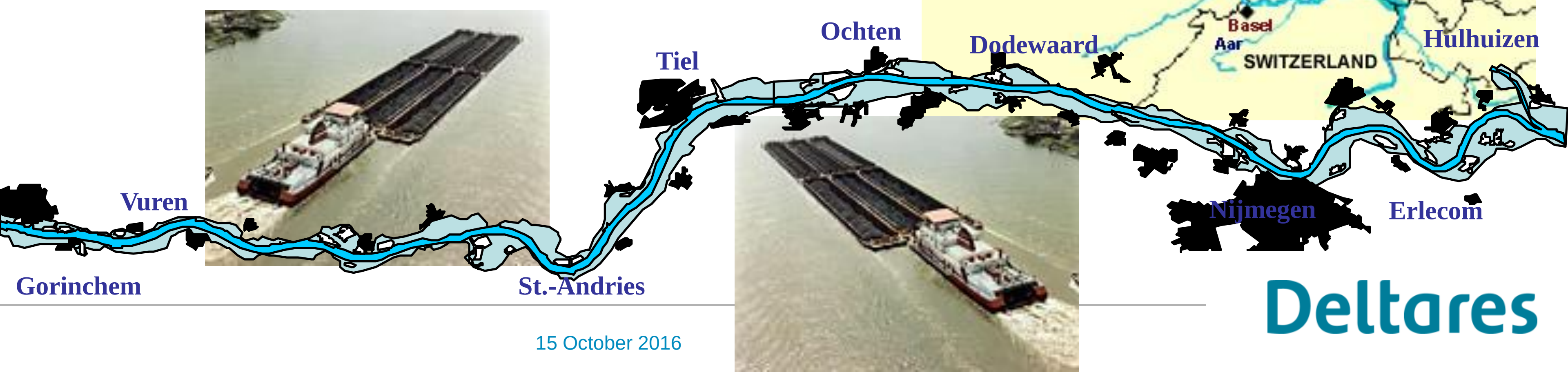
Wednesday, 12 October 2016

Motivation

- The Rhine River is considered the backbone of the Northwest European waterways network.
- Efforts are made to maintain and improve the navigation channel.
- A need for a tool that enables:
  - analysis of historical trends,
  - prediction of future trends,
  - evaluating different measures

➔ a **numerical model**,
that is **accurate** and (**fast**)



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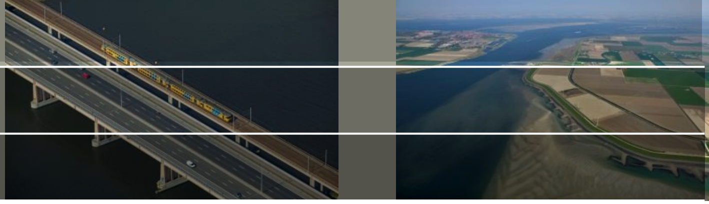
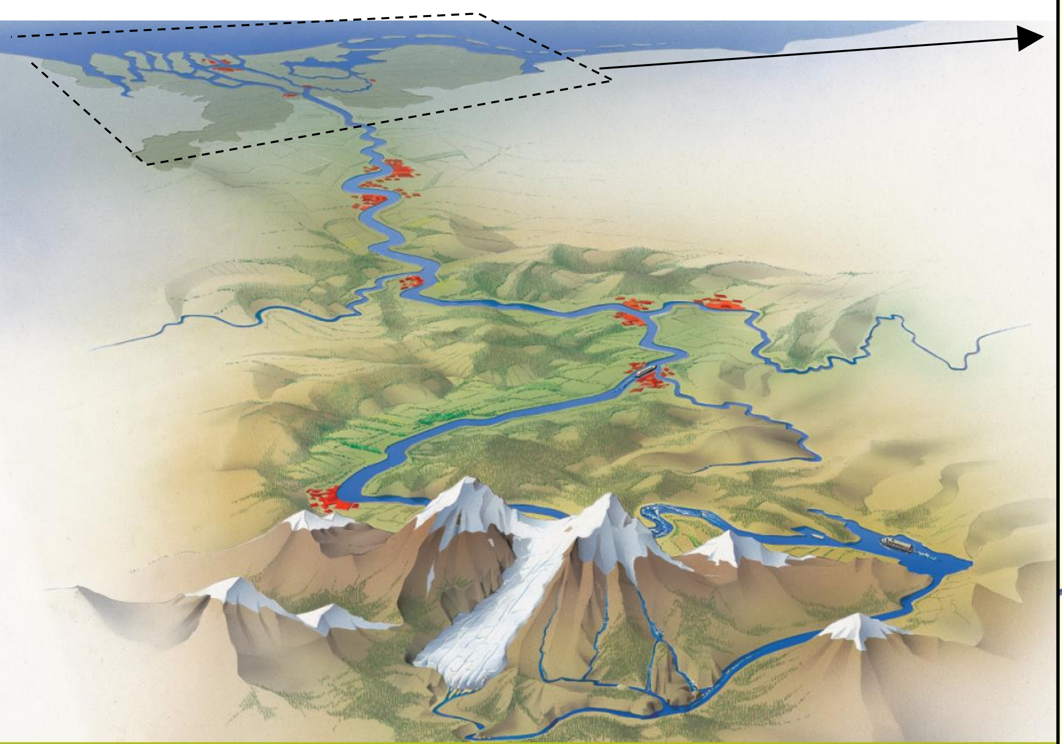
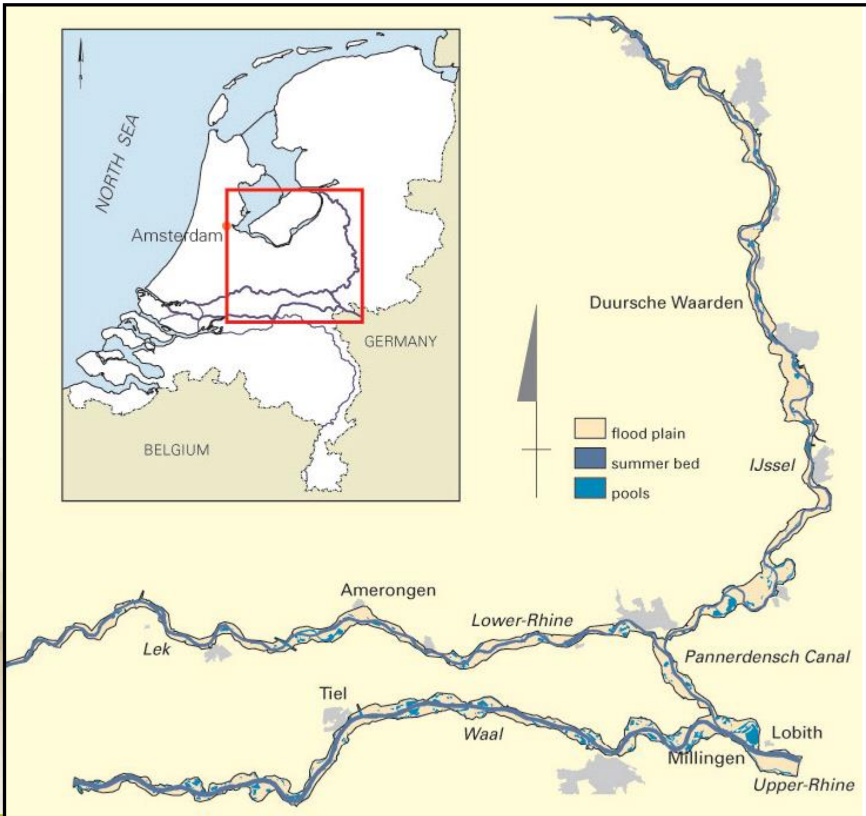


DVR

- Client: Rijkswaterstaat Oost-Nederland: **the river manager**
- Target: maintain a sustainable navigation channel NL+D.
- The project is called “**D**uurzame **V**aardiepte **R**ijndelta”
  (*Sustainable Navigation Channel Rhine delta*)

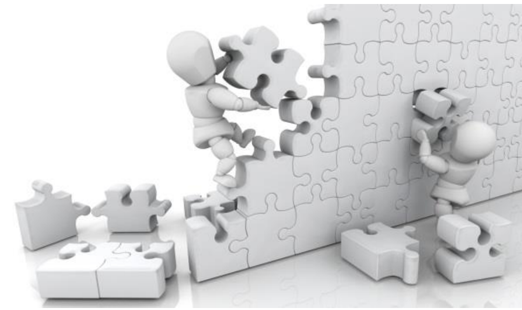




Outline

Construction

- Grids
- Schematization
- Time management
- Dredging



Calibration

- Hydrodynamics
- Morphology
- Dredging

Application

- Effect of longitudinal dams
- Dredging the navigation channel
- Sediment nourishment experiment

Project phases

- **Phase 1 (2005**)
  - **Model construction**
  - Development, implementation and testing of innovative aspects
- **Phase 2 (2006)**
  - Primary calibration
  - Case studies
- **Phase 3 (2007**)
  - Model operationalization: **Calibration & optimise for speed**

Initial phase

- **Phase 4 (2008)**
  - The operational model → further improvements
  - Testing measures (by different consultants)
- **2009**
  - Extension to **complete all branches**
  - Testing measures (different consultants, supported by Deltares)
- **2010**
  - update of the model (extend the hydrograph)
  - Testing several measures (different consultants , supported by Deltares)
- **2011**
  - Testing measures (different consultants , supported by Deltares)
- **2012-2014**
  - Improvements and Application to give advice (Deltares & different consultants)
- **2015**
  - Extension to **graded sediment** and nourishment testing (Deltares)
- **2016-2017**
  - **Migration to flexible mesh**

Model Construction

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Model construction → Extent

The model is around **360 km long**, covering:

Bovenrijn

km 853-867 (Emmerich – Pannerdensche Kop)

Waal

km 867-953 (Pannerdensche Kop –Werkendam)

Pannerdensche Kanaal

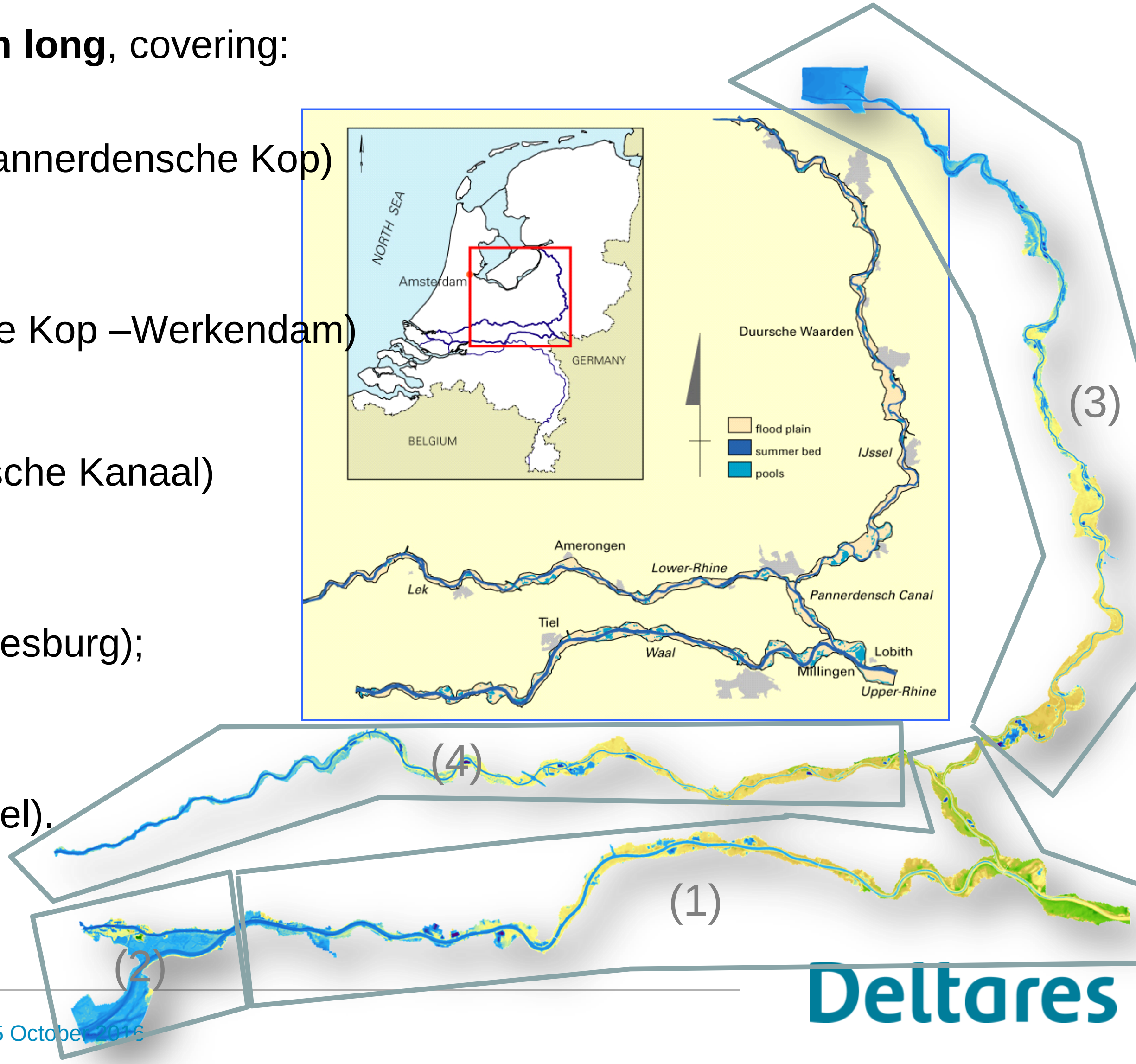
km 876-879 (all Pannerdensche Kanaal)

IJssel

km 879-912 (IJsselkop – Doesburg);

Nederrijn

km 879-889 (IJsselkop – Driel).



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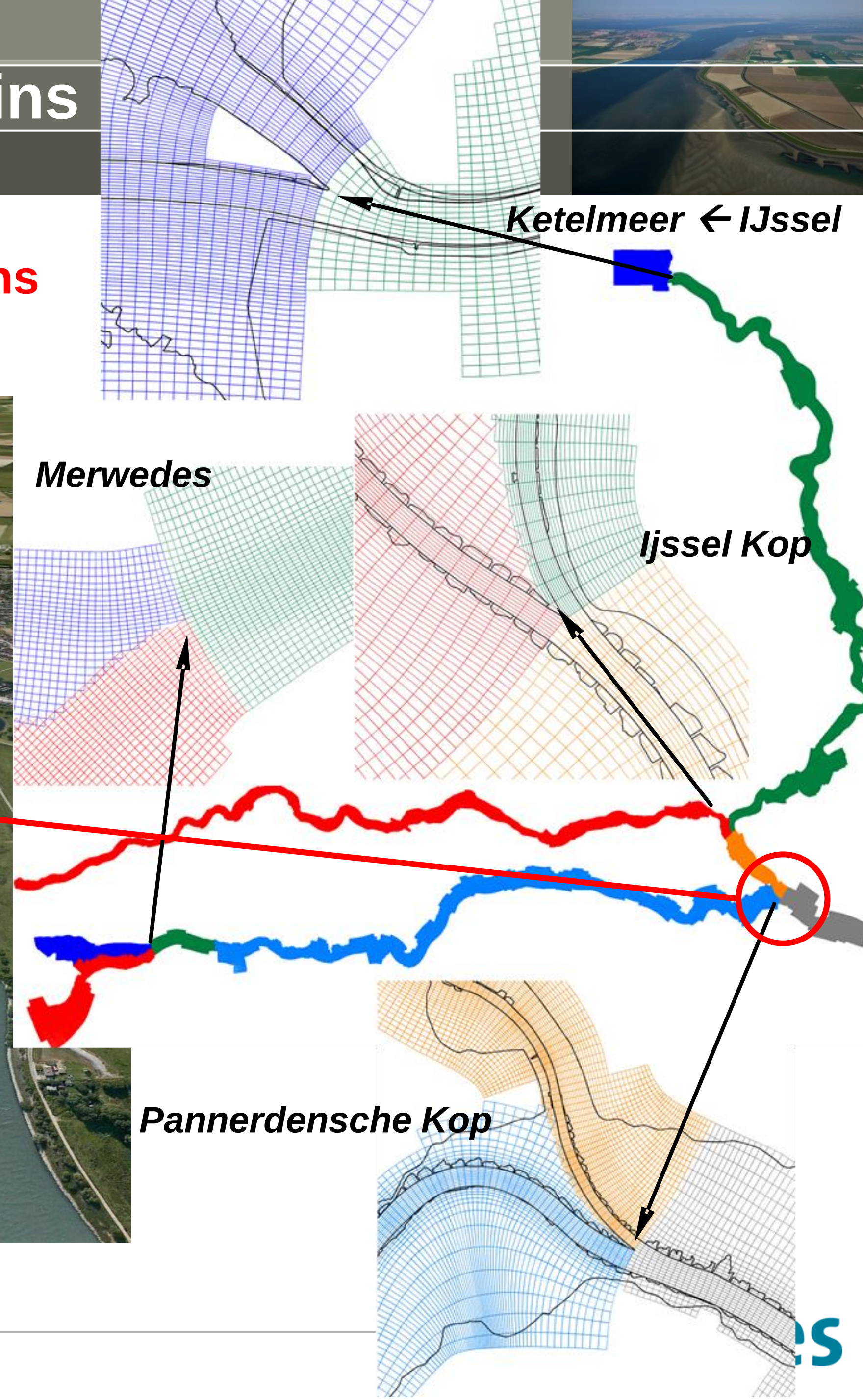
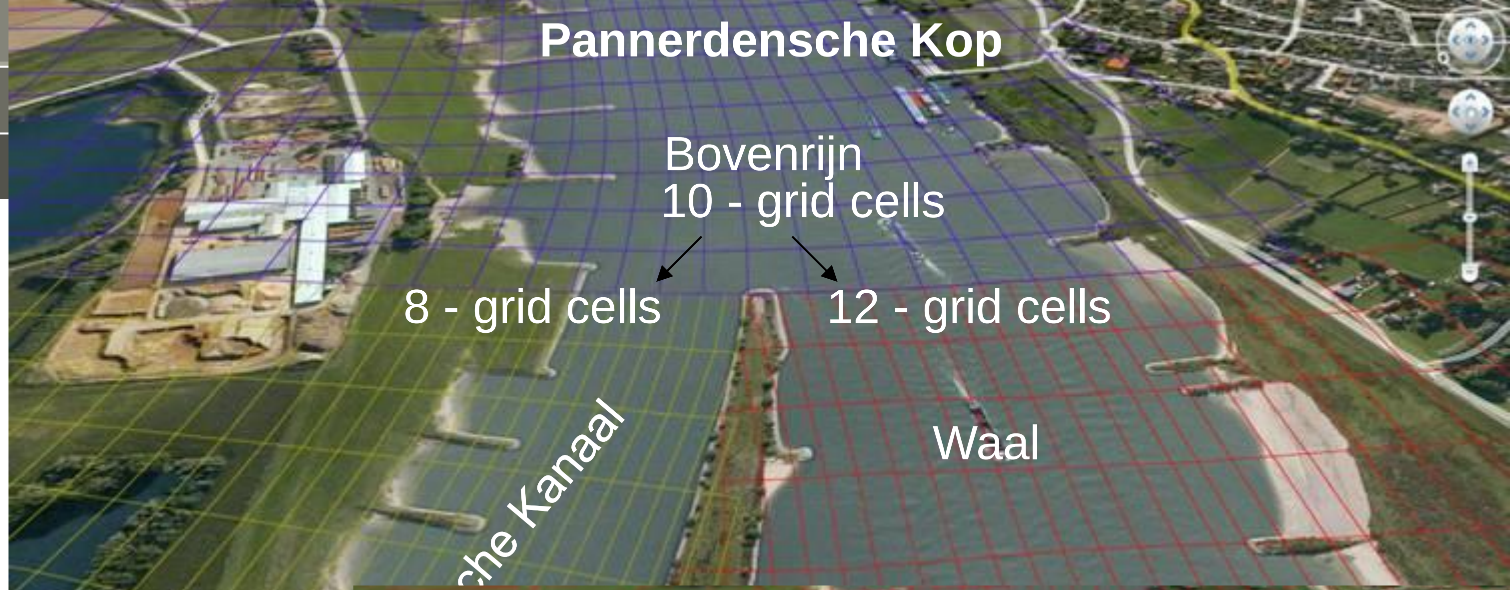
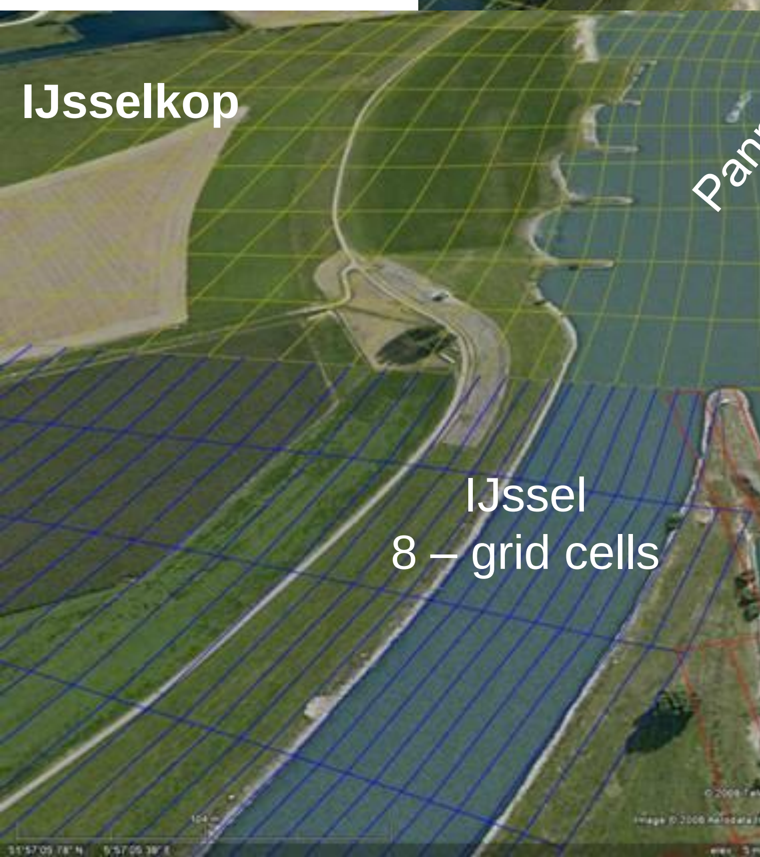
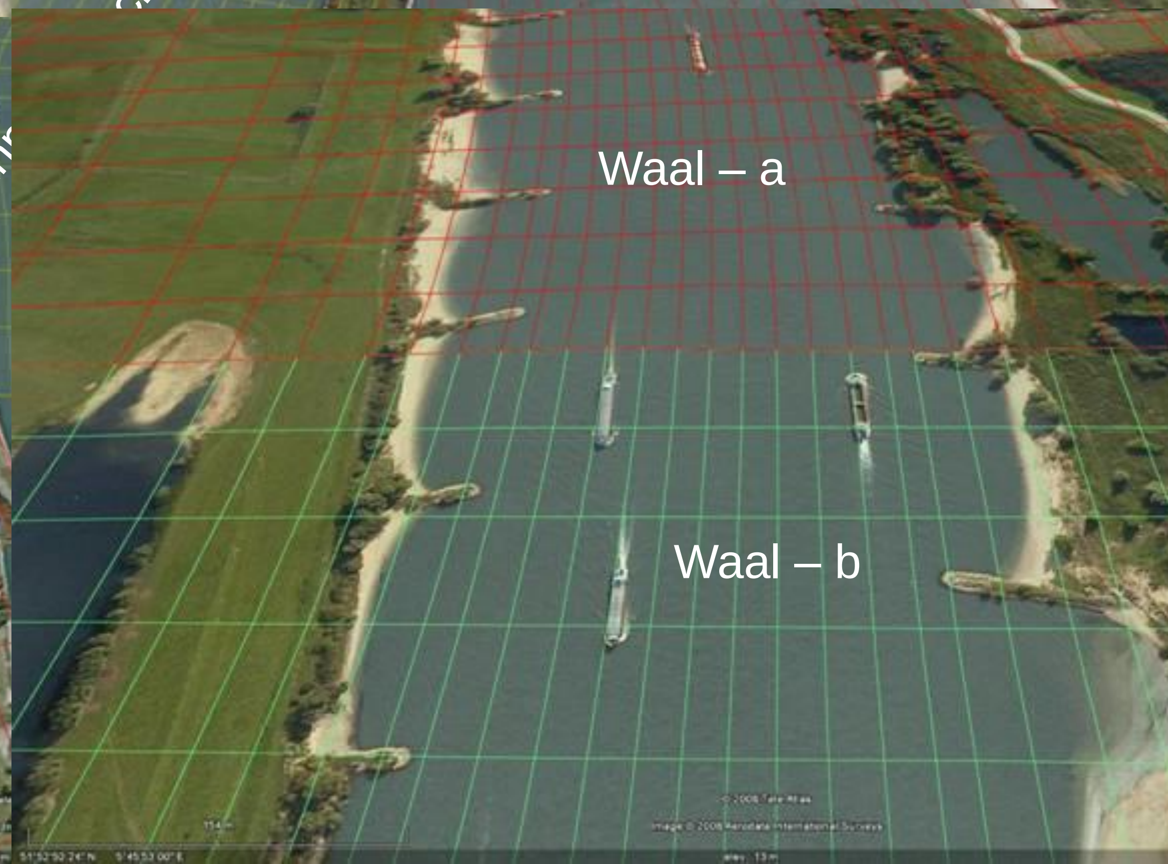
Model construction → Domains

Use of domain decomposition at bifurcations

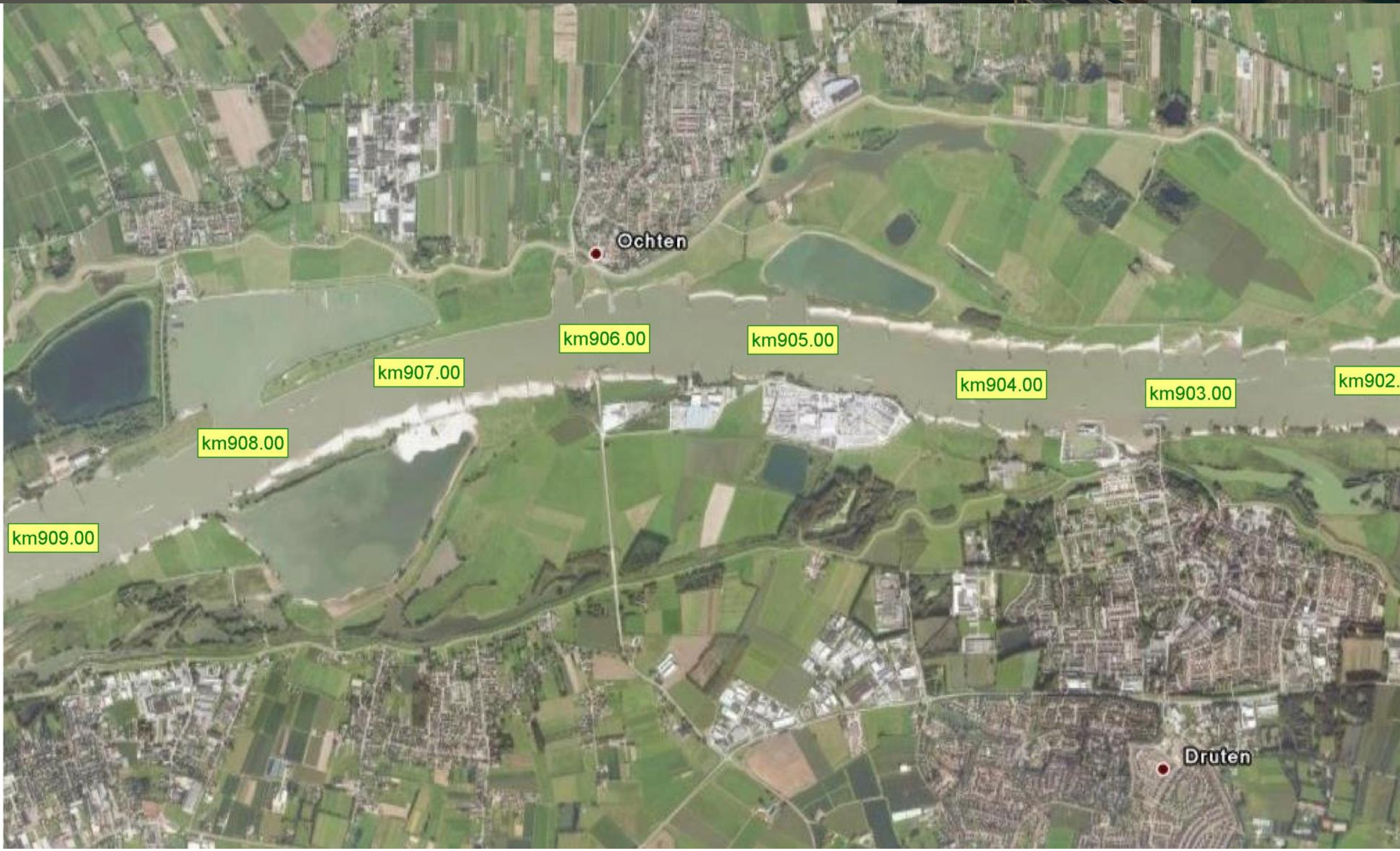



Pannerdensche Kop
Bovenrijn
10 - grid cells
8 - grid cells
12 - grid cells
Waal
Kanaal

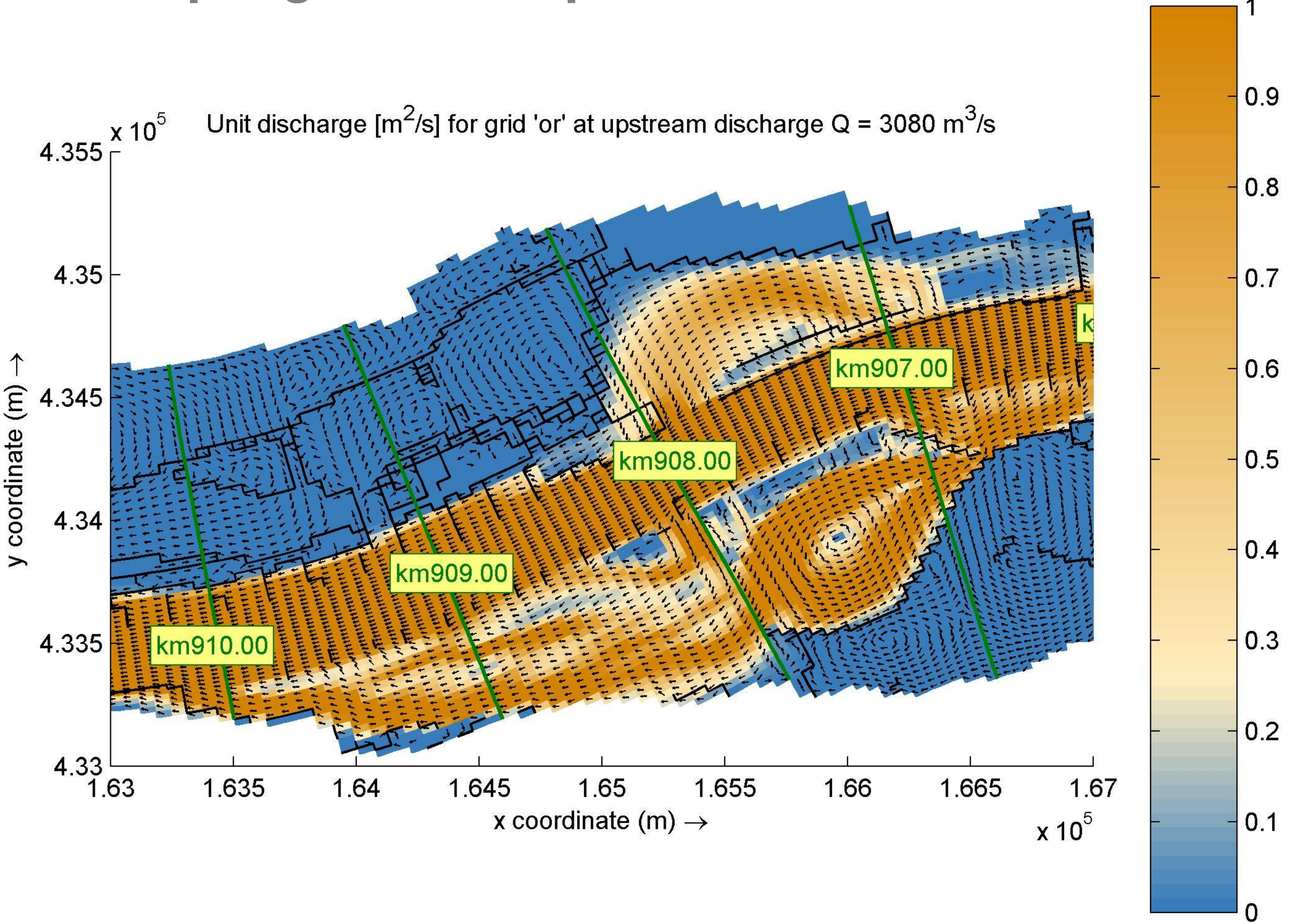

IJsselkop
IJssel
8 – grid cells


Waal – a
Waal – b

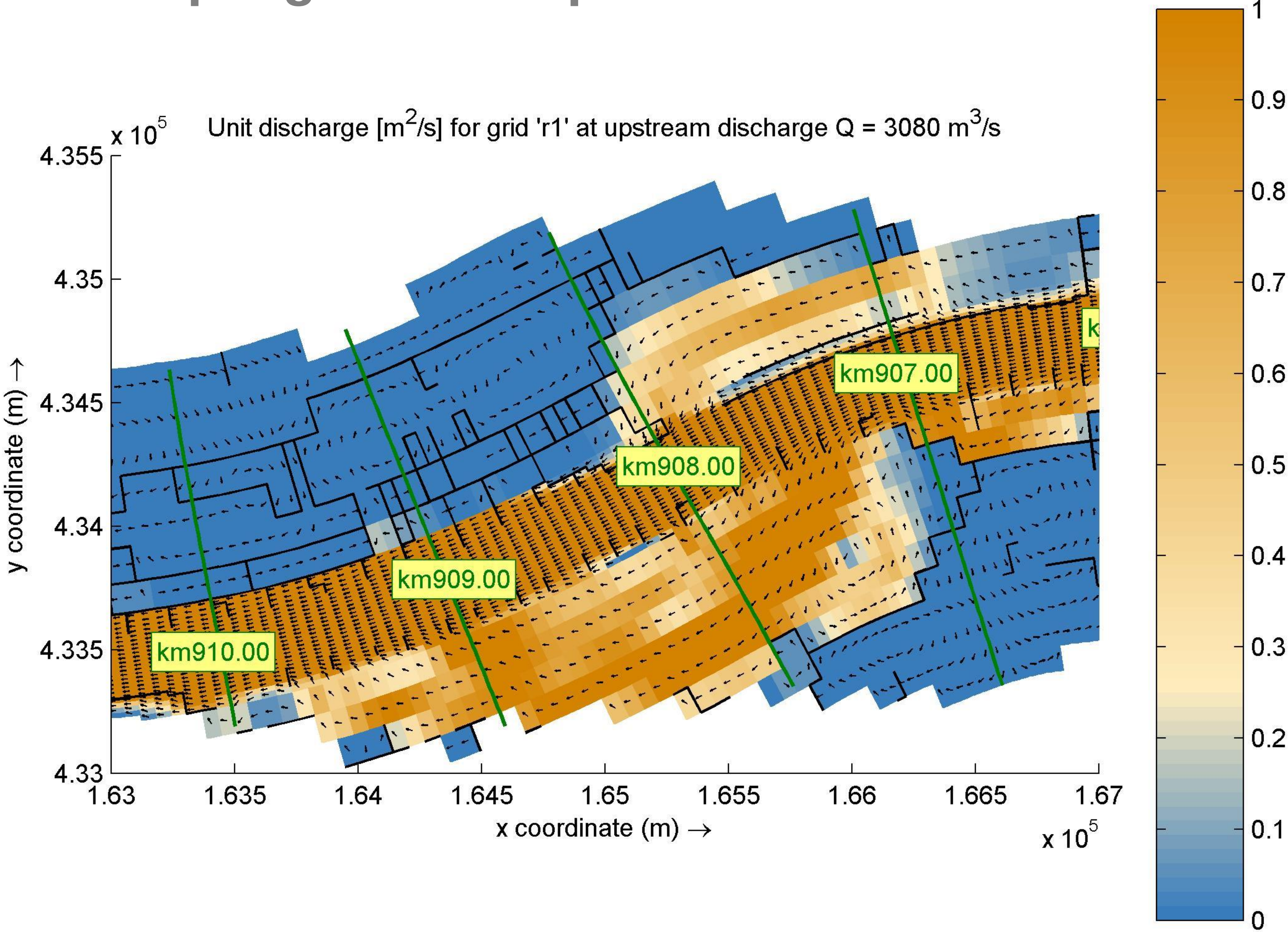
Example grids → impact on results



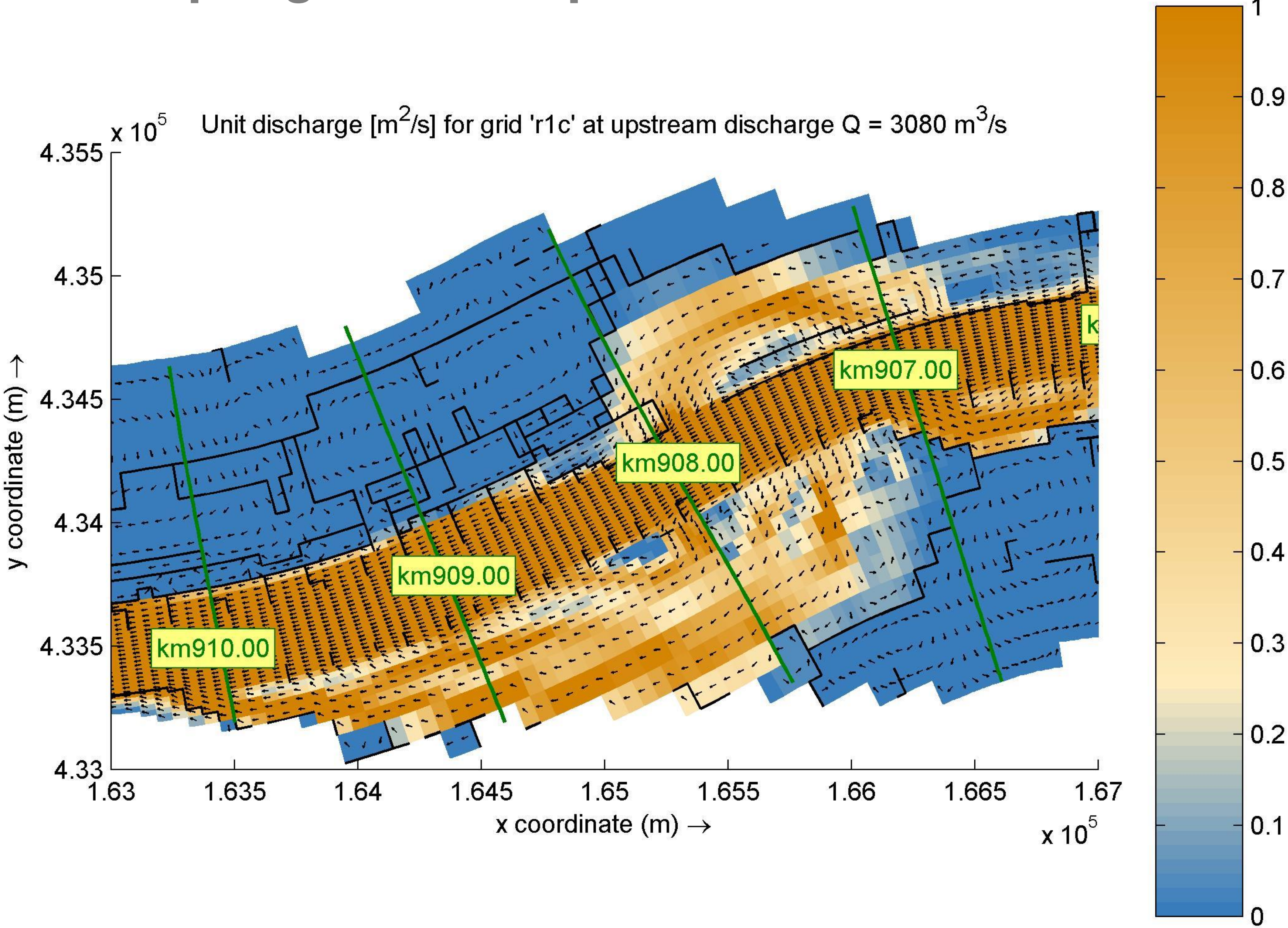
Example grids → impact on results



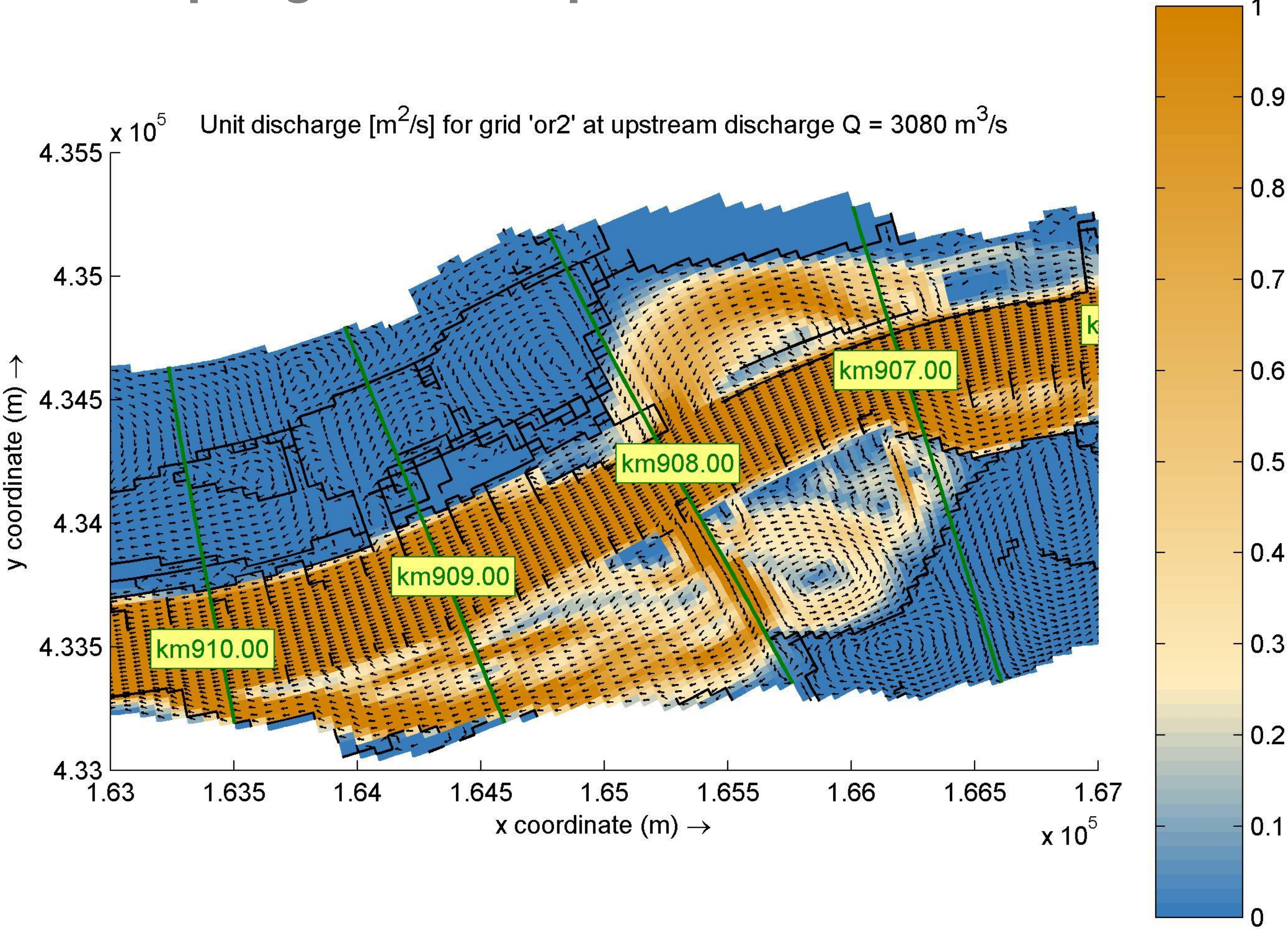
Example grids → impact on results



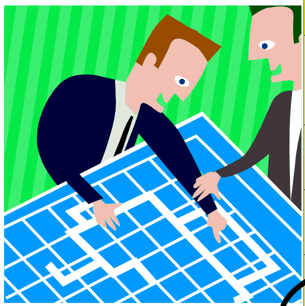
Example grids → impact on results



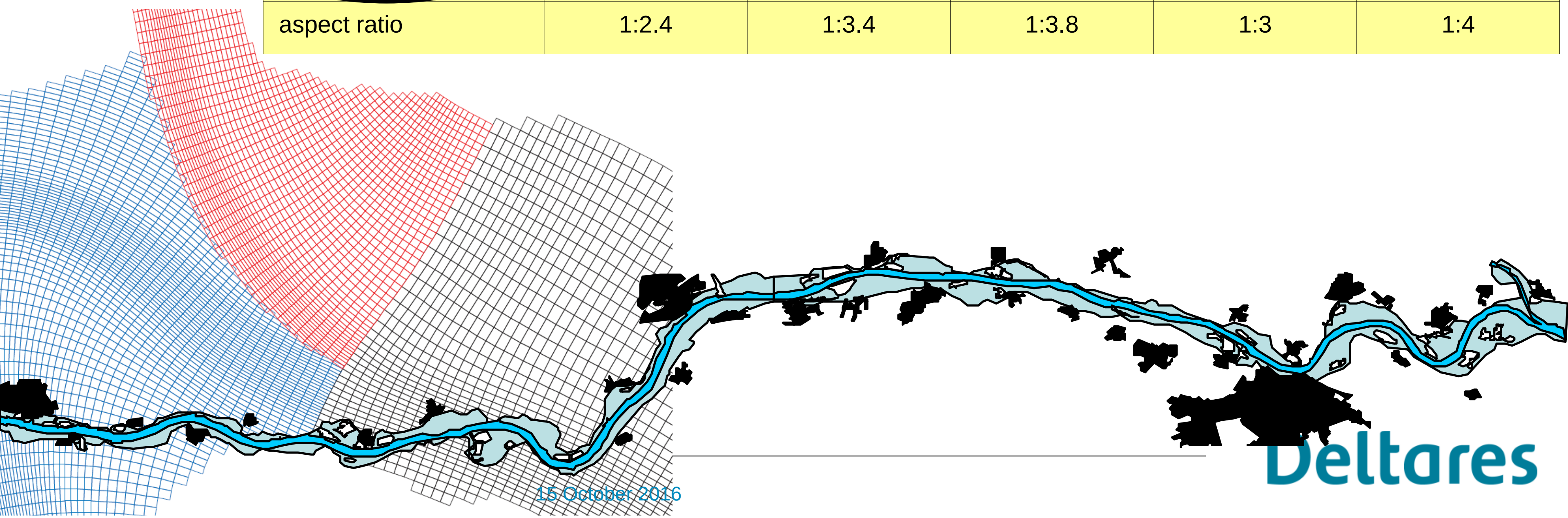
Example grids → impact on results



Model construction → Grid characteristics



Gridname	Bovenrijn	Waal – part a	Waal – part b	Waal – part c	Pannerdensch Kannal
number of grid cells **≈ 68 000**	55x177 9735	47x296 13616	47x401 18847	47x353 16591	67x137 9179
main channel					
number of grid cells	10	12	12	12	8
grid cell width (m) ≈	**34**	**23**	**21**	**26**	**20**
grid cell length (m) ≈	**80**	**80**	**80**	**80**	**80**
aspect ratio	1:2.4	1:3.4	1:3.8	1:3	1:4



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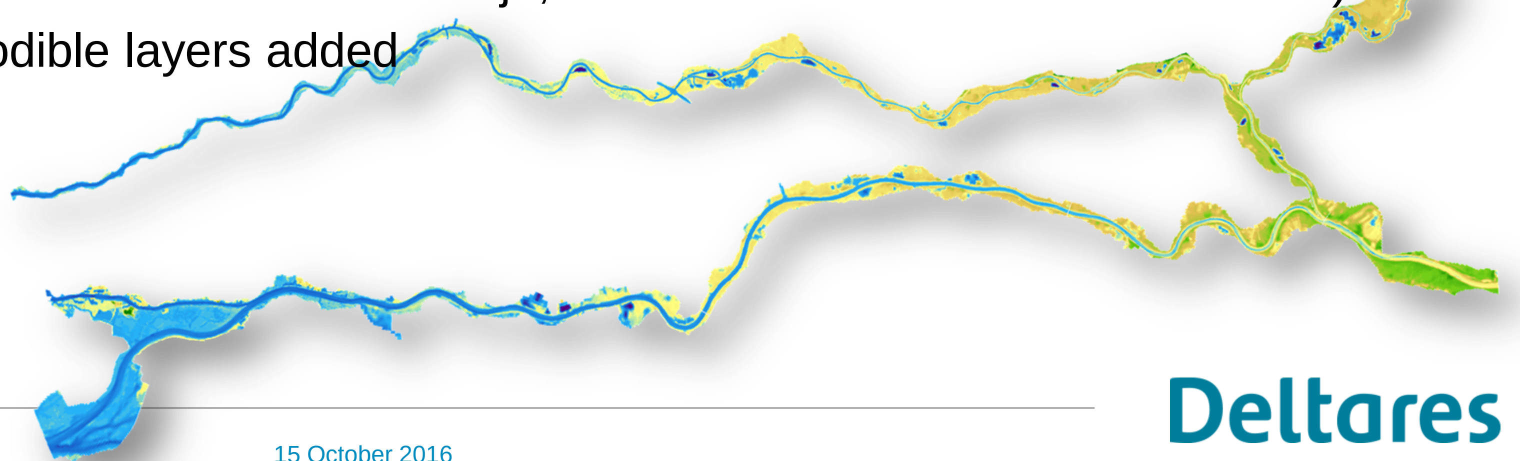
Model construction → Schematisation

- **GIS stored information (BASELINE: ArcView add-on)**
- Reference schematisation including:
  - bed topography,
  - hydraulic roughness,
  - Structures:
    - > barriers
    - > groynes (as weirs),
    - > dikes
    - > steep obstacles in the floodplains.
- Initial topography (year 1997), replaced by the multi-beam measurements (1999 for the Waal and Bovenrijn, 2002 for the Pannerdensche Kanaal)
- Non-erodible layers added



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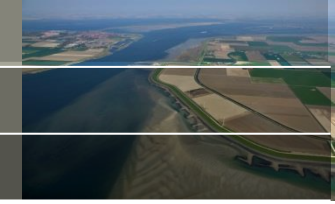
Model construction → Roughness

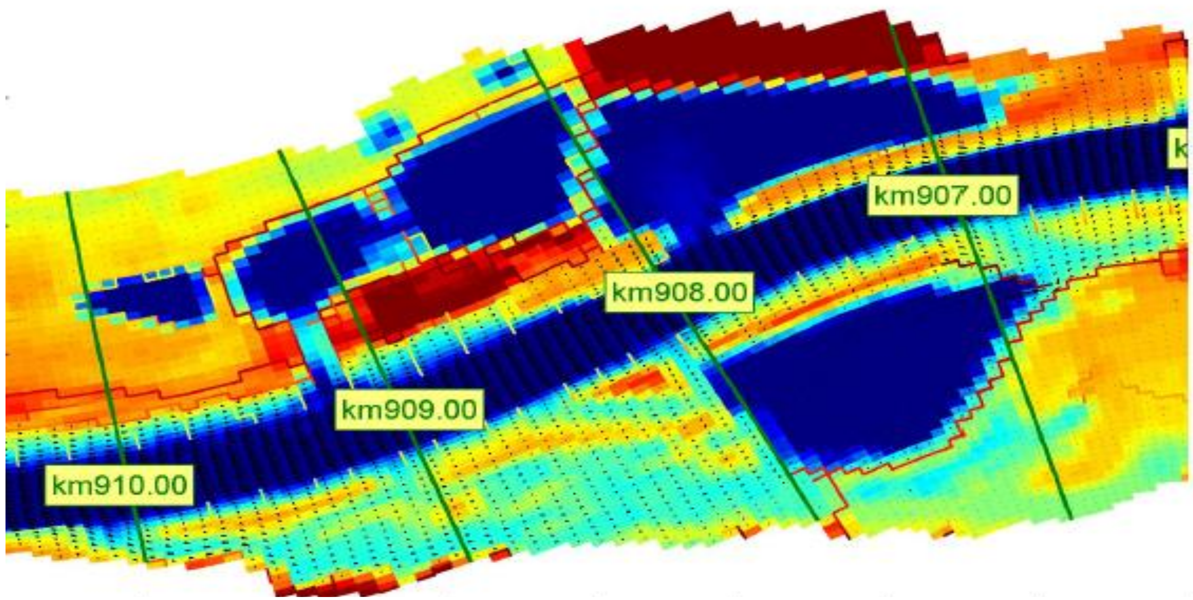


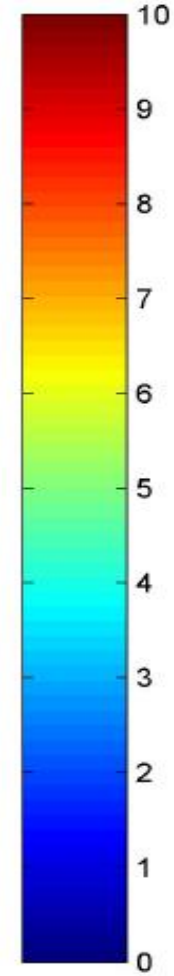
- Main channel:
  - Roughness is based on alluvial roughness (dune height prediction)
  - Roughness specified per river reach (between measurement stations) and variable in longitudinal direction (based on hydraulic calibration)
  - Avoid sharp transitions in roughness

- Floodplain
  - Roughness based on vegetation coverage, with analytical model to calculate vegetation roughness.

Model construction → Structures

- Groynes, weirs, other obstacles: all defined in the model as weirs.
- Measures such as groyne removal, lowering, shortening or extending can be simulated easily.





Initial bed level, weir heights, and flow pattern showing depth-averaged velocity

Time management

Discharge schematization
Simulation management tool

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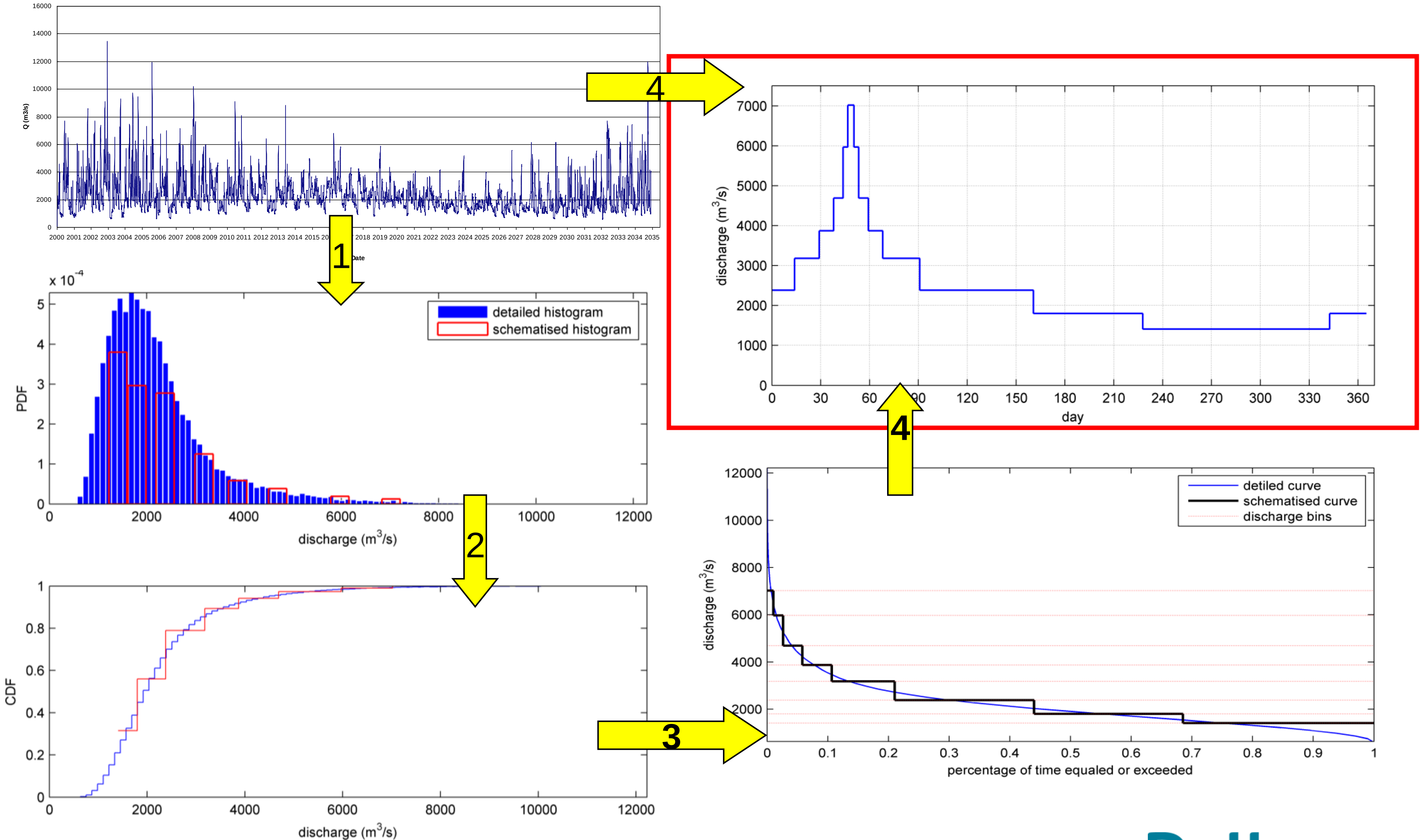
Discharge schematisation → upstream boundary



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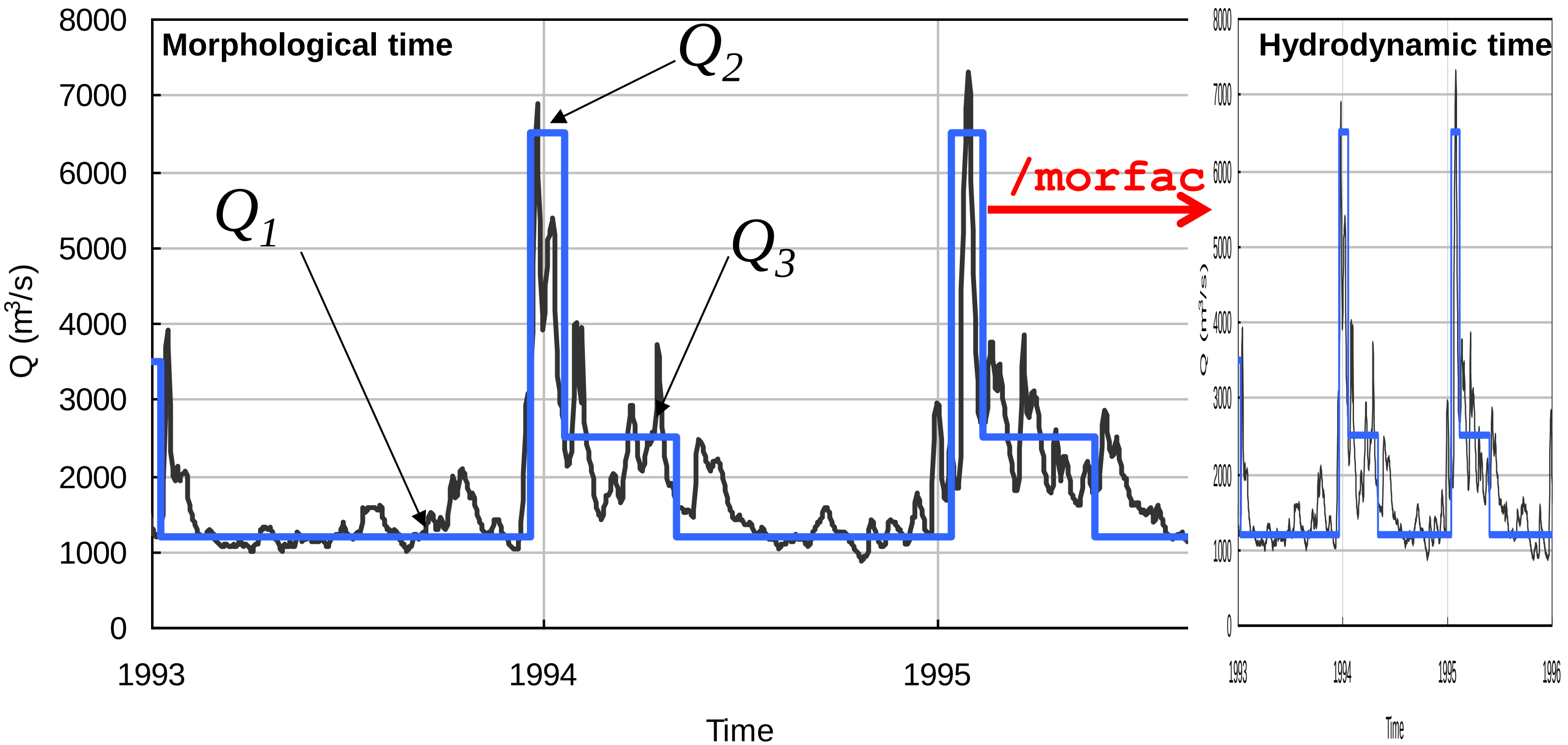
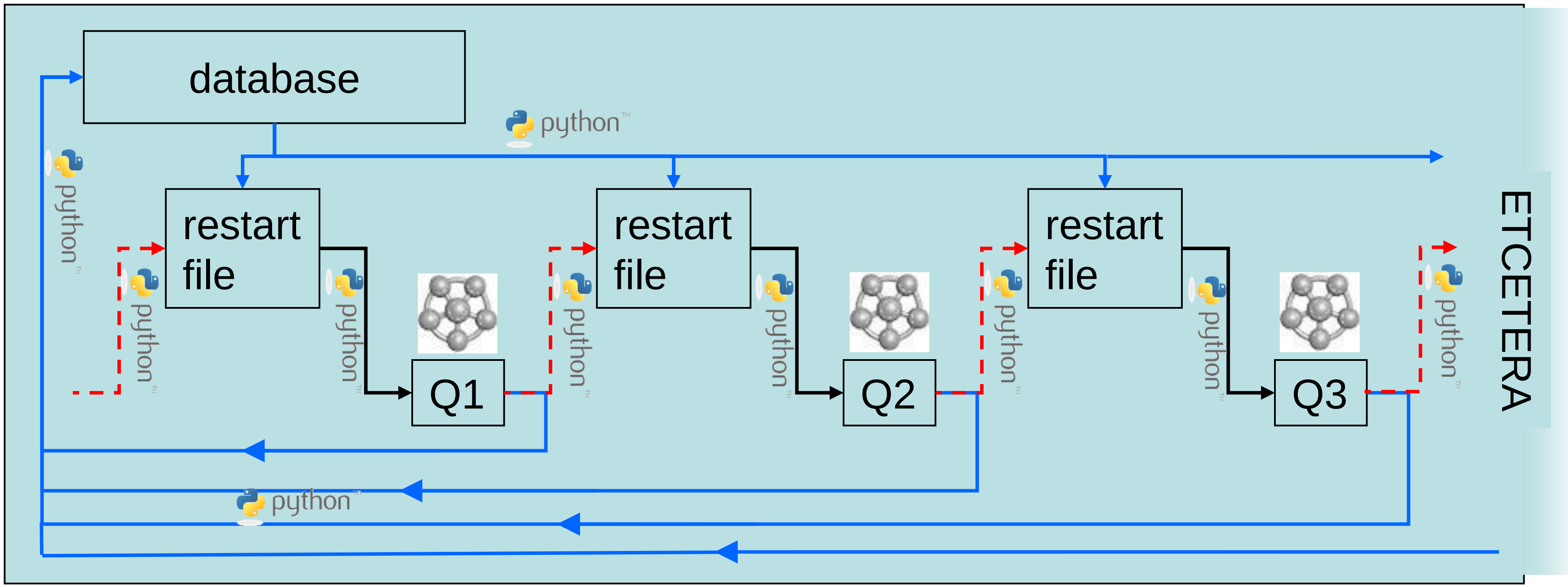
Running long simulations: quasi-steady & accelerated

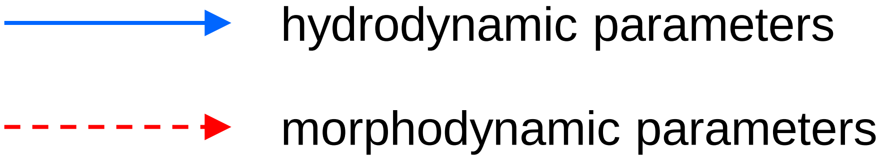
- Repeat a yearly schematised hydrograph using a sequence of steady discharges
- Apply a “morphological acceleration factor” to speed up morphology (same morphological changes in shorter flow period): factor 50 – 200
- `morfac` is inversely proportional to discharge



Simulation management tool → running long simulations

Operated using Python scripts





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Dredging

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Dredging and dumping module

Functionality

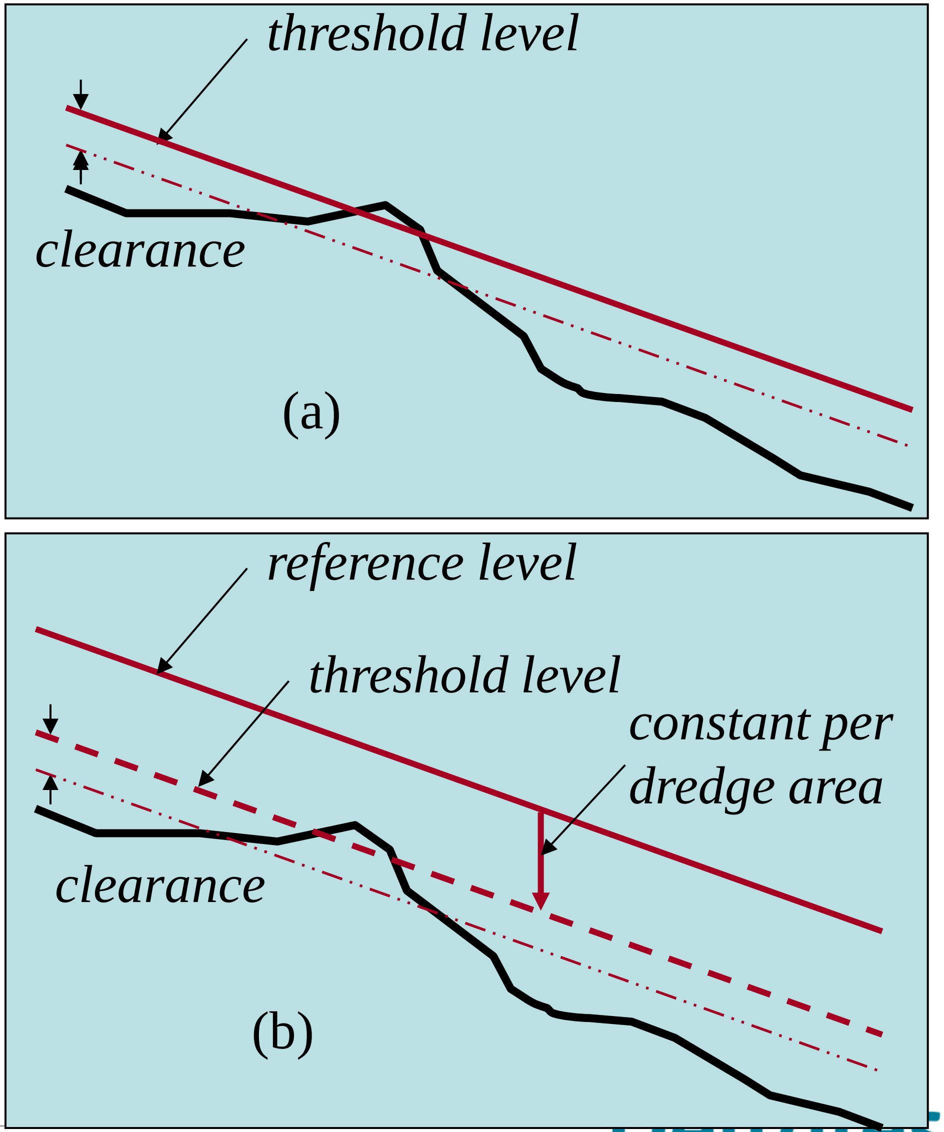
- dredging within user defined polygons (arbitrary number)
    - may encompass large or small areas (flexible)
- dumping within user defined polygons (arbitrary number)
    - distribution of dredged material over dumping areas given by user in advance (new)
- dredging and nourishment intervals (new)
- sequential dumping in a series of dumping blocks (new)

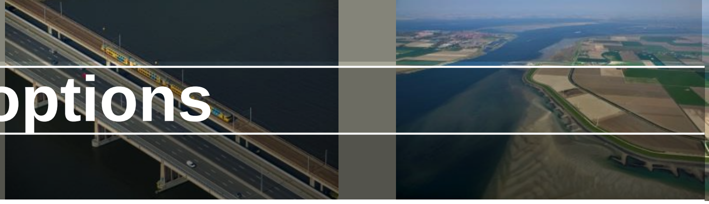
Dredging and dumping → criterion

Trigger dredging when:

- Bed level above threshold
    a) threshold level prescribed (spatially varying threshold level allowed), or
    b) constant (per polygon) water depth below specified reference water level (spatially varying water level allowed e.g. OLR)
- with, a given dredging rate

- externally provided sediment (nourishment)

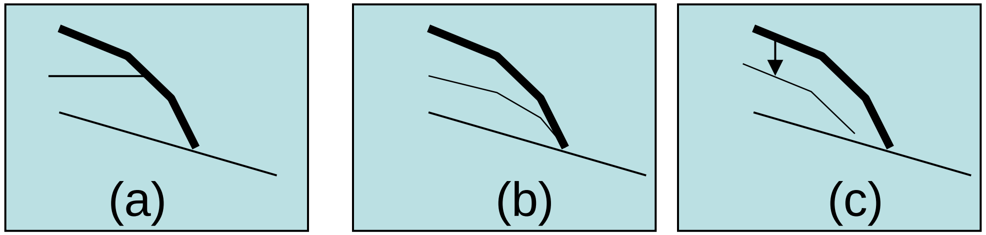




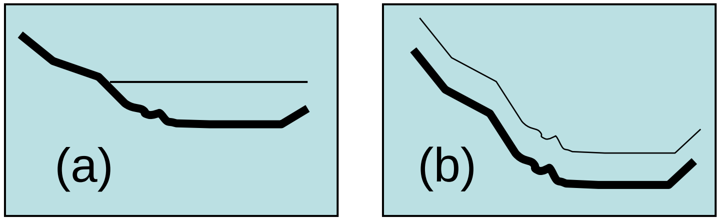
Dredging and dumping → method/options

Options

- dredge method
  - a) dredge top first,
  - b) dredge proportional,
  - c) dredge uniform



- dumping method
  - a) dump deepest first,
  - b) dump uniform



- dredge time constraints
  - only within certain period
  - minimum time since previous dredge action
  - only below a certain minimum water depth

Calibration

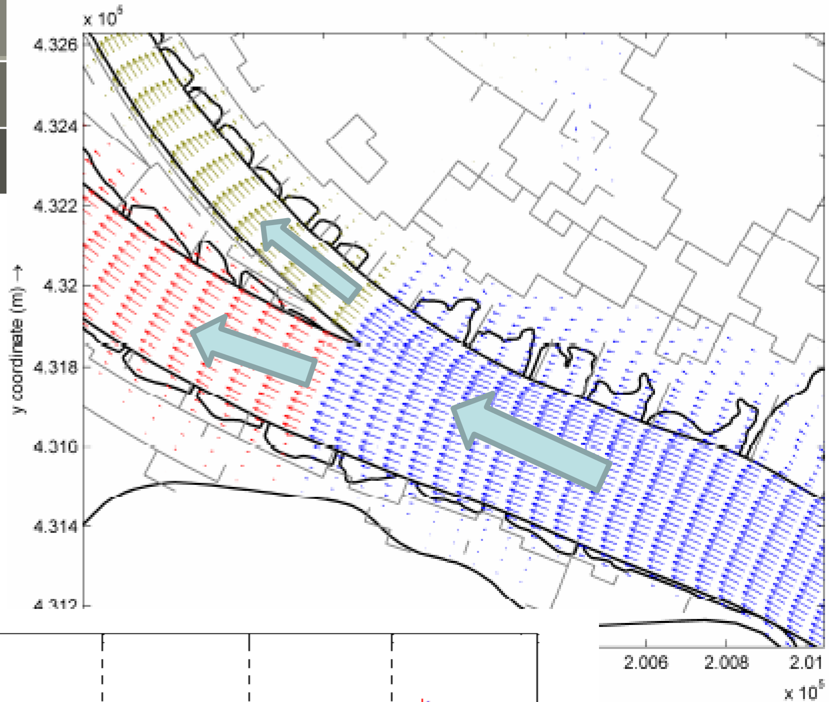
- **Hydrodynamic calibration**
- **Choose a transport formula suitable for all branches.**
- **morphological calibration of the model**
- **Calibration for the dredging activities in the Waal.**

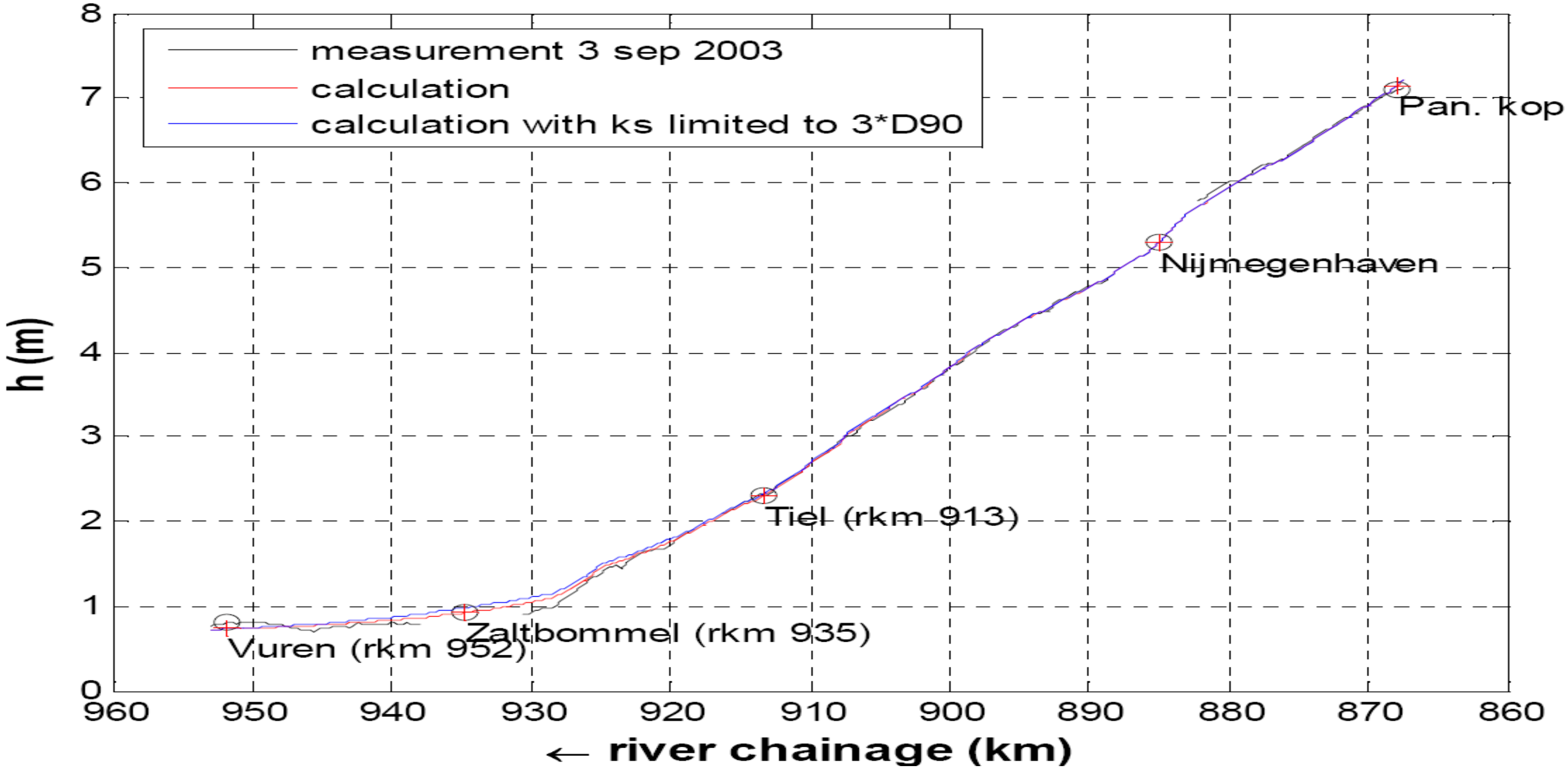
Hydraulic calibration

- **Discharge distribution**
- **Water levels**

Tips:

1st step → split branches;
use desired discharge per branch
start from the downstream end
avoid large jumps in roughness values





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Transport formula

Requirements

- The formula should have a similar behaviour as the **MPM formula** for Shields parameter values below 0.09, which corresponds to the conditions in the **Bovenrijn**.

- The formula should have a similar behaviour as the **EH** formula for Shields parameter values above 0.3, which corresponds to the conditions in the **Midden-Waal and the Beneden-Waal**.

- For physical reasons, n in ($S = mu^n$) should always be larger than 3. Preferably, the degree of nonlinearity should decrease monotonously as the Shields parameter increases.

- n should be about 4 or 5 for large Shields parameter values. The value of 5 complies with the EH predictor.

Transport formu

Tested Formulations

Engelund & Hansen, (1967)
preferred for lower parts

$$S_{EH} = \alpha_{EH}\, m_{EH}\, u^5$$

$$m_{EH} = \frac{0.05}{\sqrt{g}\, C^3 \Delta^2 D_{50}}$$

Combined formula → test

$$\alpha_P = \left(\frac{\theta_{cr}}{\mu\theta}\right)^P$$

$$S_{AS_a} = \underbrace{\left(\alpha_{MPM}\, m_{MPM}\right)^{\alpha_P} \left(\mu\theta - \theta_{cr}\right)^{\alpha_P}}_{MPM}$$

$$S_{AS_b} = \underbrace{\alpha_P \cdot S_{MPM}}_{MPM} + \underbrace{\left(1-\alpha_P\right)\cdot S_{EH}}_{EH}$$

van Rijn (1984) →

$$S_{VR} = \alpha_{BED}\cdot S_{BED} + \alpha_{SUS}\cdot S_{SUS}$$

A Van Rijn (1984)

The formula of Van Rijn (1984) takes the form:

$$S = S_s + S_b \qquad \text{(A.1)}$$

where:

$$S_b = \begin{cases} 0.053\sqrt{\Delta\, g\, D_{50}^3}\, D_*^{-0.3} T^{2.1} & \text{for } T < 3.0 \\ 0.1\ \sqrt{\Delta\, g\, D_{50}^3}\, D_*^{-0.3} T^{1.5} & \text{for } T \geq 3.0 \end{cases} \qquad \text{(A.2)}$$

First the bed-load transport expression will be explained. In Eq. A.2 T is a dimensionless bed shear parameter, written as:

$$T = \frac{\mu_c \tau_{bc} - \tau_{bcr}}{\tau_{bcr}} \qquad \text{(A.3)}$$

It is normalised with the critical bed shear stress according to Shields (τ_{bcr}), the term $\mu_c \tau_{bc}$ is the effective shear stress. The formulas of the shear stresses are:

$$\tau_{bc} = \tfrac{1}{8}\rho_w\, f_{cb}\, u^2 \qquad \text{(A.4)}$$

$$f_{cb} = \frac{0.24}{\left[\log_{10}\left(12h/\xi_c\right)\right]^2} \qquad \text{(A.5)}$$

$$\mu_c = \left(\frac{18\log_{10}\left(12h/\xi_c\right)}{C'}\right)^2 \qquad \text{(A.6)}$$

where $C_{g,90}$ is the grain related Chézy coefficient:

$$C' = 18\log_{10}\left(\frac{12h}{3D_{90}}\right) \qquad \text{(A.7)}$$

The critical shear stress is written according to Shields:

$$\tau_{bcr} = \rho_w\, \Delta\, g\, D_{50}\theta_{cr} \qquad \text{(A.8)}$$

in which θ_{cr} is the critical Shields parameter for initiation of motion, which is a function of the dimensionless particle parameter D_*:

$$D_* = D_{50}\left(\frac{\Delta g}{\nu^2}\right)^{\frac{1}{3}} \qquad \text{(A.9)}$$

The suspended transport formulation reads:

$$S_s = f_{cs}\, u\, h\, C_a \qquad \text{(A.10)}$$

In which C_a is the reference concentration, u depth averaged velocity, h the water depth and f_{cs} is a shape factor of which only an approximate solution exists:

$$f_{cs} = \begin{cases} f_0(z_c) & \text{if } z_c \neq 1.2 \\ f_1(z_c) & \text{if } z_c = 1.2 \end{cases} \qquad \text{(A.11)}$$

$$f_0(z_c) = \frac{\left(\xi_c/h\right)^{z_c} - \left(\xi_c/h\right)^{1.2}}{\left(1-\xi_c/h\right)^{z_c}\left(1.2 - z_c\right)} \qquad \text{(A.12)}$$

$$f_1(z_c) = \left(\frac{\xi_c/h}{1-\xi_c/h}\right)^{1.2} \log_e\left(\xi_c/h\right) \qquad \text{(A.13)}$$

where ξ_c is the reference level or roughness height (can be interpreted as the bed-load layer thickness) and z_c the suspension number:

$$z_c = \min\left(20, \frac{w_s}{\beta\,\kappa\, u_*} + \phi\right) \qquad \text{(A.14)}$$

$$u_* = u\sqrt{\frac{f_{cb}}{8}} \qquad \text{(A.15)}$$

$$\beta = \min\left(1.5, 1 + 2\left(\frac{w_s}{u_*}\right)^2\right) \qquad \text{(A.16)}$$

$$\phi = 2.5\left(\frac{w_s}{u_*}\right)^{0.8}\left(\frac{C_a}{0.65}\right)^{0.4} \qquad \text{(A.17)}$$

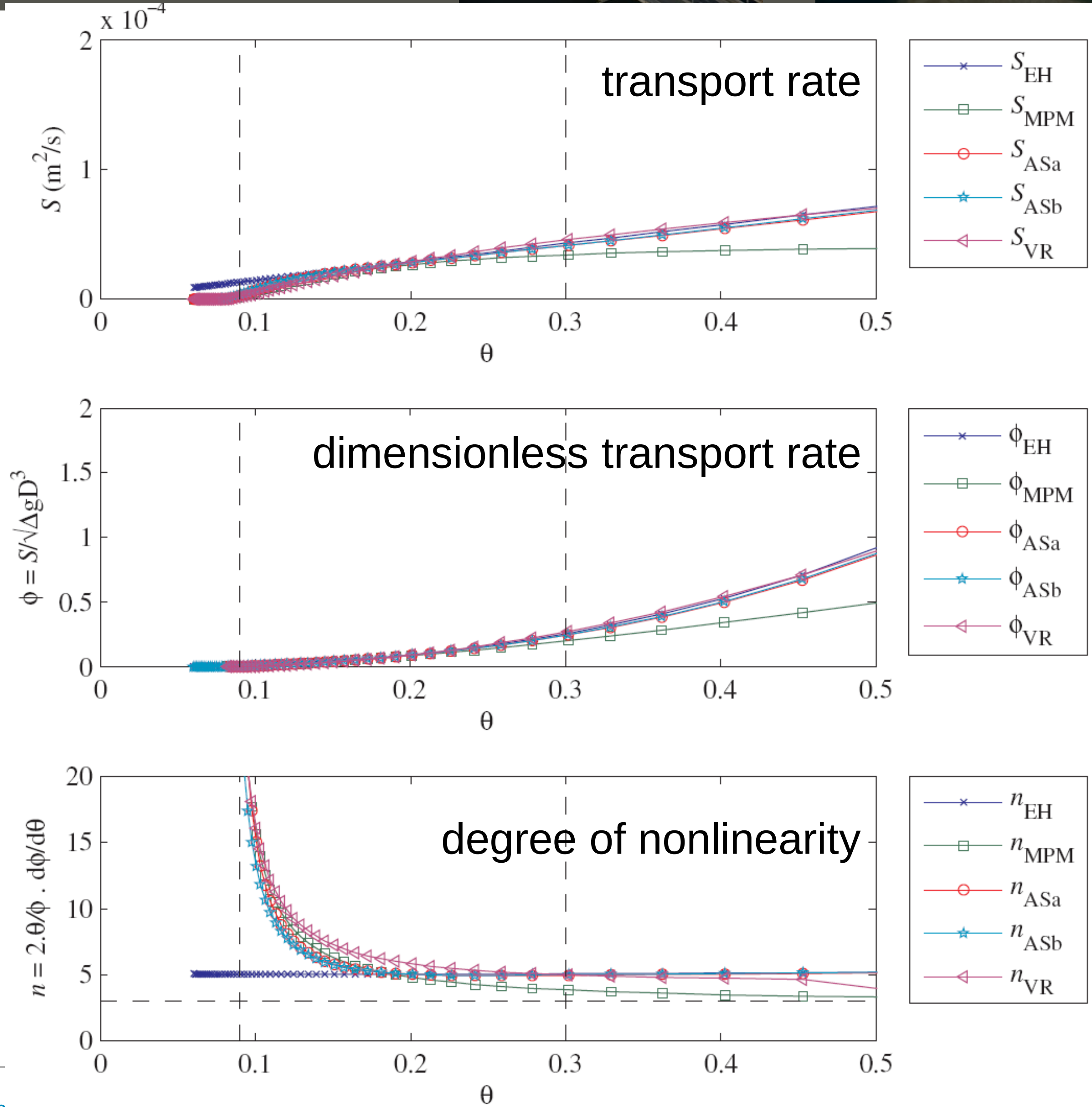
The reference concentration is written as:

$$C_a = 0.015\alpha_1 \frac{d_{50}}{\xi_c}\frac{T^{1.5}}{D_*^{0.3}} \qquad \text{(A.18)}$$

The following formula specific parameters have to be specified as input to the model.

Transport formula – offline analysis

the formula of van Rijn yields the desired behaviour



note:
αEH = 0.5;
reduced van Rijn equation with
ws = f(d50), αSUS = 0.3, αBED = 1.5.

Transport formula

Conclusions:

- We favour using the formula of van Rijn (1984).

- The implementation in Delft3D is modified such that:
  - it is possible to calibrate bed load and suspended load separately (α_{BED} and α_{SUS}),

  - it is possible to opt for a reduced formula; total load: suspended load is added to bed load (no advection-diffusion equation for suspended load) → using option `'bedload'`

  - it is possible to use a constant critical Shields parameter for the initiation of motion; user defined as a calibration parameter.

Calibration of the morphodynamic model

1D-behaviour:

- annual sediment transport volumes/rates,
- bedforms celerity (highest priority)
- annual bed level changes, and
- period-averaged bed level gradient.

Parameters:

- α (coefficient in transport formula)
- θ_{cr}
- $D_{50} = f(x)$
- $D_{90} \approx 4 \times D_{50}$

Procedures:

- offline calculations (100s)
- online calculations (10s)

2D-behaviour (bar-pool patterns):

- transverse slopes in bends, and
- position of crossing between two opposite bends

Parameters:

- coefficient affecting the spiral flow intensity due to curvature (*Espir*)
- coefficient influencing the effect of transverse bed slope (*Ashld*).

Procedures:

- online calculations (10s)

we are using the sediment transport formula of van Rijn (1984), with a tweak.

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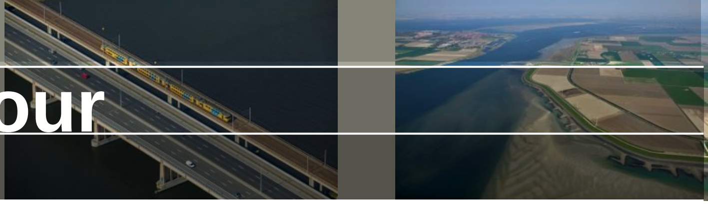
Morphological boundary conditions

- The following morphological boundary conditions are available:
  1. free bed level, i.e. bed level change at boundary equals the internal bed level change (not recommended).
  2. fixed bed level, (default)
  3. prescribed bed level variation [m]
  4. prescribed bed level change rate [m/s]
  5. prescribed sediment transport rate with pores (sand volume) [m^3/s/m], and
  6. prescribed sediment transport rate without pores (stone volume) [m^3/s/m]

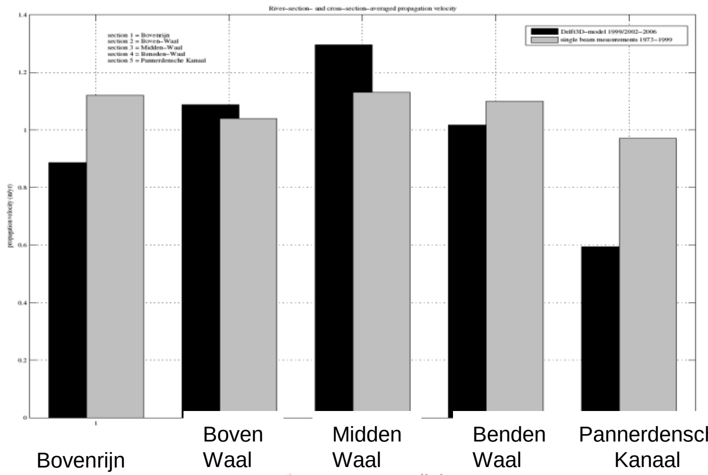
Calibration result – 1D behaviour

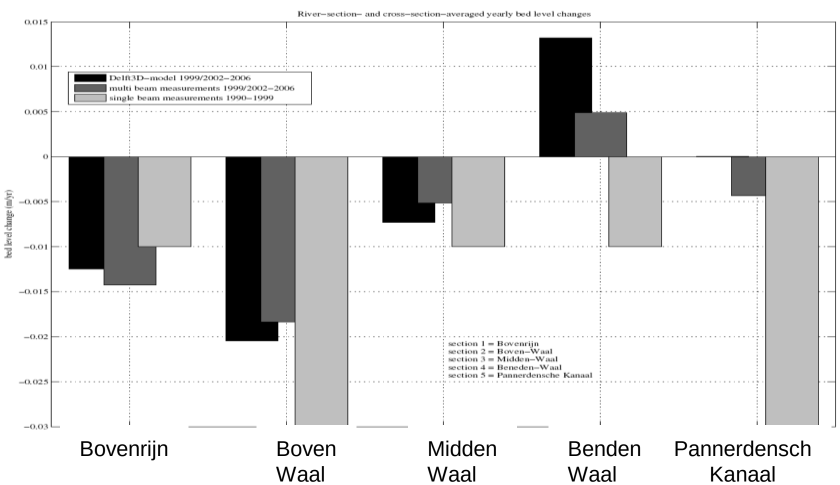


Firstly, sediment budget for the Rhine branches

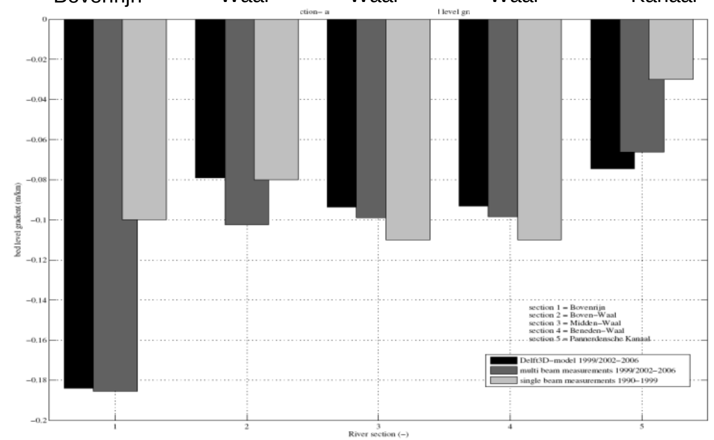
River branch	**Computed** annual transport [m³/yr]	**Observed** annual transport (Ten Brinke, 2001) [m³/yr]
Bovenrijn	250 000 (in) - 480 000 (out) **390 000** (average)	577 000 (out)
Waal	350 000 (in) **410 000** (average)	507 000 (in) 300,000 ~ 400,000 (average)
Pannerdensch Kanaal	110 000 (in) – 110 000 (out) **107 000** (average)	70 000 (in) – 97000 (out)

Bed-form celerity





cross-section and reach-averaged yearly bed level change



cross-section and reach-averaged bed level gradient

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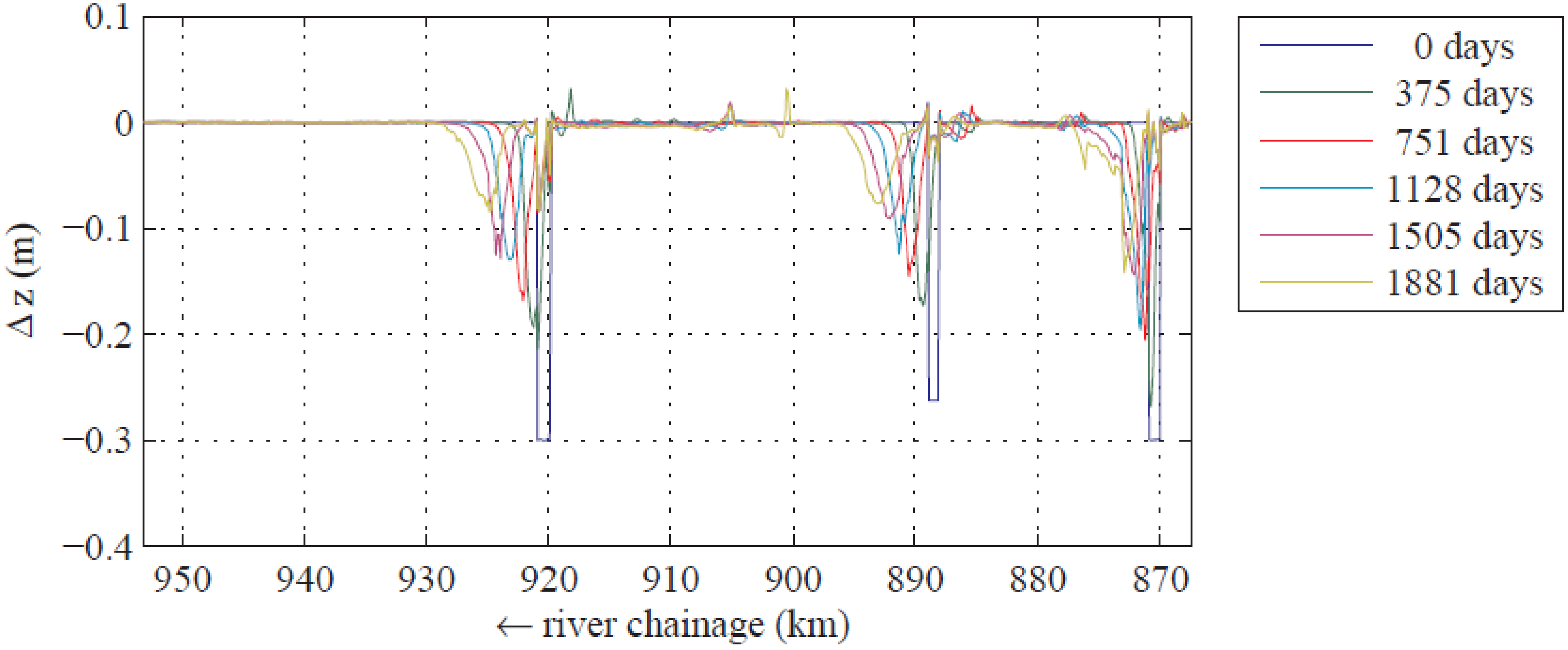
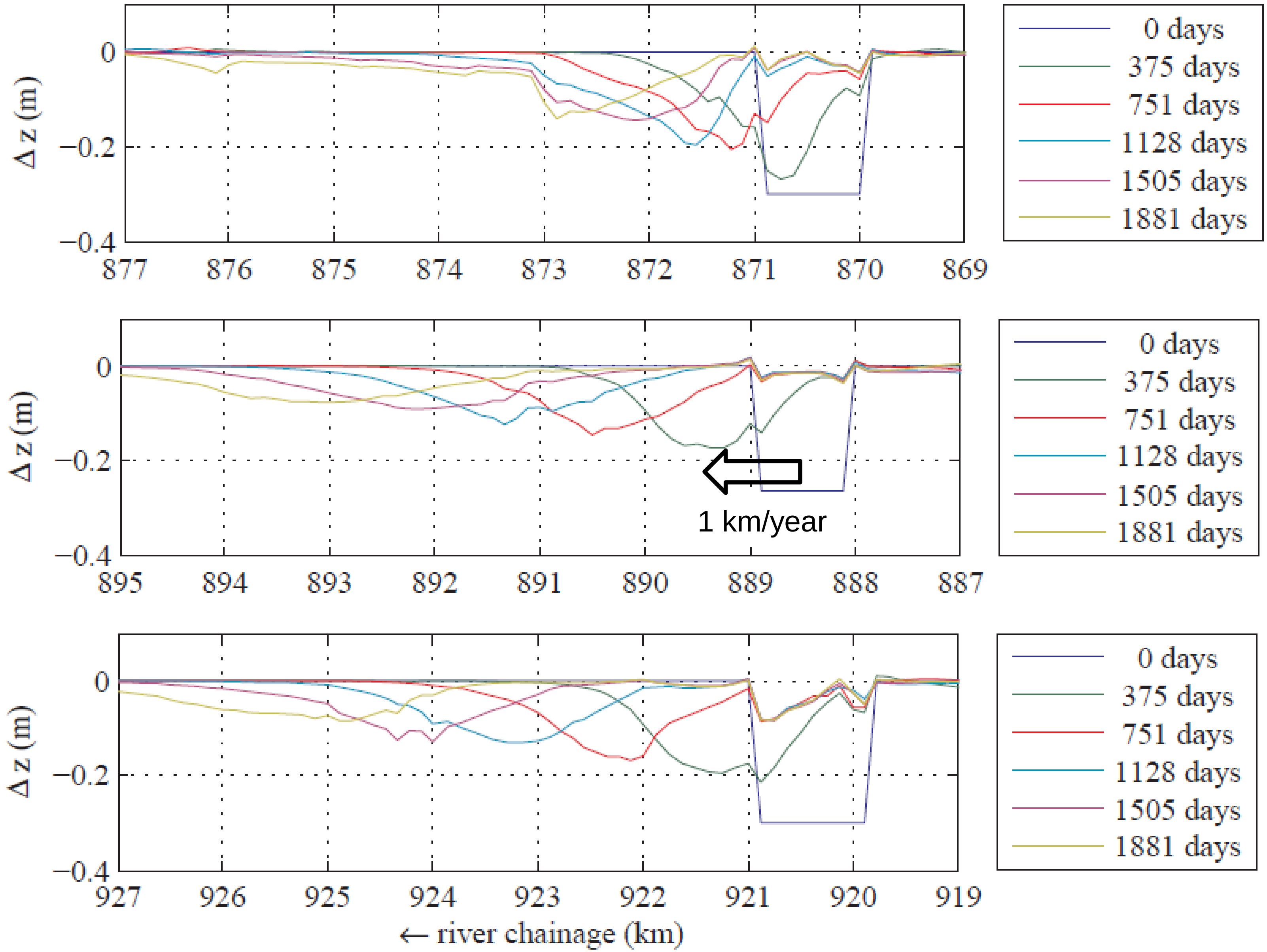
Calibration result – 1D (trench)

Bed celerity ca. 1 km/year → using 3 trenches

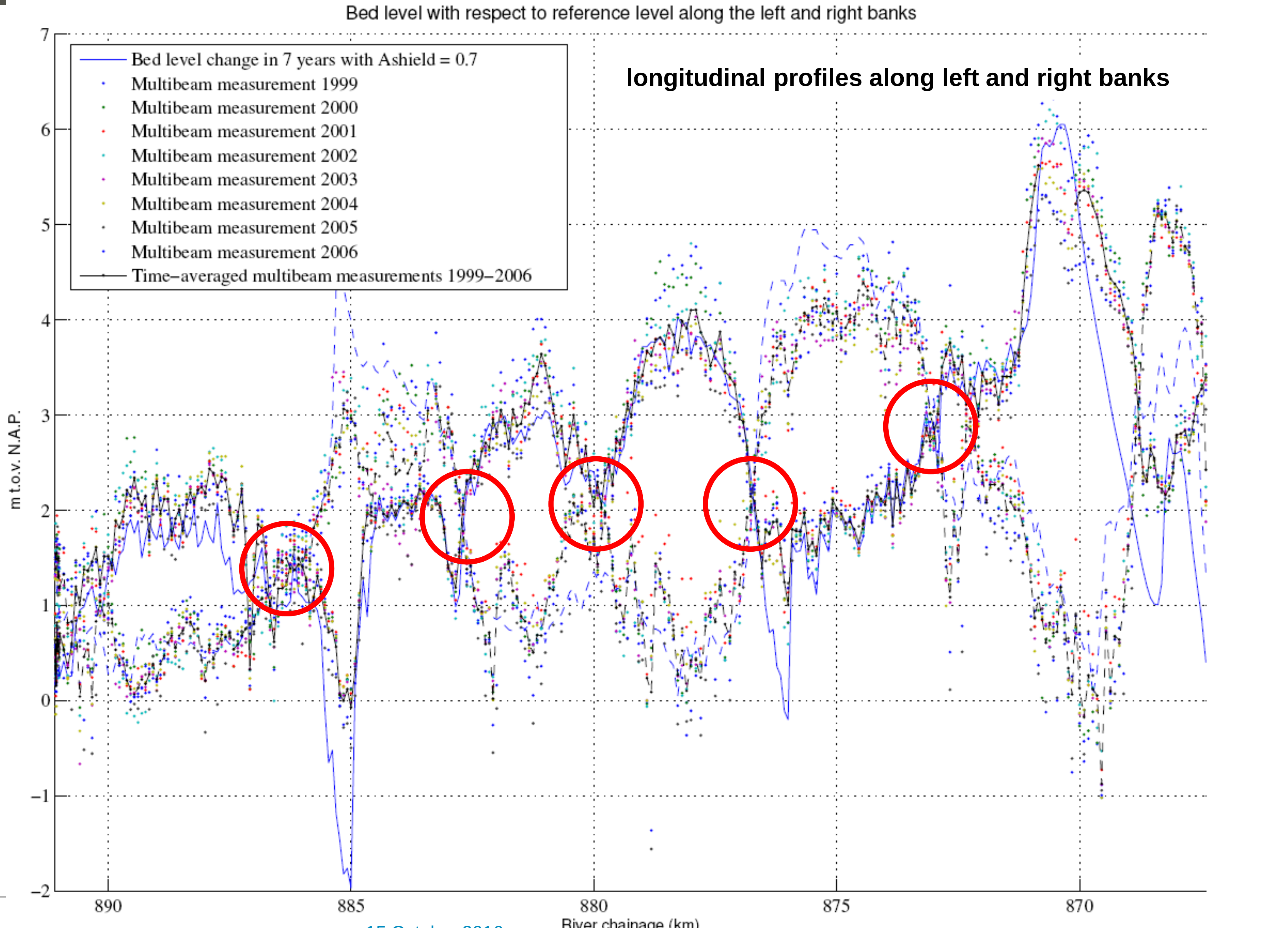


Deltares

Calibration result – 1D (trench)



2D calibration

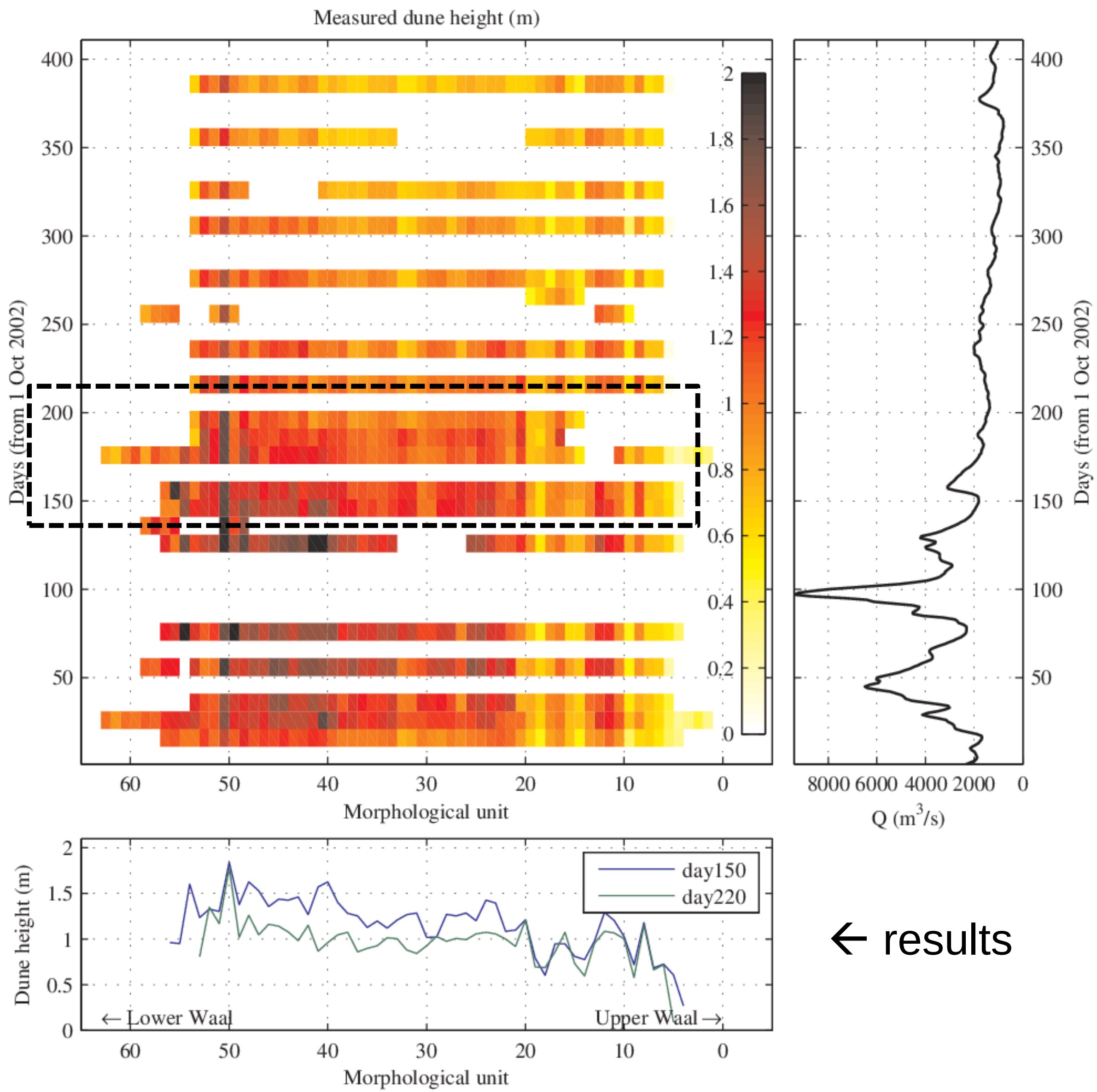


Dune height – for dredging

- Four dune height predictors have been implemented: Van Rijn (1984c), Fredsøe (1982) or Engelund and Hansen (1967), and a power relation.

- Temporal and spatial variations; implemented by means of an advection relaxation equation.

```
Settings
  Bdf          = Y
  BdfMor       = Y
  BdfH         = FredsoeMPM
  BdfL         = vanRijn84
  BdfR         = vanRijn84
  BdfEps       = 0.8
  BdfRlx       = THConst
  BdfT_H       = 57600
  BdfADV       = N
  BdfThetaC    = 0.047
```

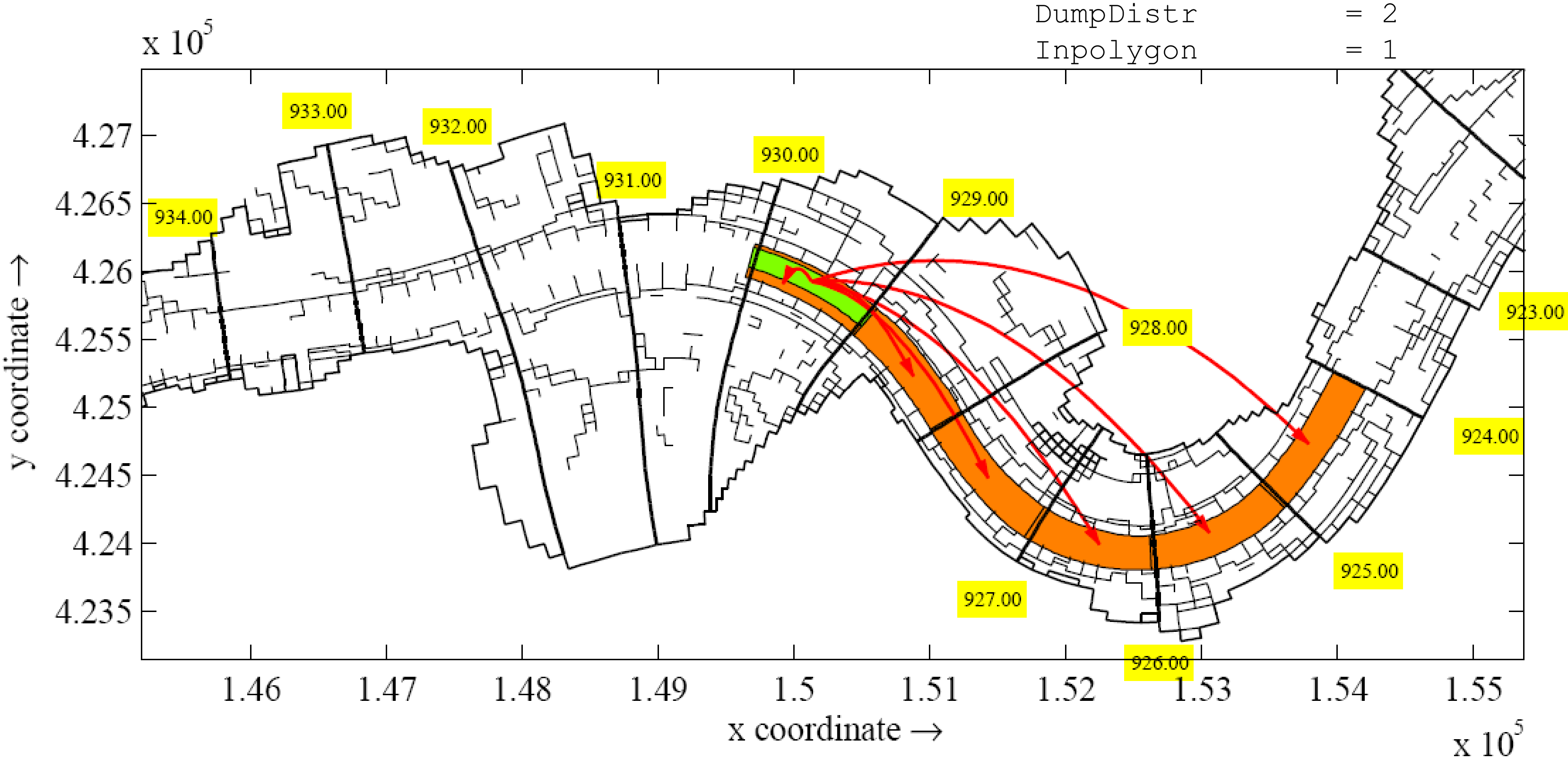


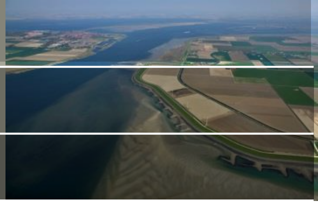
← results

Dredging model

- Dredging and dumping according to prescribe criteria
- Dredging in specified areas and dumping at a prescribed distance upstream

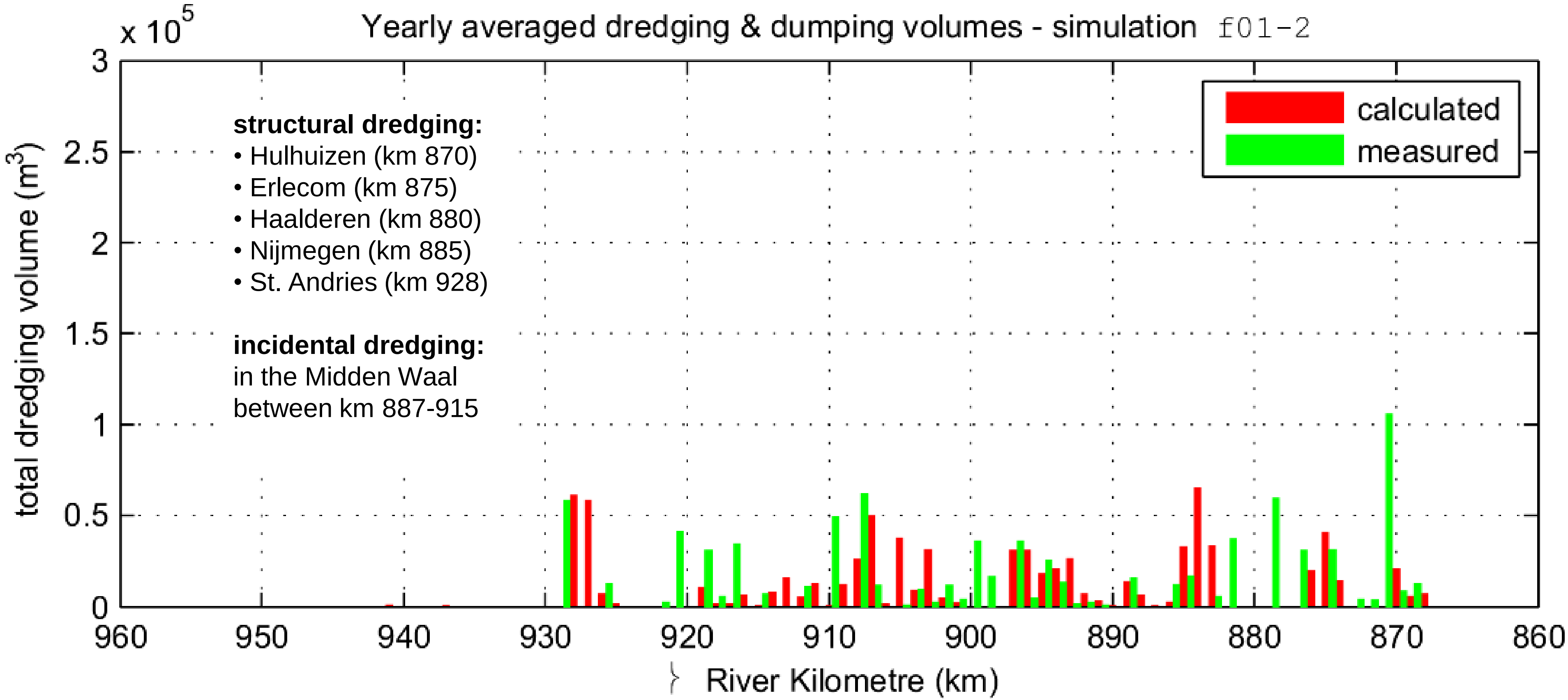
```
PolygonFile        = Dredge150b.pol
MaxVolRate         = 1.0E16
DredgeDepth        = 2.80
Clearance          = 0.30
MinimumDumpDepth   = 2.5
AlphaDuneHeight    = 0.5
DredgeDistr        = 2
DumpDistr          = 2
Inpolygon          = 1
```





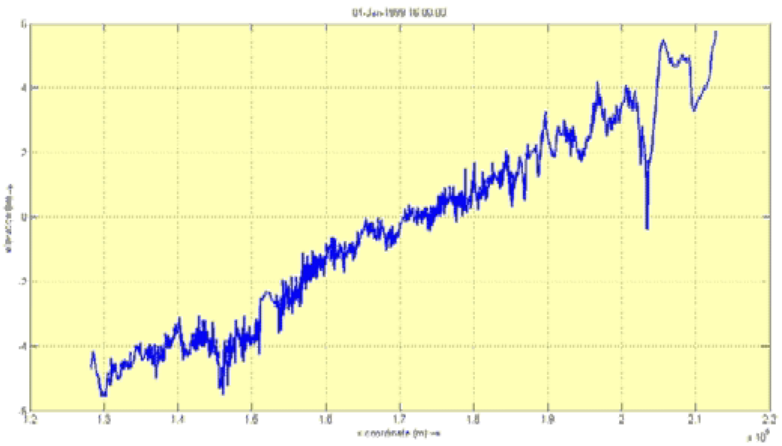
Dredging model

- Comparison with data 2000-2002: confirms that Upper Waal dominated by dredging in bends (structural), and the Middle Waal due to dunes (incidental)

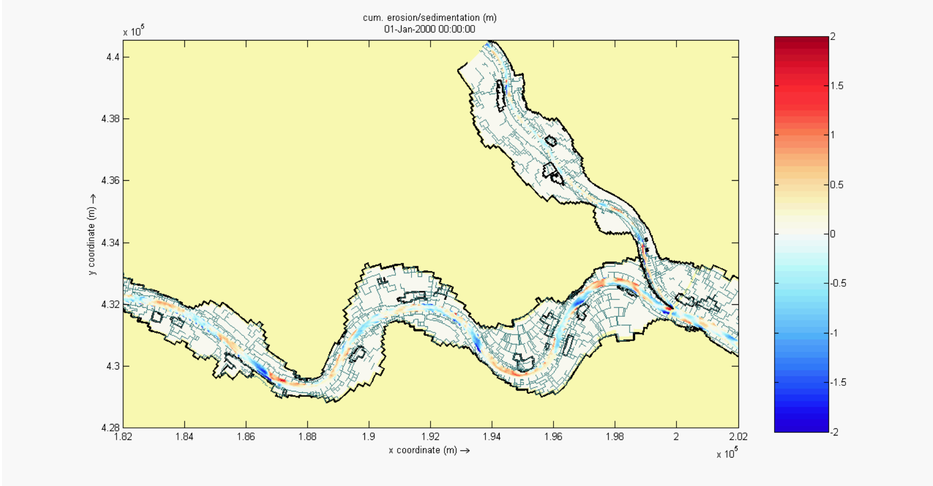


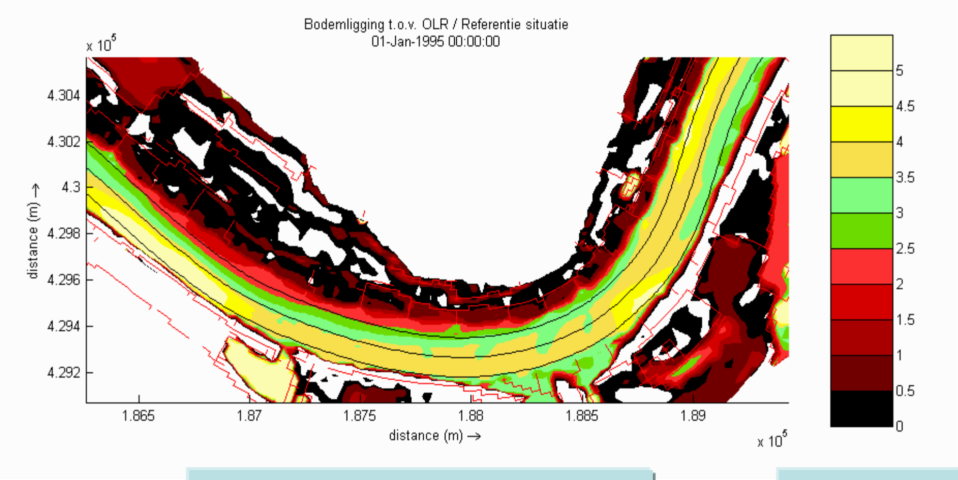
Rhine Model – overall results

1D-behaviour (40-years)

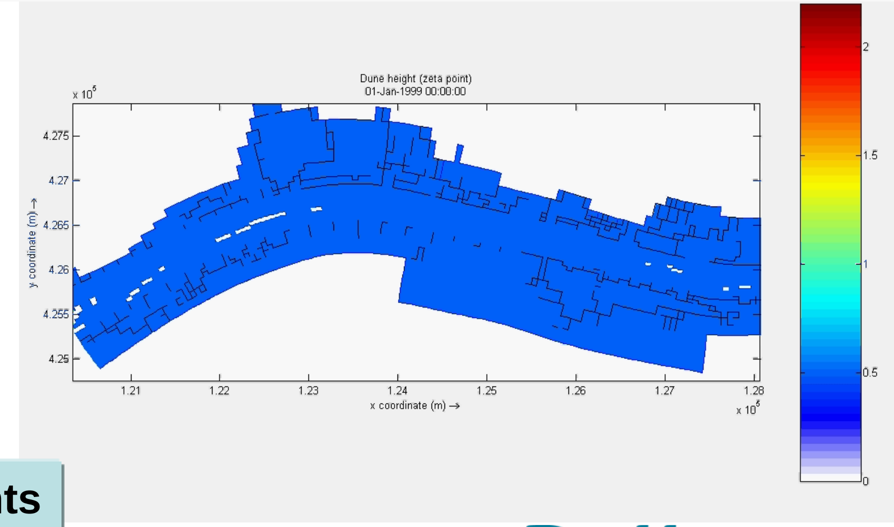


2D-behaviour (40-years)



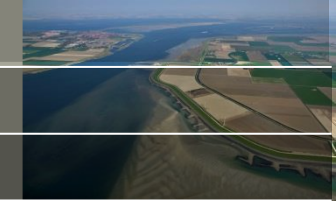


2D-behaviour (detail)

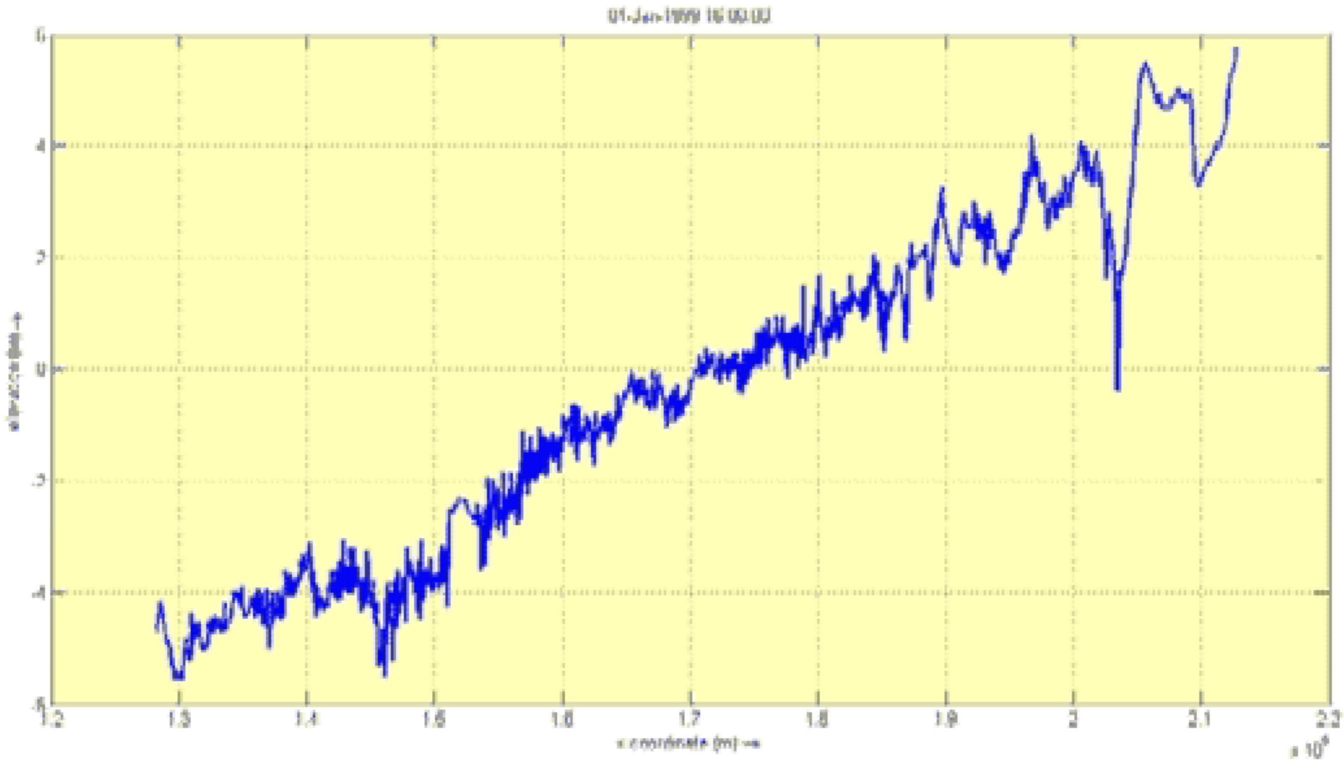


Dune heights

Rhine Model – 1D behaviour



1D-behaviour (40-years)

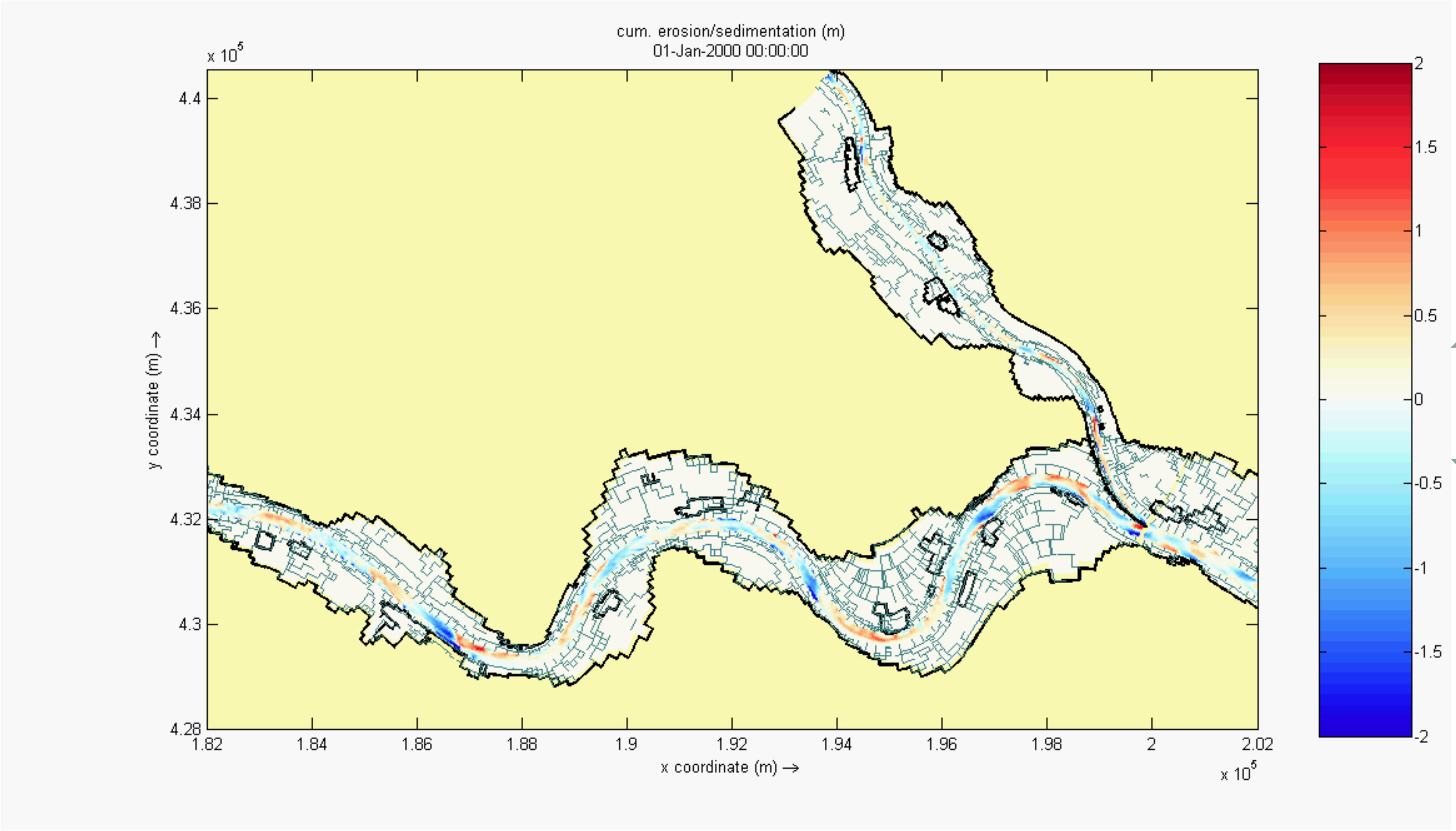


Cross-section averaged bed level
black → initial

Deltares

Rhine Model – 2D large-scale

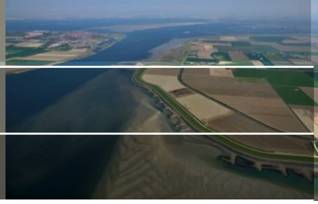
2D-behaviour (40-years)



deposition

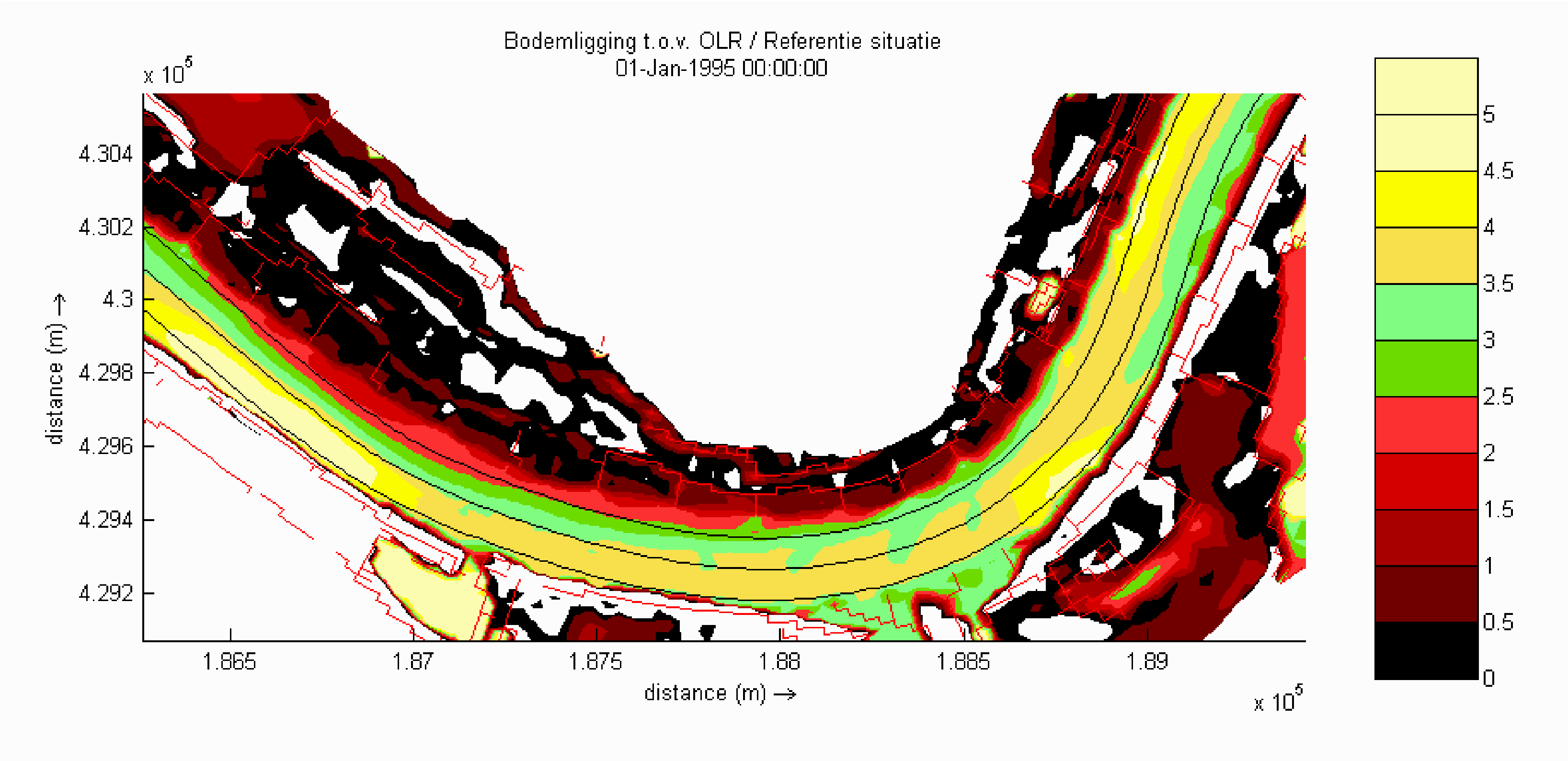
erosion

Deltares

Rhine Model – 2D local

2D-behaviour (detail)
depth (m)



Black lines define navigation channel
red colors too shallow

Case studies

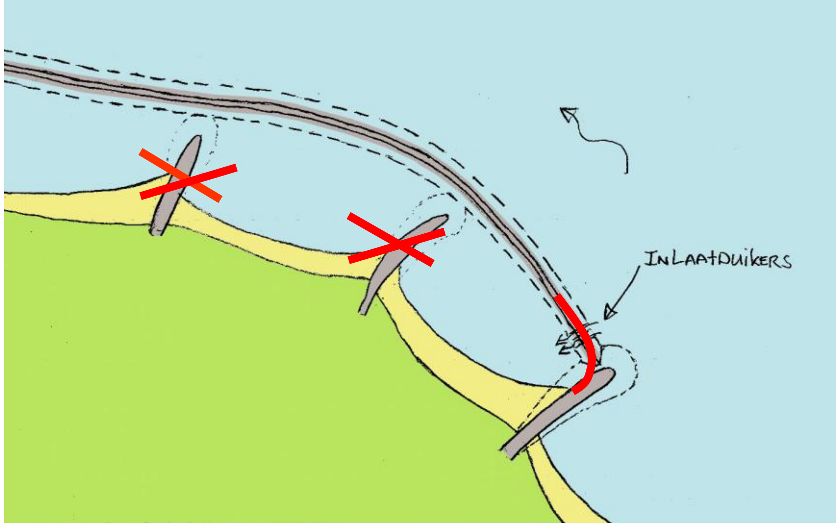
- Effect of longitudinal dams
- Dredging the navigation channel
- Sediment nourishment experiment

Effect of longitudinal dams

Longitudinal dams to replace groyne lowering

Function:

- constriction of main channel during discharges below bank full
- increase flood conveyance capacity during floods



Parallelwerk Walsum-Stap, Rijn km 793,5 – 795.
Wasser- und Schiffahrtsverwaltung des Bundes,
Wasser- und Schifffahrtsdirection West

Effect of longitudinal dams

The effect is due to:

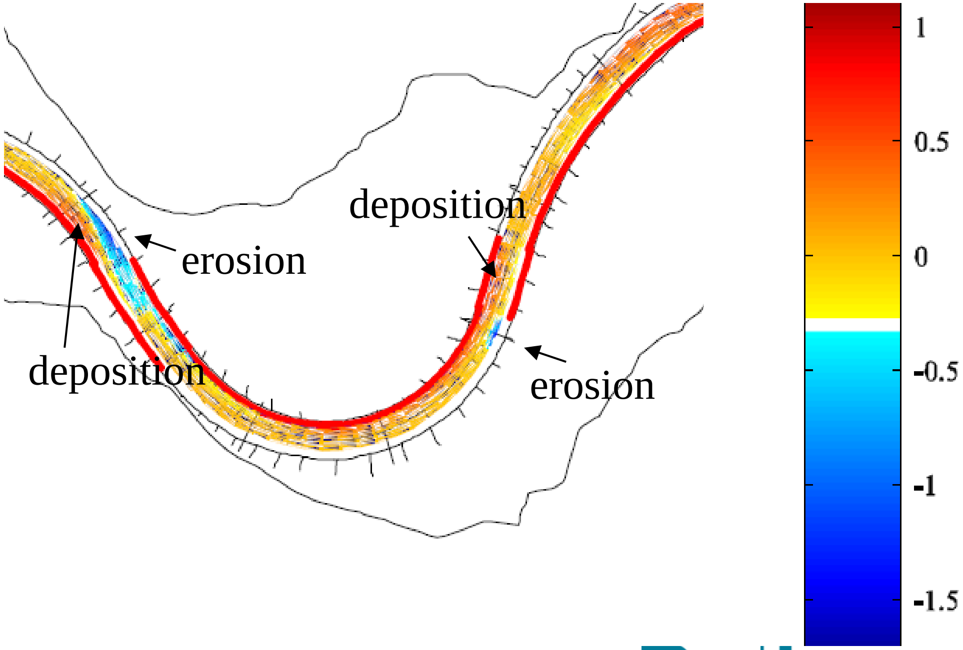
- channel constriction,
- discharge extraction and supply.

Main conclusion:

- The **local effect** of longitudinal dams are rather significant.

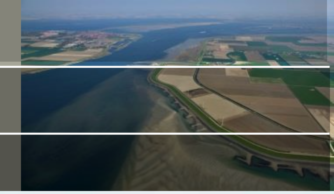
  ➔ This calls for optimization of the inflow and outflow sections,

  ➔ we need an additional analysis tool



Deltares

Dredging the navigation channel



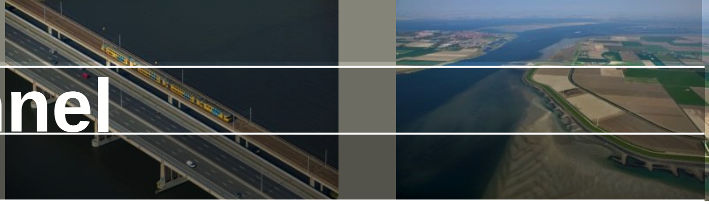
Evaluation of dredging volumes for:

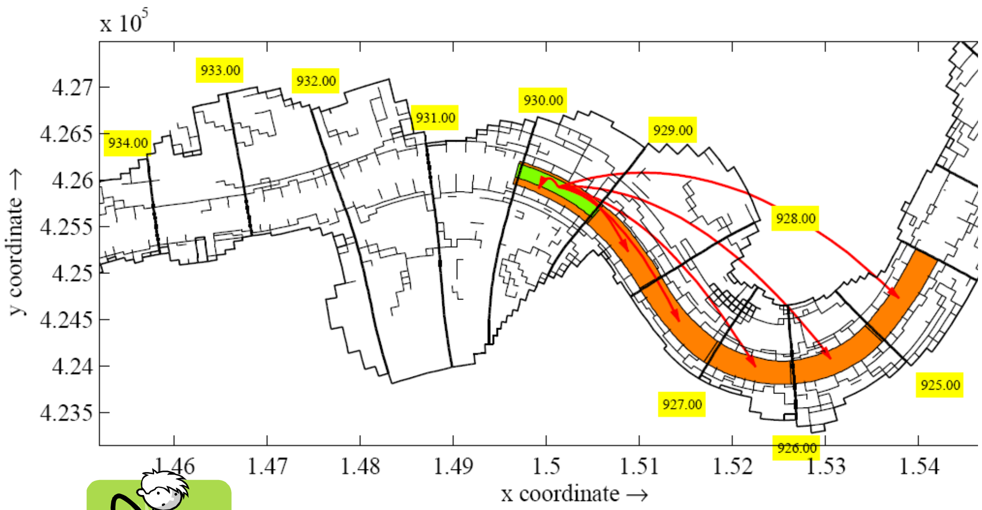
- **Navigation channel of 150 m x 2.50 m (Case B150)**
- **Navigation channel of 170 m x 2.50 m (Case B170)**
- **Navigation channel of 150 m x 2.80 m (Case B152)**

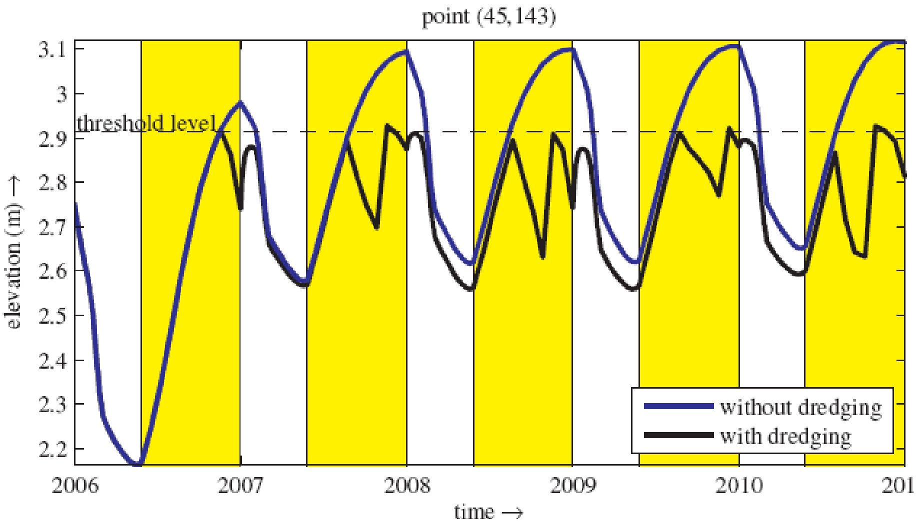
This called for additional functionalities to be implemented:

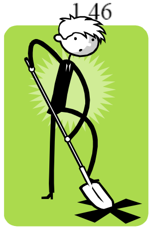
- **Dredging and Nourishment intervals**
- **Sequential dumping in a series of dumping blocks**
- **Dredging considering dune heights (not utilised yet)**

Dredging the Navigation Channel

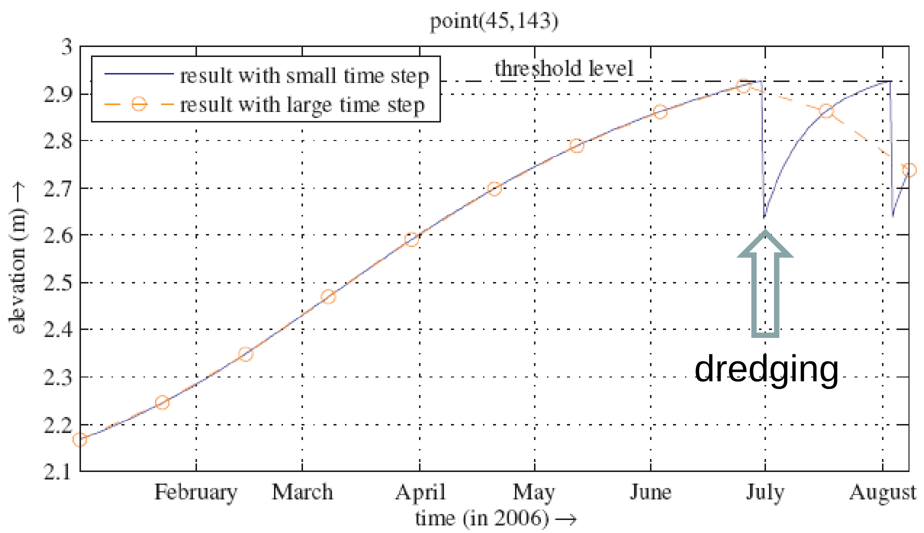




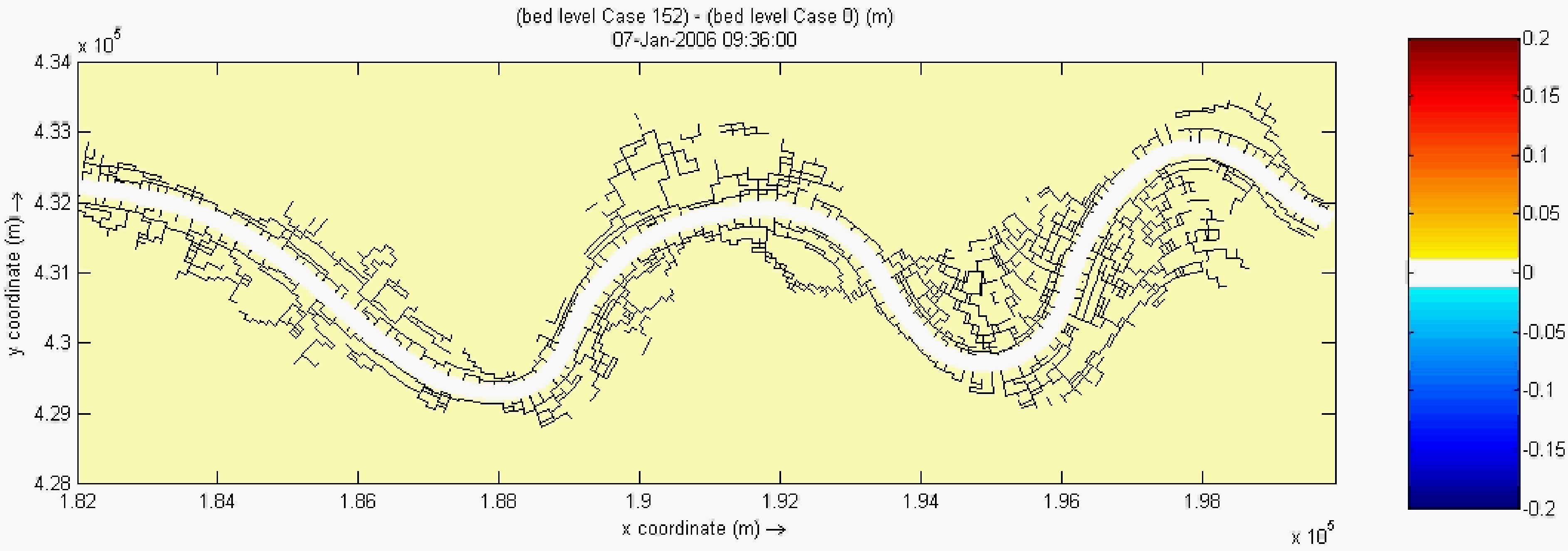




Dredging from the navigation channel and dumping in the normal line; with a 1.0 km unit.

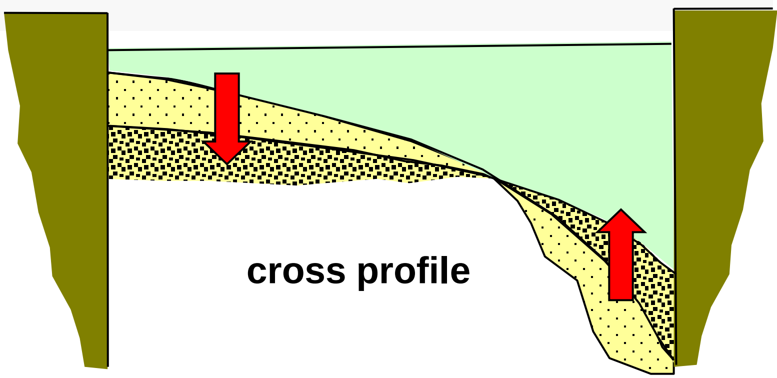


Morphological response to dredging



simulation of 10 years (bed level difference)
see the effect of dredging near the end
red is dumping
blue is dredging

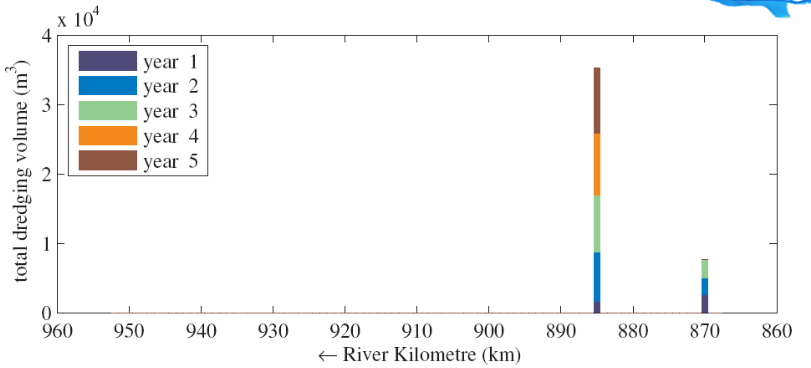
Dredging also affects the transverse cross-section, it is not a simple 1D problem



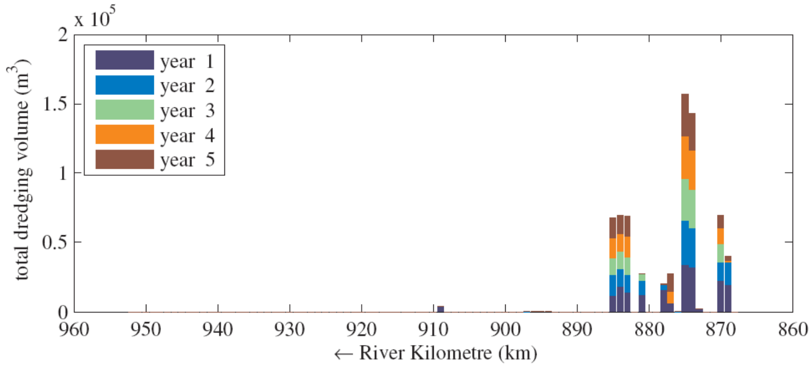
Deltares

Effect of channel dimensions on dredging volumes

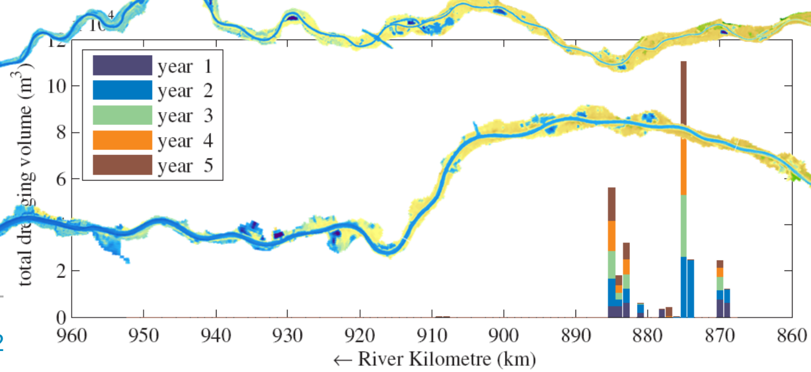
width = 150m & depth 2.50m: **43,000** m³



<u>width</u> = 170m & depth 2.50 m: **700,000** m³ (x16 times)

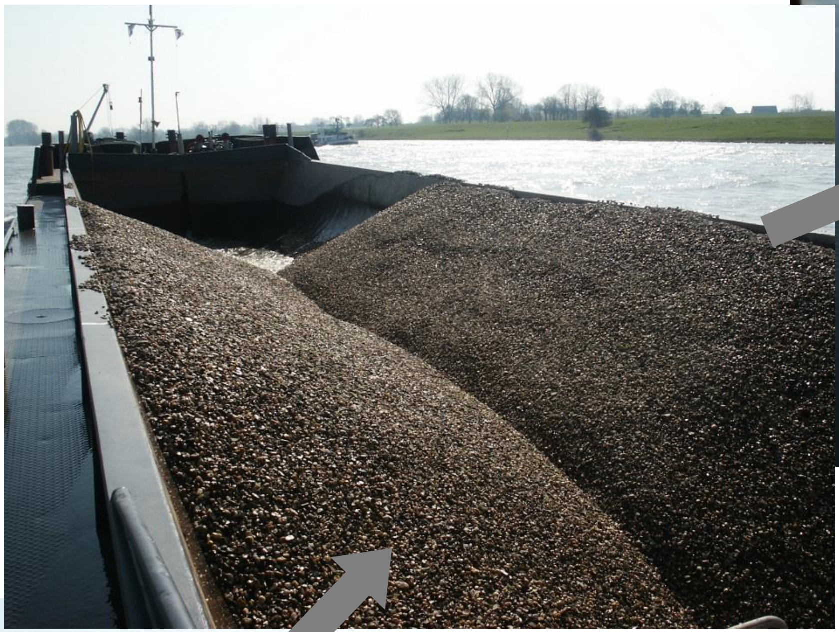


width 150m & <u>depth</u> 2.80 m: **290,000** m³ (x7 times)

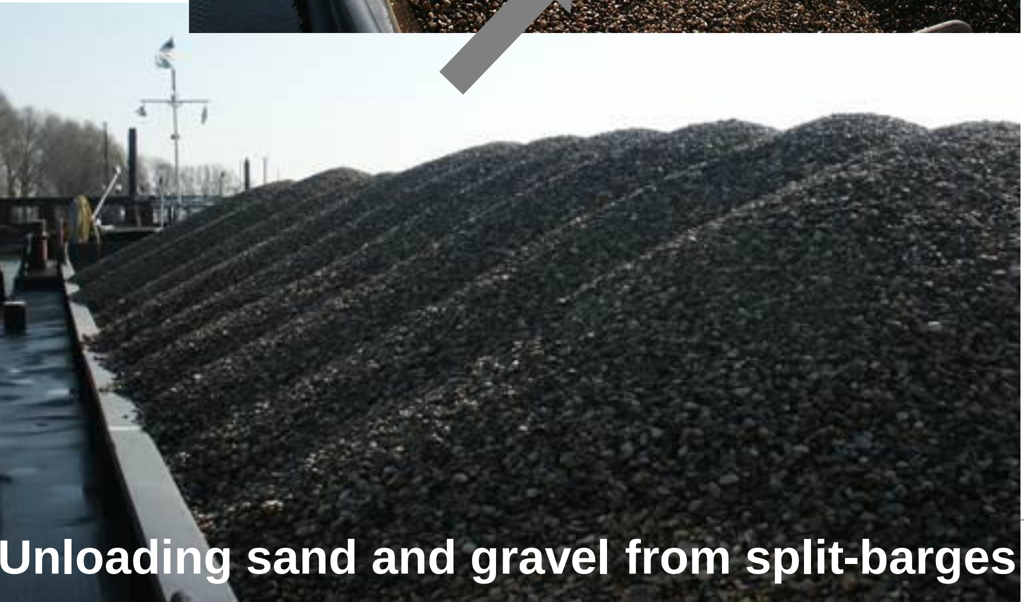


eltares

Sediment nourishment



photos Rees



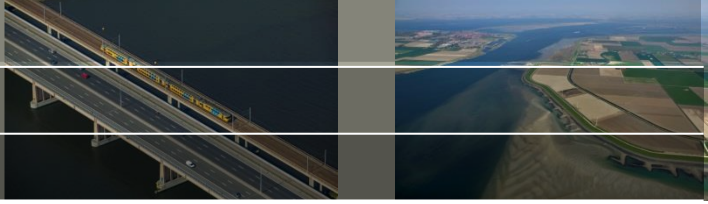
Unloading sand and gravel from split-barges

Key parameters for success are:

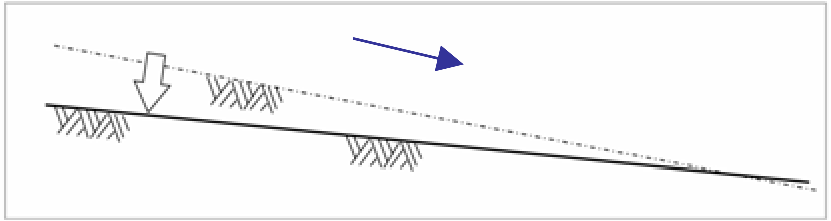
- Quantity
- Location and section-length
- **Composition** of sand/gravel mixture

Modeling is needed for optimization!

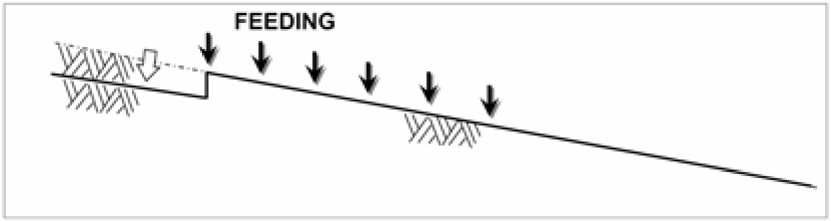
Sediment nourishment

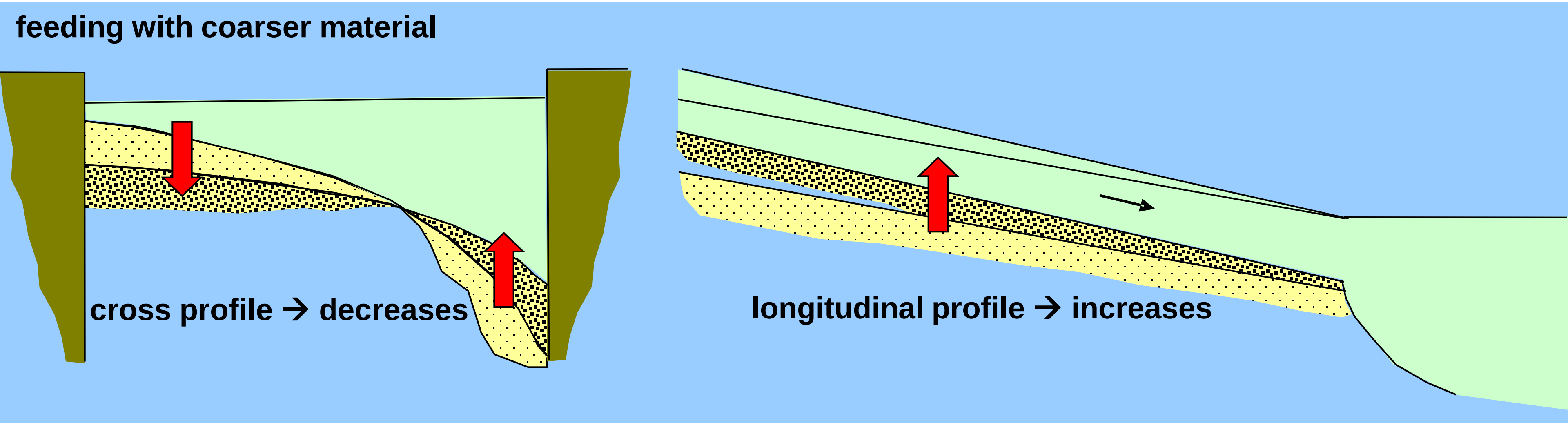


Stop degradation by levelling-off the sediment-transport gradient



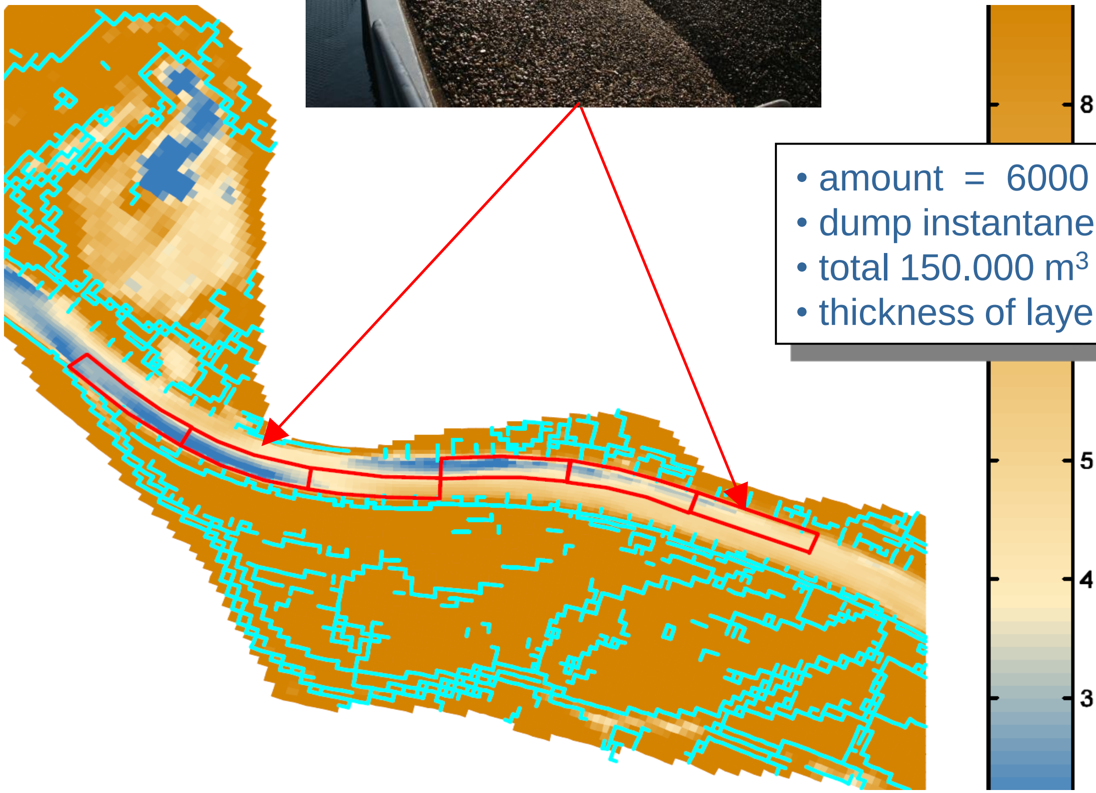
Increase efficiency by dumping coarse sediment (coarser than original bed composition)





Deltares

Sediment nourishment → test Bovenrijn

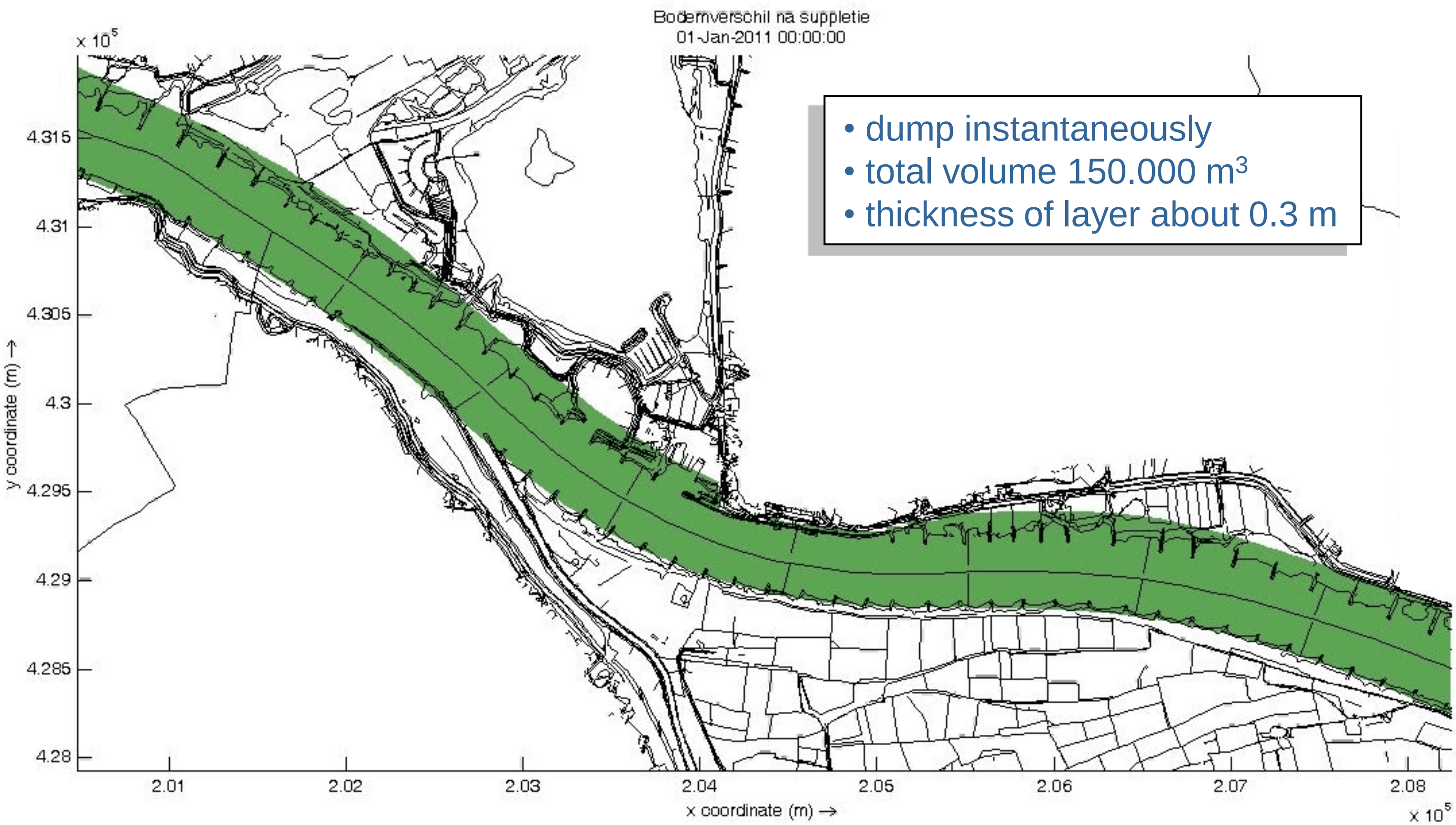


- amount = 6000 ton/week
- dump instantaneously
- total 150.000 m^3
- thickness of layer about 0.3 m

Deltares

Sediment nourishment behaviour

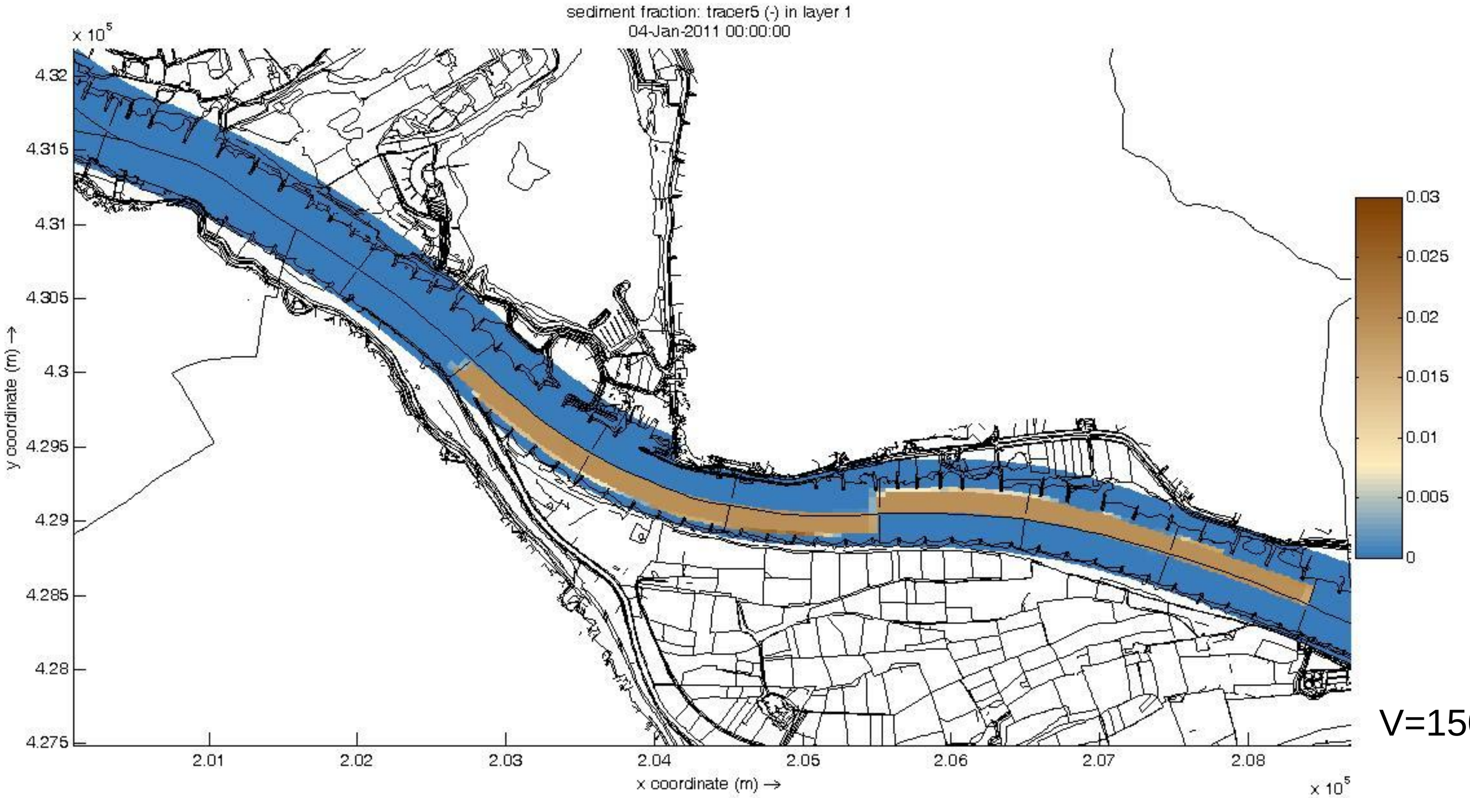
Δz = “Bed-level Nourished (t)” minus “Bed-level Reference (t)”



- dump instantaneously
- total volume 150.000 m^3
- thickness of layer about 0.3 m

Deltares

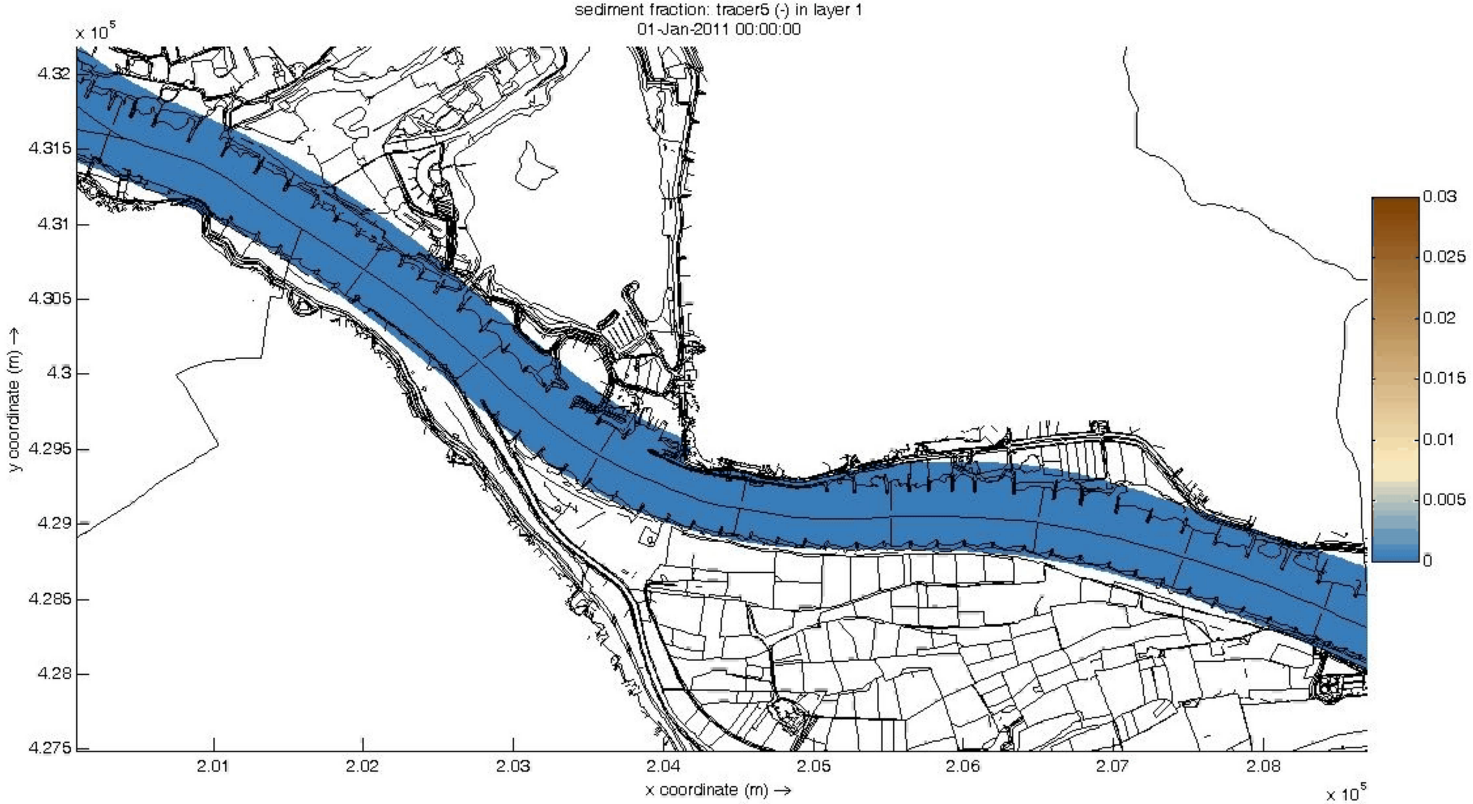
Result - Nourishment test near Lobith



V=150,000 m^3

spreading of tracer fraction

Result - Nourishment test near Lobith



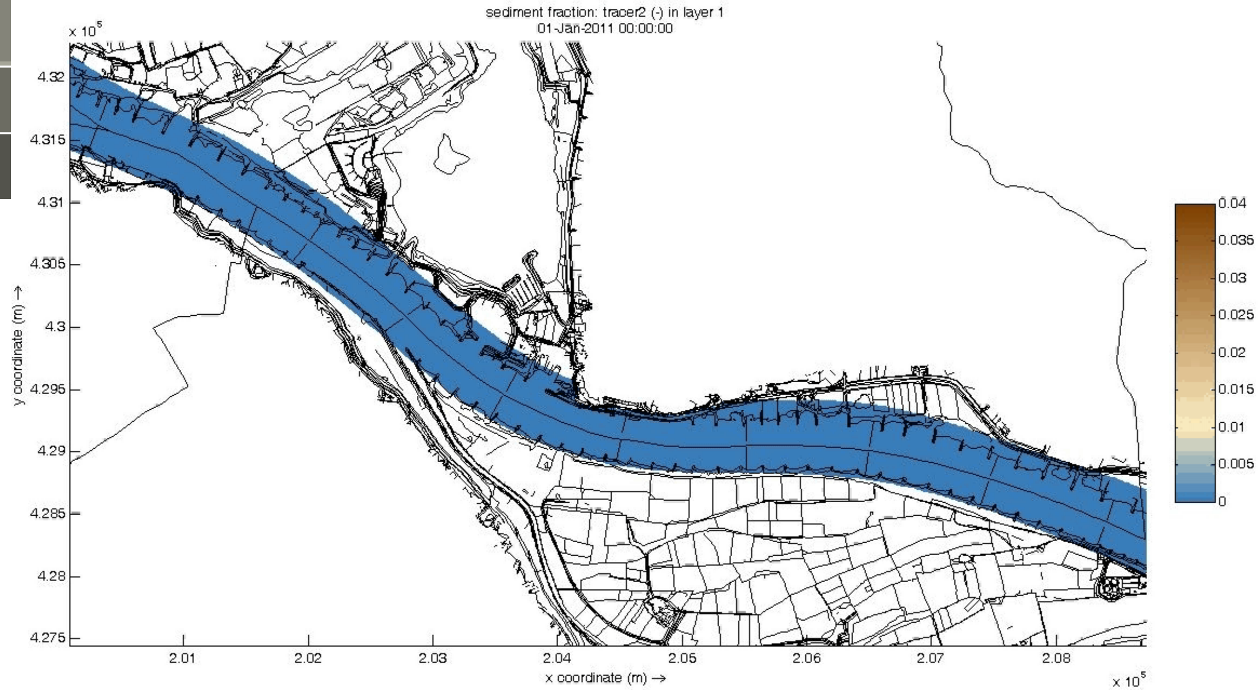
spreading of tracer fraction

Deltares

Tracer. 2

0.5 < D < 1 mm

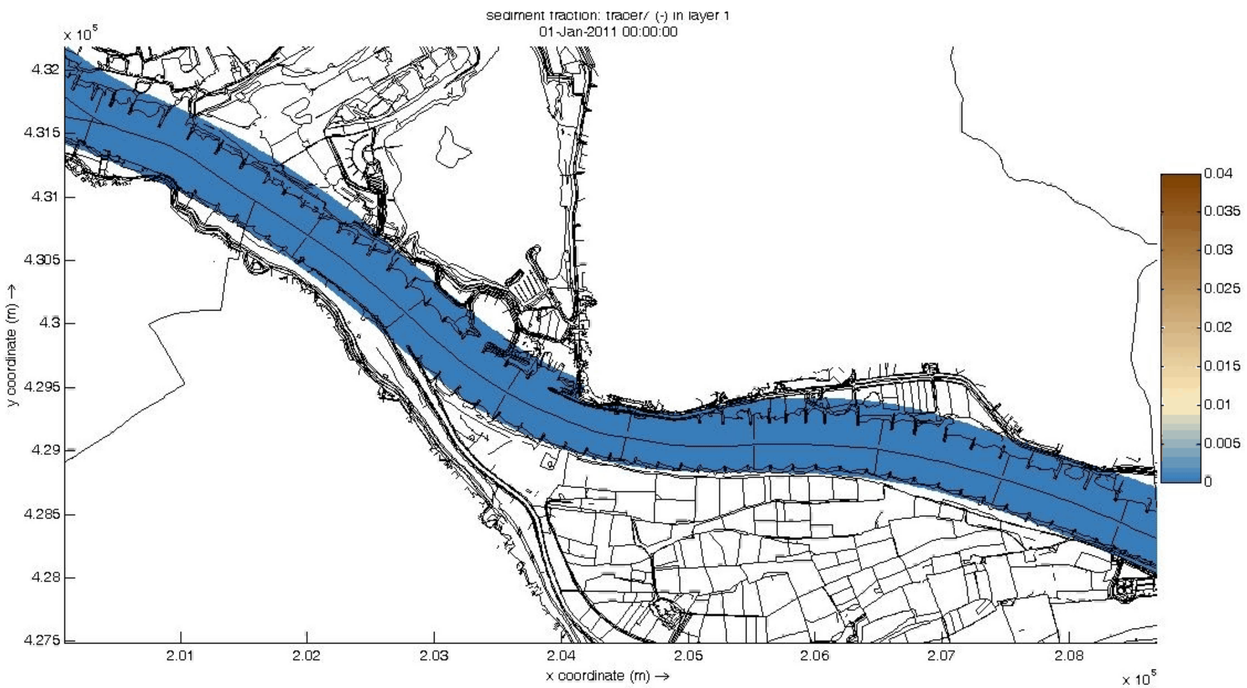
(**fine**)



Tracer. 7

8 < D < 16 mm

(**coarse**)



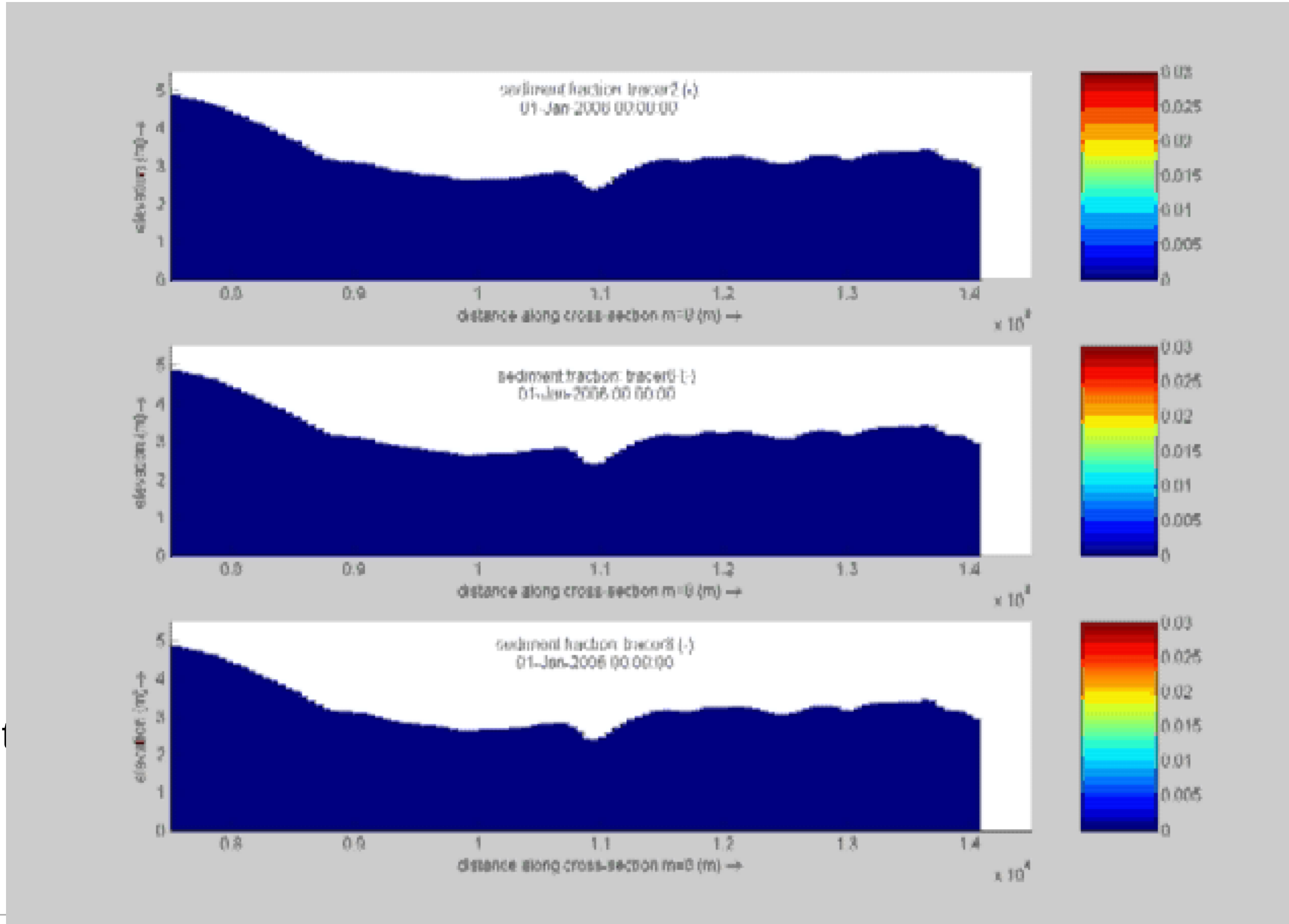
.tares

Propagation speed of different fractions

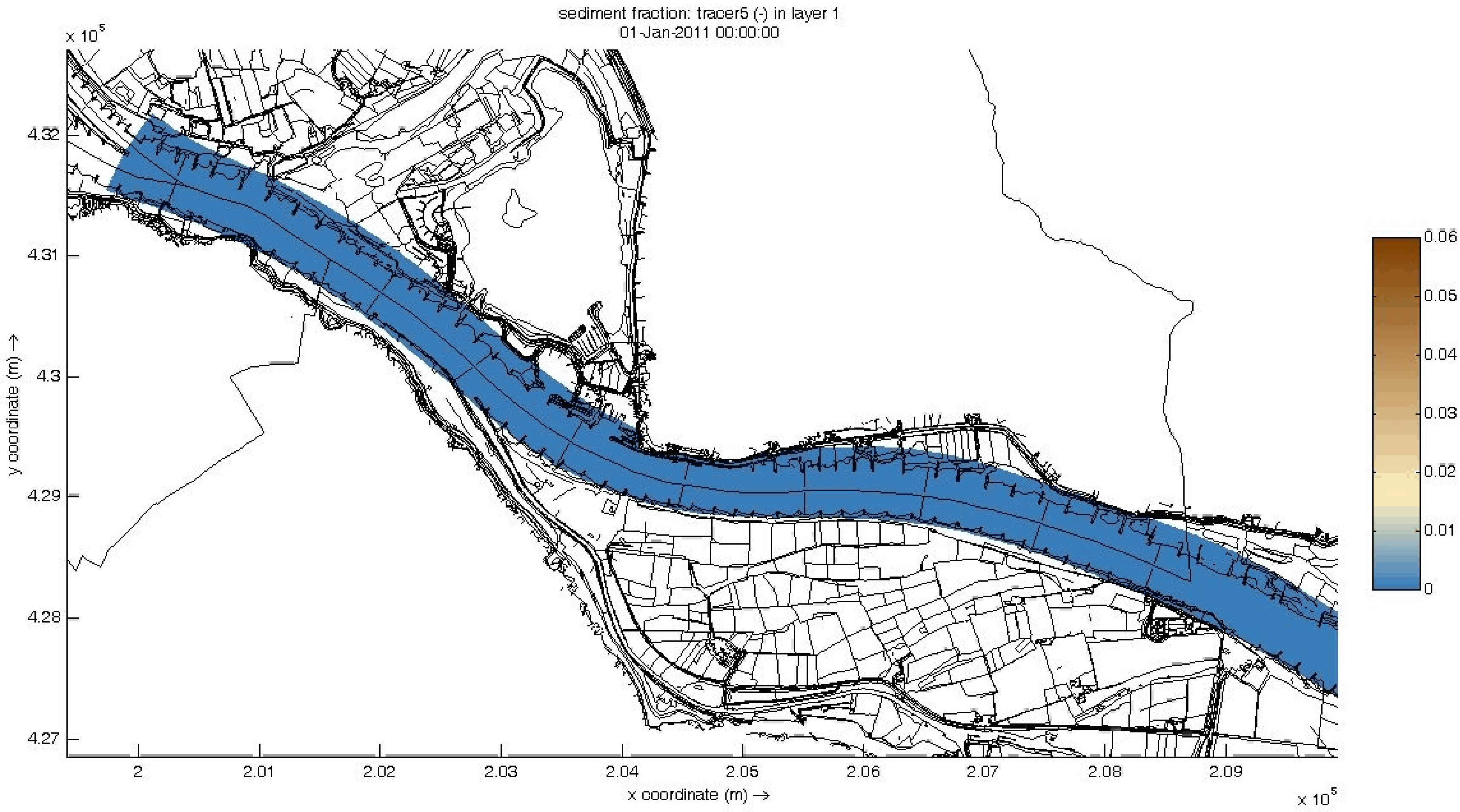
Fine

Medium

Coarse
partial mobilit



Yearly repeated feeding (150,000 m³/yr)



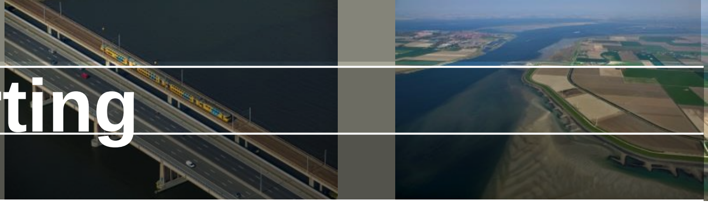
Overall conclusions

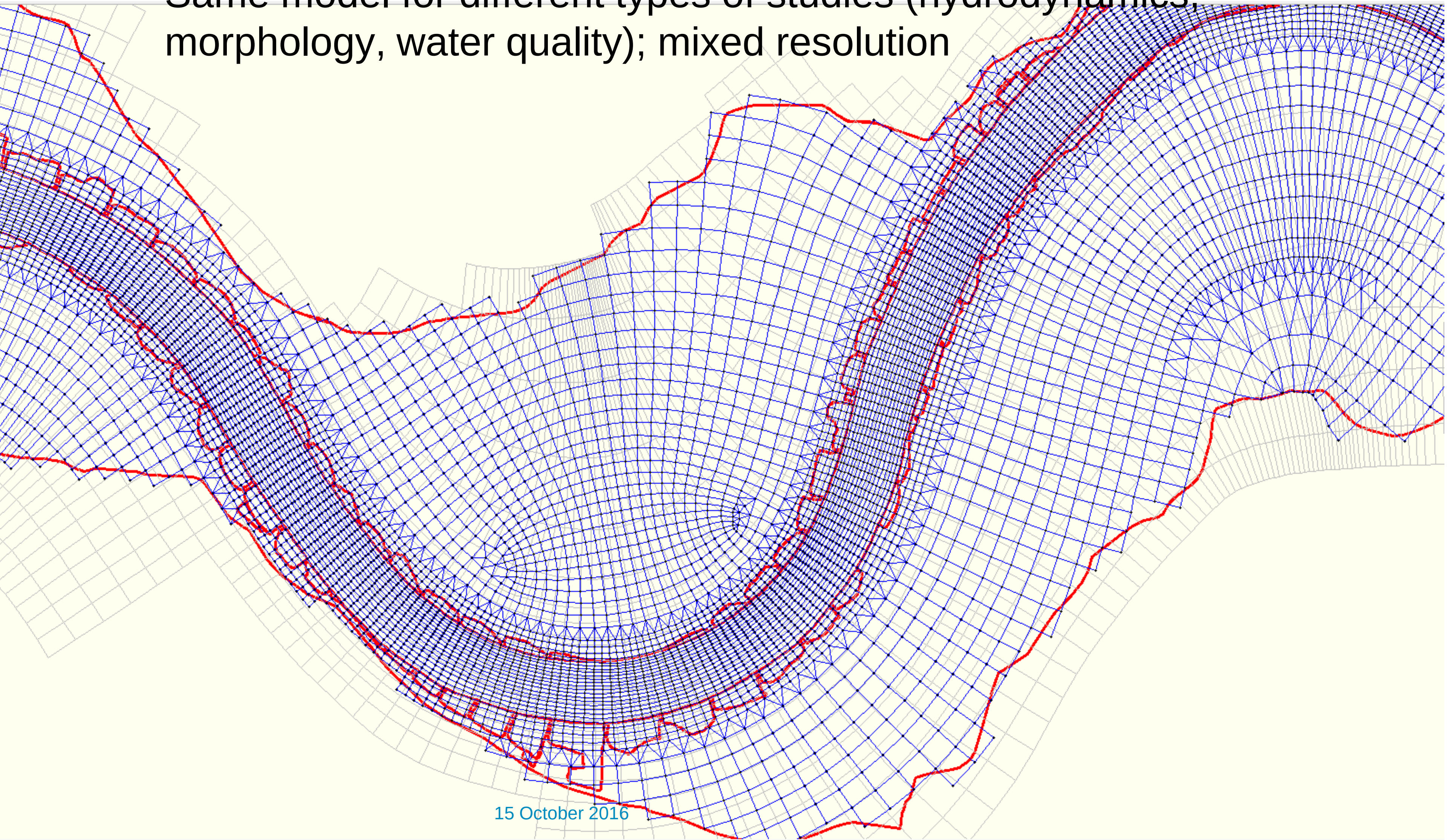
- We have a morphological model that covers the Rhine Branches in the Netherlands.
- Well calibrated
  - Hydrodynamics
  - 1D morphological behaviour ← bed celerity
  - 2D morphological behaviour ← bar-pool pattern
- Unique model:
  - Large-scale, yet detailed
  - Refined dredging and dumping
  - Able to simulate different types of measures
  - rather fast, 40 years in 4 days.
- The model can be used effectively for evaluation of the effect of different engineering measures with continuous application in projects
- The model is disseminated to all consultants in the Netherlands for application in different projects
- Processes extended to include graded sediment (not discussed today)

Deltares

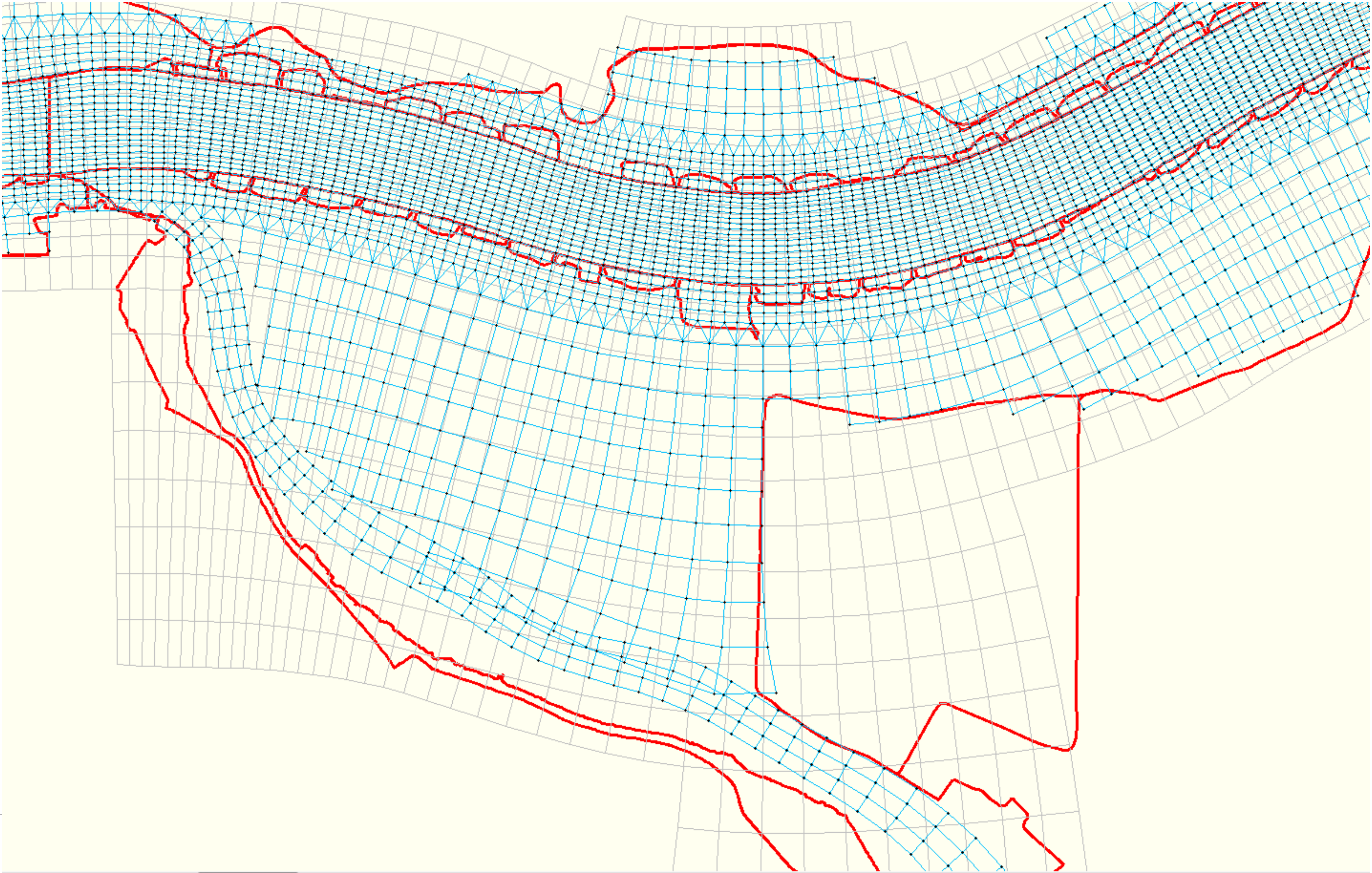
Moving to flexible mesh – starting

- More flexibility
- Same model for different types of studies (hydrodynamics, morphology, water quality); mixed resolution

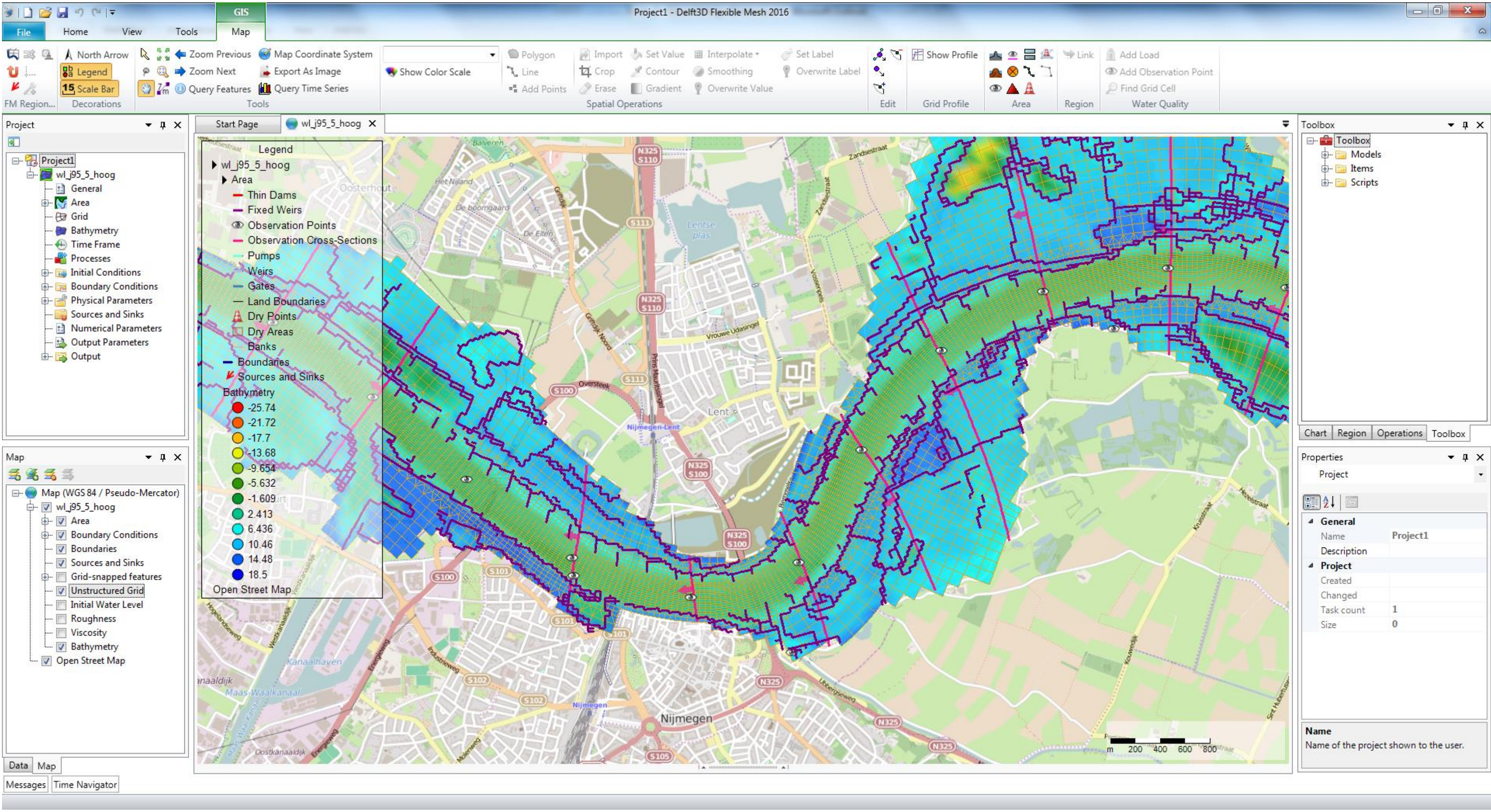




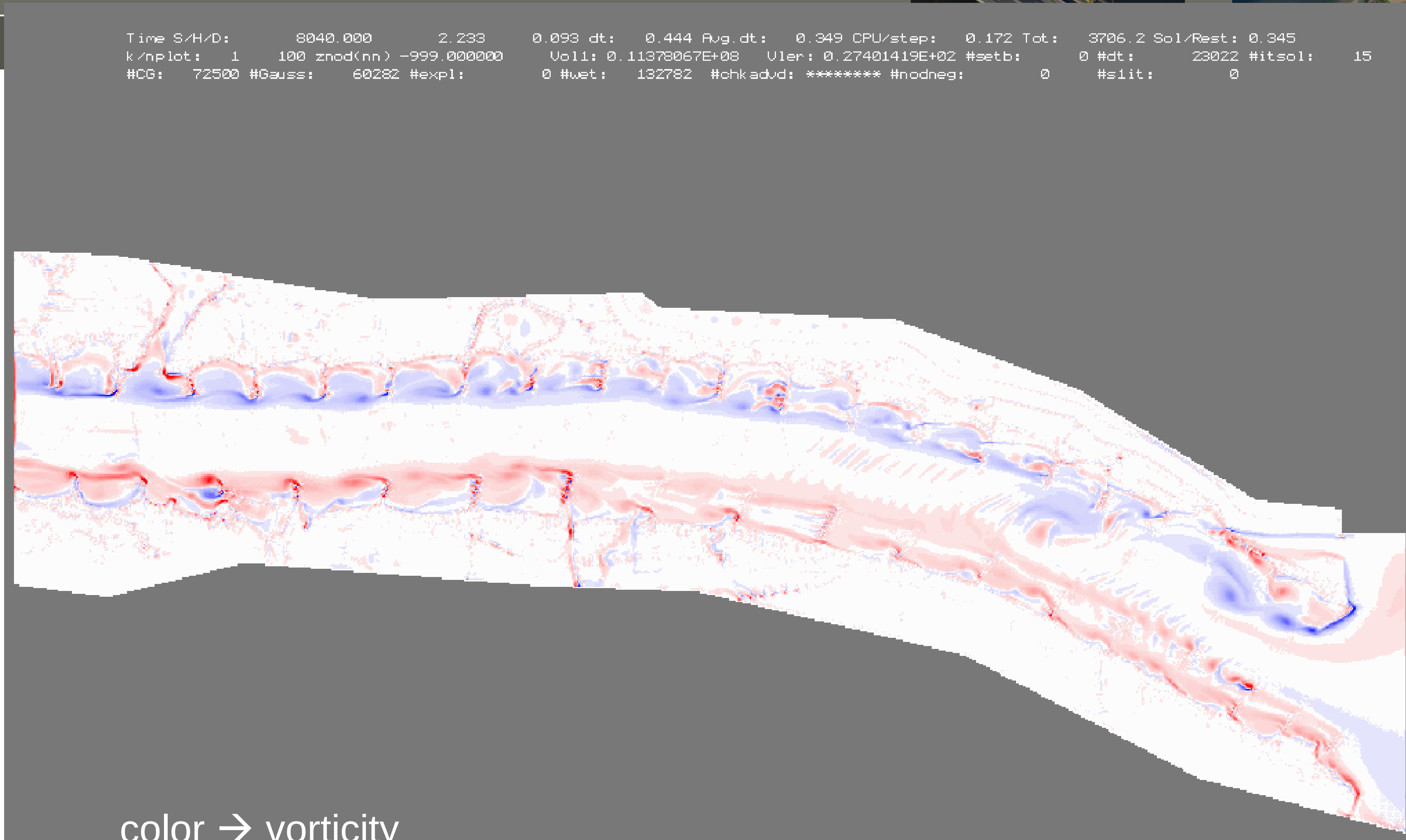
Moving to flexible mesh – starting



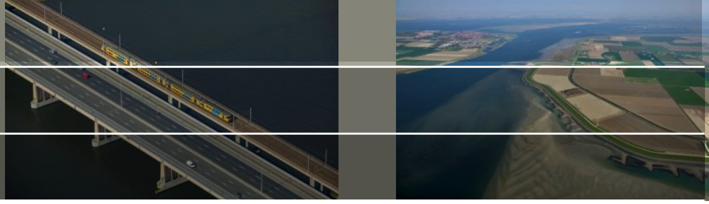
Moving to flexible mesh – starting



Deltares



color → vorticity



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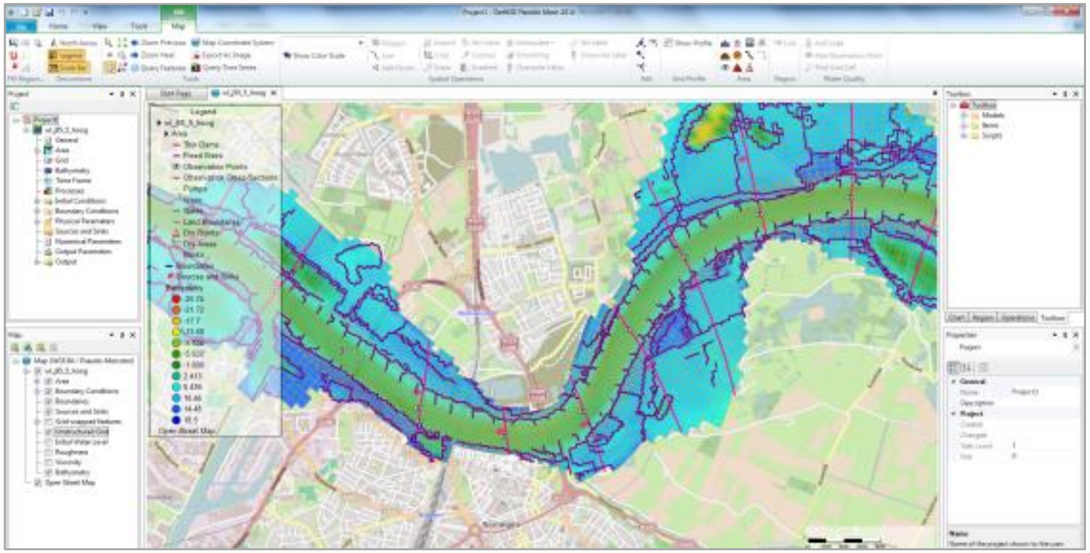
Course

Delft3D Flexible Mesh – River modeling 26-27 October 2016

- 1D and 2D river hydrodynamics
- Real-time control
- Automatic calibration with OpenDA
- Python scripting



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Deltares