Morphological model of the River Rhine branches in The Netherlands

from the concept to the operational model

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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)
• Client: Rijkswaterstaat Oost-Nederland: the river manager
• Target: maintain a sustainable navigation channel NL+D.
• The project is called “Duurzame Vaardiepte Rijndelta”
  (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**

- **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 Deltasres)

- **2010**
  - Update of the model (extend the hydrograph)
  - Testing several measures (different consultants, supported by Deltasres)

- **2011**
  - Testing measures (different consultants, supported by Deltasres)

- **2012-2014**
  - Improvements and Application to give advice (Deltasres & different consultants)

- **2015**
  - Extension to **graded sediment** and nourishment testing (Deltasres)

- **2016-2017**
  - Migration to flexible mesh
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).
Use of domain decomposition at bifurcations
Example grids ➔ impact on results
Example grids $\rightarrow$ impact on results

Unit discharge \([m^2/s]\) for grid 'or' at upstream discharge \(Q = 3080 \, m^3/s\)
Example grids $\Rightarrow$ impact on results

Unit discharge [m$^2$/s] for grid 'r1' at upstream discharge $Q = 3080$ m$^3$/s
Example grids $\rightarrow$ impact on results

Unit discharge [m$^2$/s] for grid 'r1c' at upstream discharge $Q = 3080$ m$^3$/s
Example grids $\rightarrow$ impact on results

Unit discharge [m$^2$/s] for grid 'or2' at upstream discharge Q = 3080 m$^3$/s
Model construction → Grid characteristics

<table>
<thead>
<tr>
<th>Gridname</th>
<th>Bovenrijn</th>
<th>Waal – part a</th>
<th>Waal – part b</th>
<th>Waal – part c</th>
<th>Pannerdensch Kannal</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of grid cells</td>
<td>≈ 68 000</td>
<td>55x177 9735</td>
<td>47x296 13616</td>
<td>47x401 18847</td>
<td>47x353 16591</td>
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<tr>
<td></td>
<td></td>
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<td>67x137 9179</td>
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<tr>
<td>main channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of grid cells</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
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<td>21</td>
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<tr>
<td></td>
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<td></td>
<td></td>
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<tr>
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<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>aspect ratio</td>
<td></td>
<td>1:2.4</td>
<td>1:3.4</td>
<td>1:3.8</td>
<td>1:3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1:4</td>
</tr>
</tbody>
</table>
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
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
Discharge schematisation → upstream boundary

1. Detailed histogram vs schematised histogram
2. CDF of discharge
3. Cumulative percentage of time equalled or exceeded
4. Discharge over time
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
- \( \text{morfac} \) is inversely proportional to discharge

\[
\begin{align*}
Q_1 &\quad & Q_2 &\quad & Q_3 \\
\text{Hydrodynamic time} &\quad & \text{Morphological time}
\end{align*}
\]
Simulation management tool → running long simulations

Operated using Python scripts

database

restart file

Q1

hydrodynamic parameters

Q2

morphodynamic parameters

Q3

ETCETERA

Operated using Python scripts

Simulation management tool → running long simulations
Dredging
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)
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
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 $(S = m u^n)$ 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.
with

1. It is recommended to introduce the following changes:

A Van Rijn (1984)

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

\[ S = S_a + S_b \]  

where:

\[ S_a = \frac{0.053 \sqrt{g D_{50}^2 \gamma T}}{D_0^{0.65} T^0.4} \] for \( T < 3.0 \)

\[ S_b = \frac{0.1 \sqrt{g D_{50}^2 \gamma T}}{D_0^{0.65} T^0.4} \] for \( T \geq 3.0 \)  

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

\[ T = \frac{\tau_{wb} - \tau_p}{\tau_c} \]  

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

\[ \tau_{cwb} = \gamma D_0 \theta \]  

\[ f_a = \frac{0.24 \log \left( \frac{12b}{z_c^*} \right)}{C_c} \]  

\[ C_c = \left( \frac{12b}{3D_h} \right) \]  

where \( C_c \) is the grain related Chézy coefficient:

\[ C_c = \frac{12b}{3D_h} \]  

The critical shear stress is written according to Shields:

\[ \tau_{cwb} = \gamma D_0 \theta \]  

In which \( \theta \) is the critical Shields parameter for initiation of motion, which is a function of the dimensionless particle parameter \( D_c \):

\[ D_c = \frac{\Delta g D_{50}}{\nu^2} \]  

The suspended transport formulation reads:

\[ S = f_a u h C_c \]  

In which \( C_c \) is the reference concentration, \( u \) depth averaged velocity, \( h \) the water depth and \( f_a \) is a shape factor of which only an approximate solution exists:

\[ f_a = \begin{cases} f_d (\xi) & \text{if } \xi \geq 1.2 \\ f_s (\xi) & \text{if } \xi = 1.2 \end{cases} \]  

\[ f_d (\xi) = \frac{\left( \frac{\xi}{h} \right)^0.5 - (\xi / h)^0.25}{(1 - \xi / h) \left( 1.2 - \xi \right)} \]  

\[ f_s (\xi) = \frac{\left( \frac{\xi}{h} \right)^0.5 - (\xi / h)^0.25}{(1 - \xi / h) \left( 1.2 - \xi \right)} \]  

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

\[ \zeta = \min \left\{ \frac{20 \frac{w_r}{\beta \kappa u}}{\beta \kappa u} + \phi \right\} \]  

\[ u_r = \sqrt{\frac{f_d}{\kappa}} \]  

\[ \beta = \min \left\{ 1.5 + 2 \left( \frac{w_r}{u_r} \right) \right\} \]  

\[ \phi = 2.5 \left( \frac{w_r}{u_r} \right) \left( \frac{C_r}{0.65} \right)^{0.4} \]  

The reference concentration is written as:

\[ C_r = 0.015 \alpha_{w_r} \frac{D_{50}}{\gamma} \]  

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 ($\alpha_{\text{BED}}$ and $\alpha_{\text{SUS}}$),
  
  • 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:
- $\alpha$ (coefficient in transport formula)
- $\theta_{cr}$
- $D_{50} = f(x)$
- $D_{90} \approx 4 \times D_{50}$

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

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

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)
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]
Firstly, sediment budget for the Rhine branches

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

Cross-section and reach-averaged yearly bed level change

Cross-section and reach-averaged bed level gradient
Calibration result – 1D (trench)

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

\[ \Delta z (m) \]

\[ \text{river chainage (km)} \]

0 days
375 days
751 days
1128 days
1505 days
1881 days

15 October 2016
Calibration result – 1D (trench)

1 km/year
2D calibration

Bed level with respect to reference level along the left and right banks

2000
2001
2002
2003
2004
2005
2006
Time-averaged multibeam measurements 1999–2006

Bed level change in 7 years with Ashfield = 0.7

Multibeam measurement 1999
Multibeam measurement 2000
Multibeam measurement 2001
Multibeam measurement 2002
Multibeam measurement 2003
Multibeam measurement 2004
Multibeam measurement 2005
Multibeam measurement 2006
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**

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bdf</td>
<td>Y</td>
</tr>
<tr>
<td>BdfMor</td>
<td>Y</td>
</tr>
<tr>
<td><strong>BdfH</strong></td>
<td>FredsoeMPM</td>
</tr>
<tr>
<td>BdfL</td>
<td>vanRijn84</td>
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<tr>
<td>BdfR</td>
<td>vanRijn84</td>
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<td>BdfEps</td>
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<td>BdfRlx</td>
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<td>BdfADV</td>
<td>N</td>
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<tr>
<td>BdfThetaC</td>
<td>0.047</td>
</tr>
</tbody>
</table>

← results
Dredging model

- Dredging and dumping according to prescribed 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)

**Structural dredging:**
- Hulhuizen (km 870)
- Erlecom (km 875)
- Haalderen (km 880)
- Nijmegen (km 885)
- St. Andries (km 928)

**Incidental dredging:**
in the Midden Waal between km 887-915
Rhine Model – overall results

1D-behaviour (40-years)

2D-behaviour (40-years)

2D-behaviour (detail)

Dune heights
1D-behaviour (40-years)

Cross-section averaged bed level
black → initial
Rhine Model – 2D large-scale

2D-behaviour (40-years)

deposition

erosion
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 Schifffahrtsverwaltung des Bundes, Wasser- und Schifffahrtsdirektion 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
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 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
Effect of channel dimensions on dredging volumes

width = 150m & depth 2.50m: 43,000 m³

width = 170m & depth 2.50 m: 700,000 m³ (x16 times)

width 150m & depth 2.80 m: 290,000 m³ (x7 times)
Sediment nourishment

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)
Sediment nourishment → test Bovenrijn

- amount = 6000 ton/week
- dump instantaneously
- total 150,000 m³
- thickness of layer about 0.3 m
Sediment nourishment behaviour

\[ \Delta z = \text{“Bed-level Nourished (t)” minus “Bed-level Reference (t)”} \]

- dump instantaneously
- total volume 150,000 m\(^3\)
- thickness of layer about 0.3 m
Result - Nourishment test near Lobith

spreading of tracer fraction

V = 150,000 m³
Result - Nourishment test near Lobith

spreading of tracer fraction
Tracer. 2
$0.5 < D < 1 \text{ mm}$
(fine)

Tracer. 7
$8 < D < 16 \text{ mm}$
(coarse)
Propagation speed of different fractions

Fine

Medium

Coarse partial mobility
Yearly repeated feeding (150,000 m$^3$/yr)
Overall conclusions

- We have a morphological model that covers the Rhine Branches in the Netherlands.

- Well calibrated
  - Hydrodynamics
  - 1D morphological behaviour $\leftrightarrow$ bed celerity
  - 2D morphological behaviour $\leftrightarrow$ 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)
Moving to flexible mesh – starting

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

15 October 2016
Moving to flexible mesh – starting
Moving to flexible mesh – starting
color → vorticity
Delft Software Days 2016

- 600+ participants
- 200+ organisations
- 50+ countries
- 3 symposia & user meetings
- 3 workshops
- 17 courses

www.dsd-int.nl

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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