H51A-0172

Bifurcation evolution in meandering rivers with adapting widths

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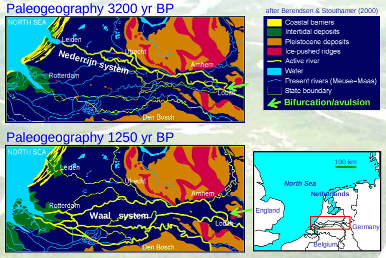
Problem: **What determines bifurcation stability and avulsion duration?**

Objective:
- **model bifurcation evolution and avulsion duration**
- **determine most important factors for duration with model**
- **verify on the worlds best-mapped case: the river Rhine**

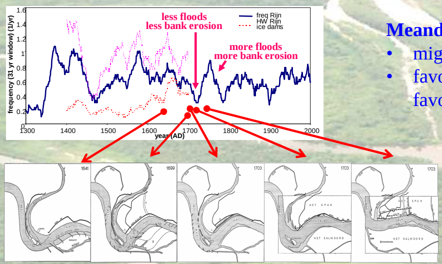
Duration of the last major Rhine avulsion



- **Avulsion duration: ~2000 years** defined as 10→90% discharge
- **Initiation**: last centuries BC
- several parallel channels
- **Evolution**:
- in 325 AD one Waal channel
- 12th century discharge Nederrijn decreased

Fig. 1. Geological maps showing the avulsion of the river Rhine to the south

Processes at the bifurcation: meandering and width adaptation

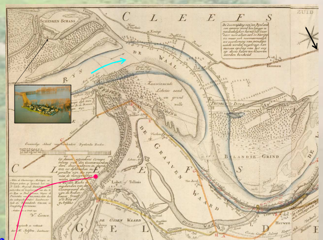


Meander bend upstream of/at bifurcation:
- migrated downstream into bifurcation
- favoured Waal with flow and favoured Nederrijn with sediment

Width and depth evolution
- Nederrijn silted up *and* narrowed further, vegetated
- **1700: avulsion finished**

Fig. 2. Meander migration at the bifurcation (historical maps redrawn by Van de Ven 1976)

Fig. 3. 1595 AD map



1751 AD map

Residual Rhine channel far downstream. Silt/clay + organics fill.

Residual Rhine channel near entrance (view on Lobith). Fining-upward sand fill on old sand-gravel channel bed. (Prelim hand coring results Hoekstra & IJmker)

How general is meandering effect and narrowing?

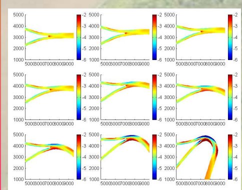
Clear cases where meander at bifurcation favours outer-bend branch:
1. two man-made bifurcations in the Netherlands
2. Ganges-Gorai bifurcation
3. two Saskatchewan bifurcations in the Cumberland Marshes (see Smith et al. (1998)):

Model formulation

1. Three **1D** model branches: 1 upstream and 2 bifurcates
   - Specified: upstream discharge Q, downstream water level H, roughness k_s, initial slope S or length L to the sea, grain size D
2. Branches connected at a nodal point
   - flow division: from backwaters of bifurcates
   - sediment division: nodal point relation Kleinhans et al. WRR
3. Width W adjustment to discharge
   - $W_{eq} = aQ^b$, $dW/dt = (W_{eq}-W)/T_W$ (relaxation, conserve sediment in bed)
4. Nodal point relation
   - sediment division proportional to width, *but*
   - modified by transverse slope effect and spiral flow of bend with radius R
5. Novelty:
   - meander effect at bifurcation
   - coupling bank erosion / bank deposition to bed sediment balance

1D model 'validation' on 3D model

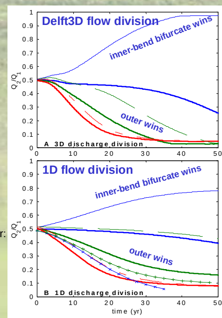
Detailed data unavailable, consider detailed 3D model as 'truth'
- Delft3D model software
- curvilinear grid, preformed bend, fixed banks
- same parameters as in 1D model
- scenarios for gradient versus bend advantage



Bed elevation maps in 3D model after 6 years illustrating bend morphology and bifurcation response (coordinates in m)

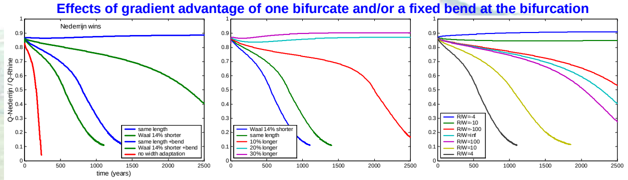
Fig. 4. Discharge division evolving in 50 years: 3D and 1D model show similar behaviour.

Only bend, equal bifurcates:
bend R/W=100
bend R/W=10
bend R/W=4 (sharpest)
Inner-bend branch 10% steeper:
bend R/W=100
bend R/W=10
bend R/W=4 (sharpest)
Other nodal point relations:
Wang
Bolla



Model results

Fig. 5. Discharge division evolving in 2500 years: Effects of gradient advantage of one bifurcate and/or a fixed bend at the bifurcation

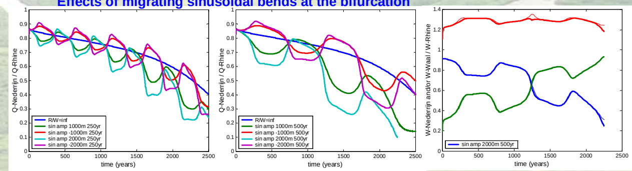


Standard scenarios
- **same length or Waal 14% shorter**
- **bend R/W=4 much larger effect**
- **faster without width adaptation**

Gradient of the Waal
- **with bend R/W=4**
- **bend compensates ~15% longer**

Fixed bend at bifurcation
- **with Waal 14% shorter**
- **bends in both directions**

Fig. 6. Discharge division and width evolving in 2500 years: Effects of migrating sinusoidal bends at the bifurcation



Fast migrating bend
- **net faster than gradient advantage alone**

Slow migrating bend
- **much faster than fast bend**
- **avulsion duration depends on initial position of the bend**

Width of slow migrating bend
- **time-adaptation nearly immediate**
- **wide residual channels**
- **sudden rapid changes**

Conclusions

1. **Avulsion/bifurcation evolution is strongly forced by meandering**
   - in competition with gradient advantage
   - migrating bend at bifurcation causes fluctuations in discharge division
   - migrating bends give net faster change than gradient advantage alone
2. **Dynamically stable bifurcations do *not* exist**
   - except when highly asymmetrical i.e. as residual channels, or when exactly equal bifurcates
   - bifurcations *only* stabilise (statically) by bank and bed protection (e.g. armouring, resistive clay, vegetation, bank protection works) of the *enlarging* bifurcate
   - evolution can be very slow when gradient advantage and bend effects balance
3. **Avulsion is strongly slowed down by width adaptation, i.e. bank and floodplain evolution**
   - too simplified here but nothing better available!
4. **Nederrijn-Waal avulsion evolution forced by meandering**
   - and gradient advantage
   - but slowed down by width-adaptation
   - *not* affected by sea level rise or tectonics
   - modelled avulsion duration with realistic bends 1500-2500 years in agreement with data

Work in progress

1. This work extended:
   Kleinhans (River Flow 2008); Kleinhans, Cohen & Stouthamer (in prep)
2. 3D modelling of bifurcations in meandering rivers:
   Kleinhans, Jagers, Mosselman & Sloff WRR (in review)
3. Case study of avulsion splay and upstream channel evolution:
   Kleinhans, Weerts & Cohen (RCEM 2007)
4. Sediment transport and morphodynamics at three Rhine bifurcations:
   Frings & Kleinhans Sedimentology (accepted)
   Kleinhans, Wilbers and Ten Brinke (2007) Netherlands J. of Geoscience
5. Sedimentology of closed bifurcates and residual channels in the Rhine
   Kleinhans, Hoekstra, IJmker & Cohen (in prep)

Acknowledgements
- grantALW-VENI-863.04.016
- Kim Cohen, Esther Stouthamer, Marco van Egmond
- Jantine Hoekstra, Janneke IJmker
- Norm Smith
- Erik Mosselman, Kees Sloff, Bert Jagers