

# Bifurcation evolution in meandering rivers with adapting widths



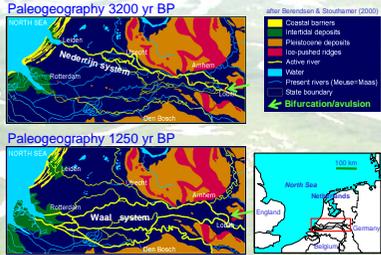
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**Problem:** What determines bifurcation stability and avulsion duration?

- 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

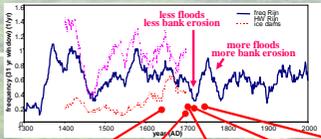
## Duration of the last major Rhine avulsion



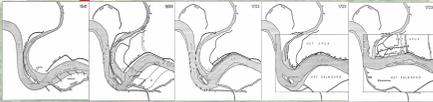
- Avulsion duration: ~2000 years defined as 10→90% discharge
- Initiation: last centuries BC
- several parallel channels
- Evolution:
  - in 325 AD one Waal channel
  - 12<sup>th</sup> century discharge Nederrijn decreased

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 and 1751 AD map



Residual Rhine channel far downstream. Residual Rhine channel near entrance (view on Lobith). Fining-upward sand fill on old sand-gravel channel bed. Silt/clay + organics fill. (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, 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

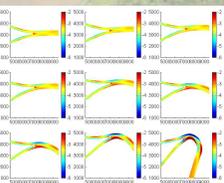
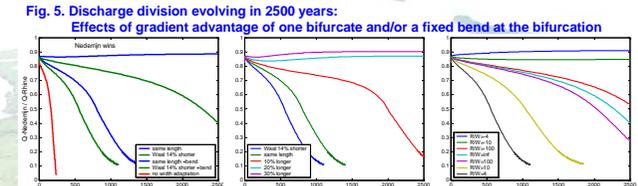


Fig. 4. Discharge division evolving in 50 years: 3D and 1D model show similar behaviour.

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

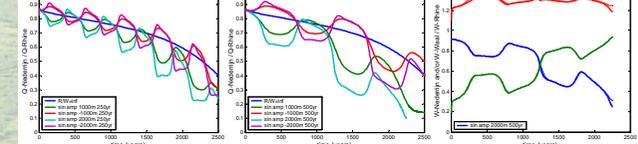
- Other nodal point relations:
- Wang
  - Bolla

## Model results



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



- Fast migrating bend**
- much faster than gradient advantage alone
- Slow migrating bend**
- avulsion duration depends on initial position of the bend
- Width of slow migrating bend**
- fine-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 (RCM 2007)
4. Sediment transport and morphodynamics at three Rhine bifurcations: Frings & Kleinhans Sedimentology (accepted)
5. Sedimentology of closed bifurcates and residual channels in the Rhine Kleinhans, Hoekstra, Ijmker & Cohen (in prep)

**Acknowledgements**

• general: the 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