How can floodplain lowering and sediment nourishments help mitigate channel bed incision?

An analysis of large-scale channel response to system measures accounting for climate change

TU Delft

Rijkswaterstaat
Ministry of Infrastructure and Water Management

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Contents

Project goal

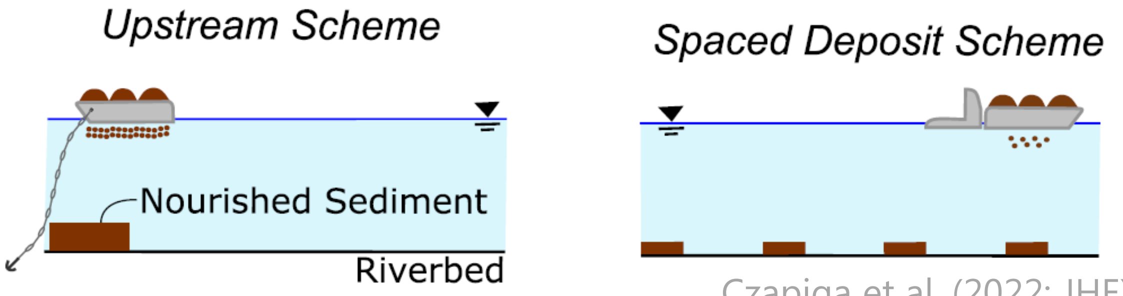
Assess the **multi-decadal impact*** of river management measures on the lower Rhine River, considering climate change.

***Impact** = large-scale bed level change

Lower Rhine River

Overview of assesssed measures

Sediment nourishments



Czapiga et al. (2022; JHE)

Floodplain lowering

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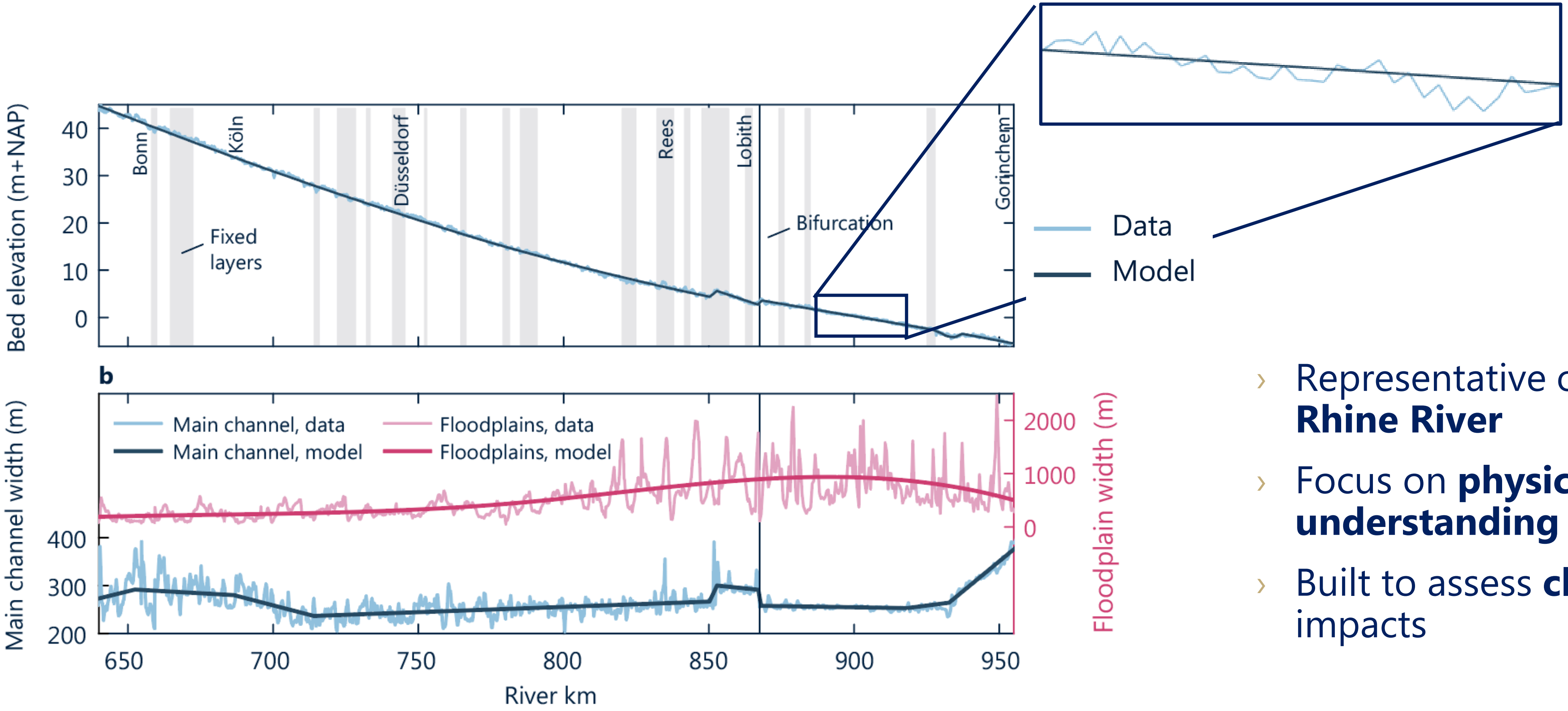
Proposed approach: schematized 1D model of the lower Rhine River



Ylla Arbós et al. (2023; GRL)

- Representative of the **lower Rhine River**
- Focus on **physics-based system understanding**
- Built to assess **climate change** impacts

What the model can and can't do

Can do

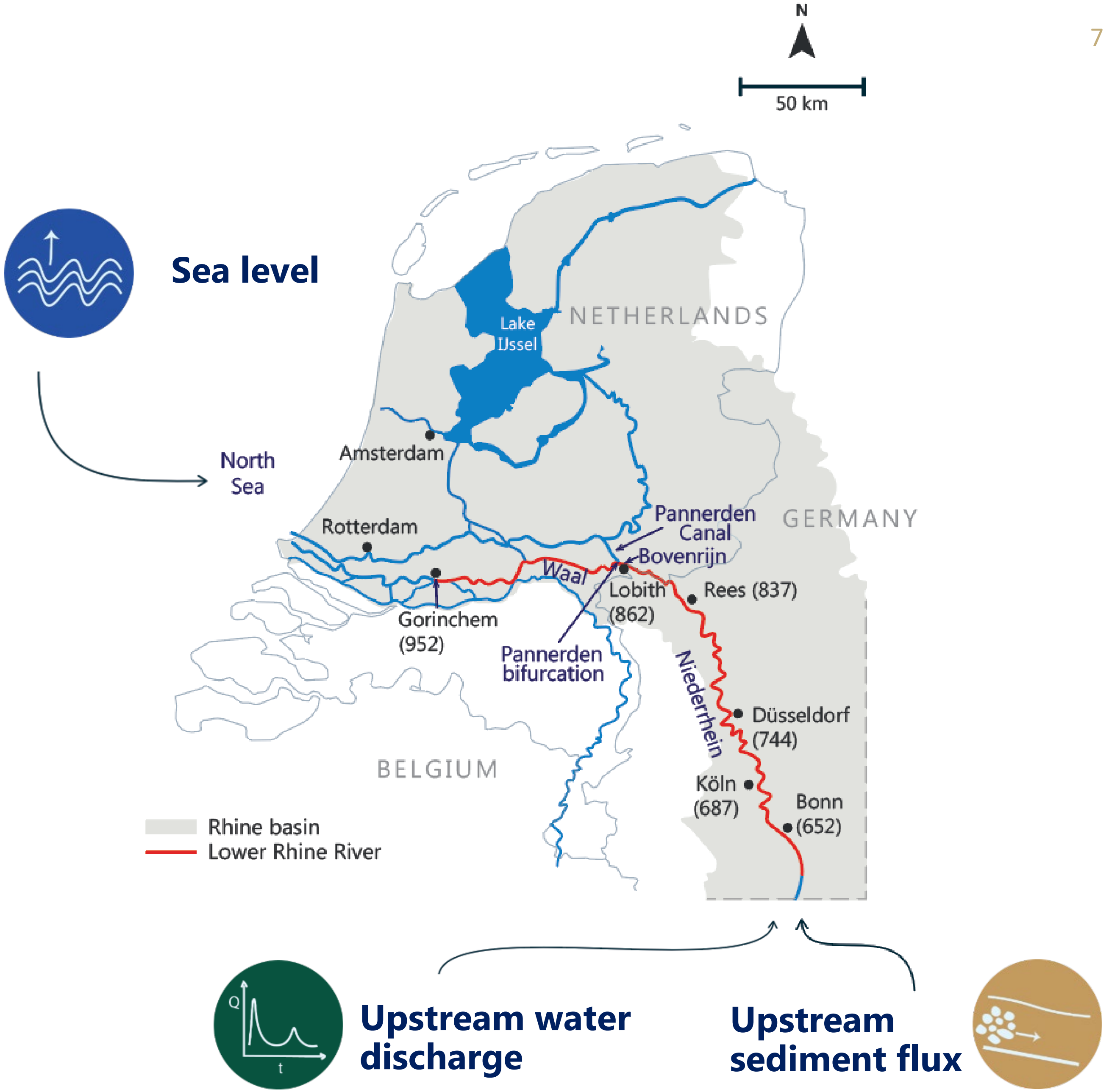
- **Large-scale** response (300 km)
- **Long-term** response (100 years)
- Understanding **system** behavior
- **Type** of response (incision/aggradation)
- **Direction and timescale** of propagation
- **Order of magnitude** of change

Can't do

- **Short-term**, natural variability of the system
- **Local** width **variations**
- **Local effects** (e.g. structures)
- **Floodplain deposition**
- **Bifurcation** dynamics (cf. PhD Chowdhury, TUD)

Climate scenarios

- **Water discharge** (historical data, KNMI'14 scenarios)
- **Sea level** (KNMI'14, IPCC'13)
- Scenario combinations for **moderate and high-end** climate change (following Ylla Arbós et al. 2023)



Floodplain lowering

Floodplain lowering measures

- **Goal we assess**: channel bed incision mitigation
- Assessment limited to the effects of changes in flow velocity during floods (no sediment floodplain deposition)
- **Relative to previous studies**: we focus on system behavior, we add climate change scenarios

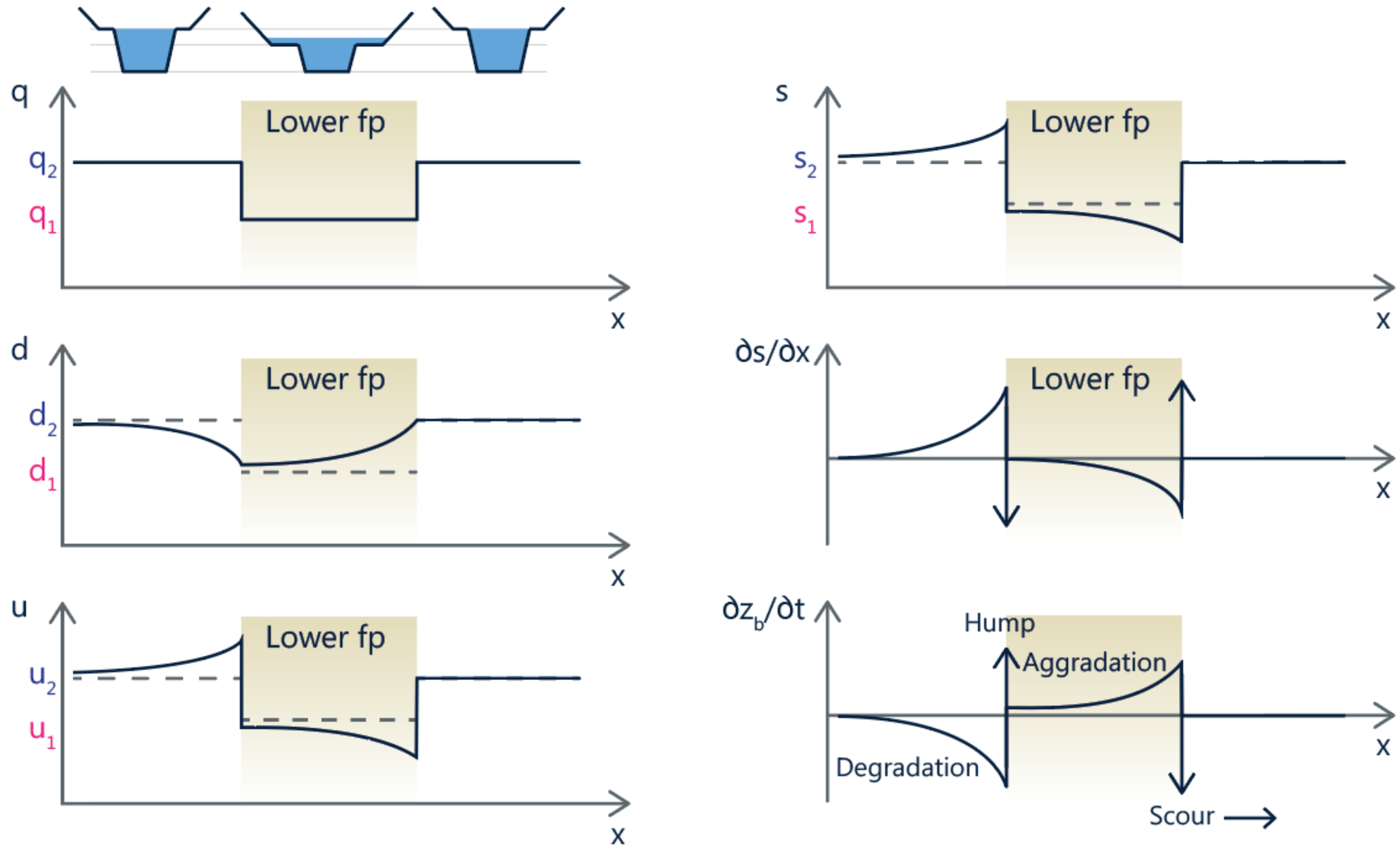
Floodplain lowering

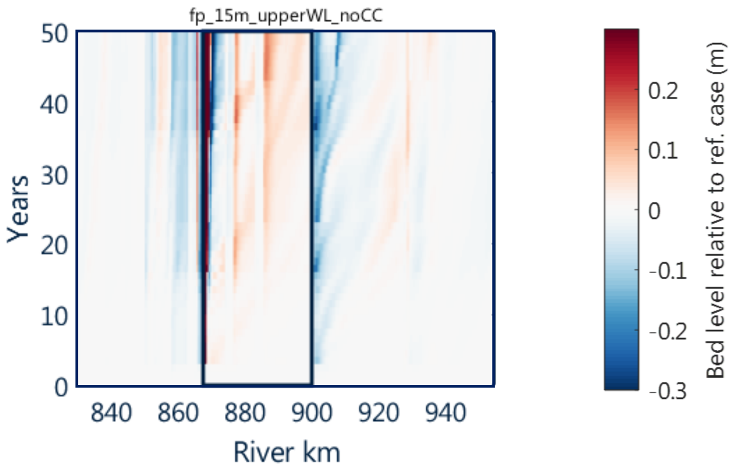
Floodplain lowering modeling plan

- Lower floodplain **elevation** by:
  - 0.5 m
  - 1 m
  - 1.5 m
- **Reaches**
  - BRWL (all)
  - BR (Spijk to PKop)
  - Upper WL (PKop to rkm 900)
  - Middle WL (rkm 900 to St Andries)
  - * No lower WL because it is already aggradational
- **Climate scenario** combination
  - Reference (no climate change)
  - Moderate
  - High-end

Total of 39 runs

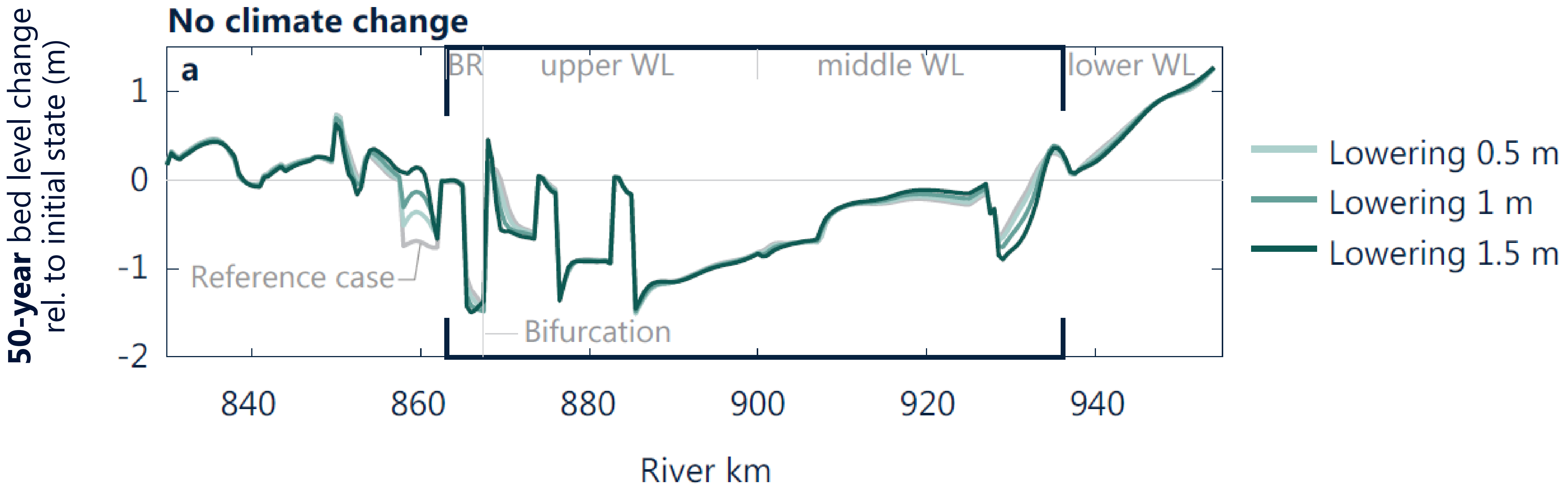
Channel response to floodplain lowering



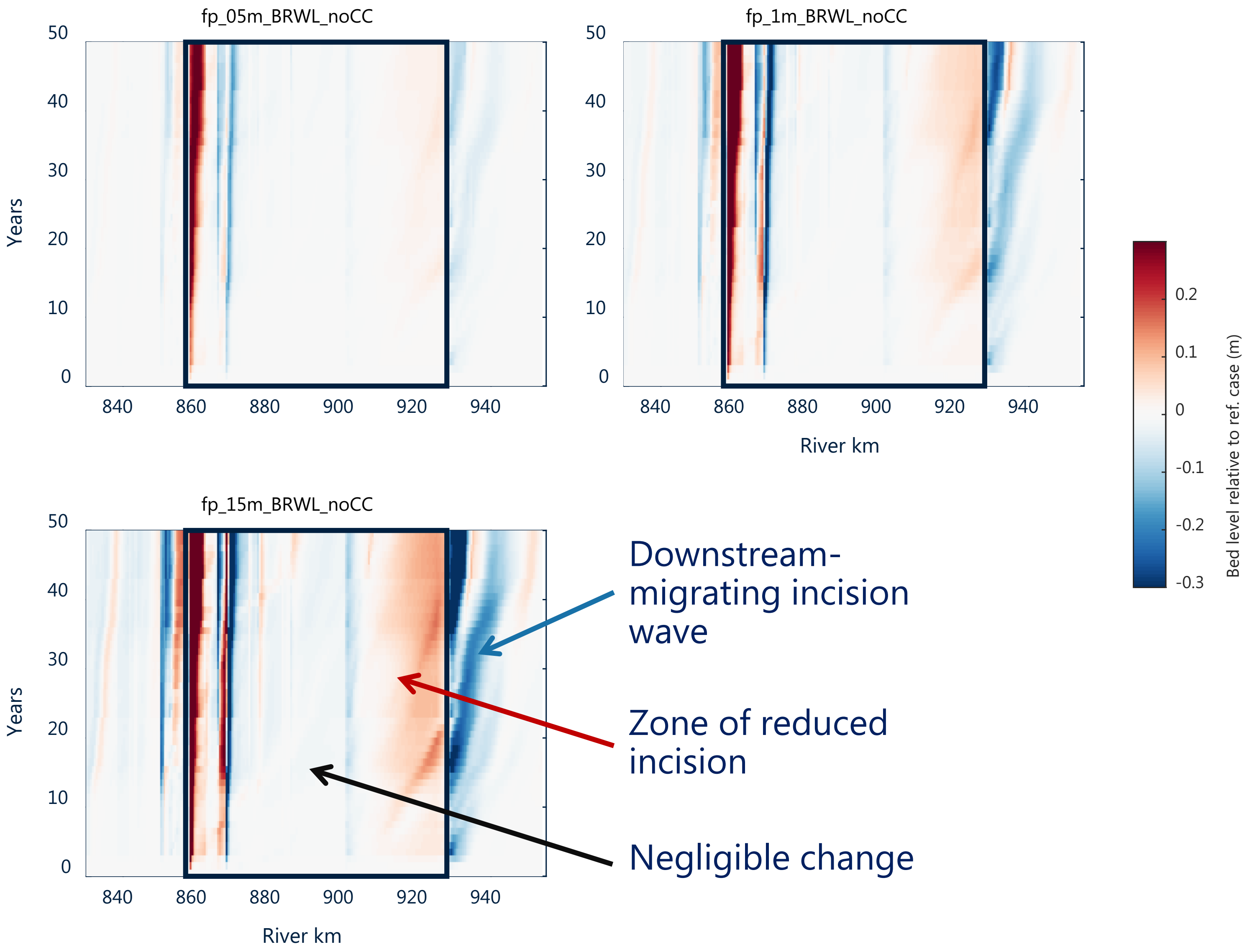


Floodplain lowering Bovenrijn-Waal – no climate change

- Negligible effects in areas of most incision
- Reduced incision in middle WL (slightly), increased incision downstream.



Floodplain lowering BRWL- effect of lowered height

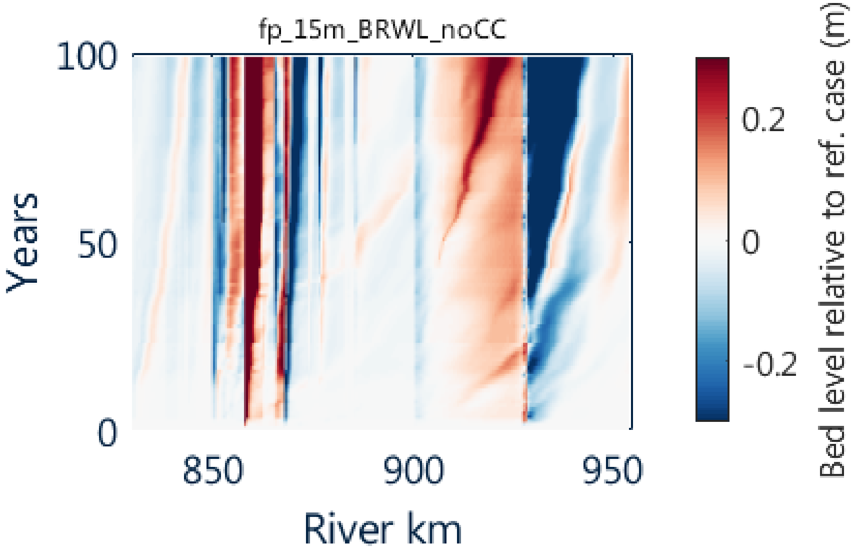


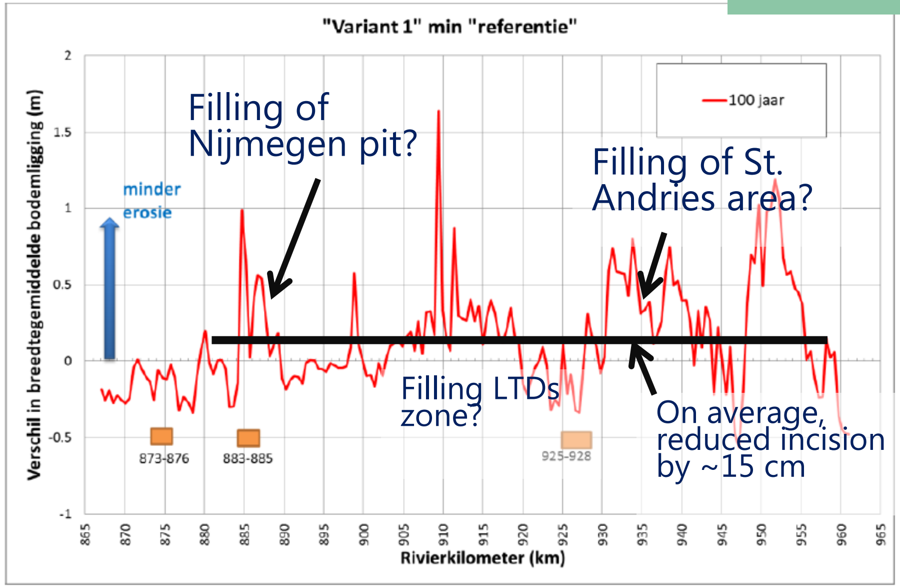
- Both erosion-mitigation efficiency and additional downstream incision scale with lowered height

Other floodplain lowering studies

This study

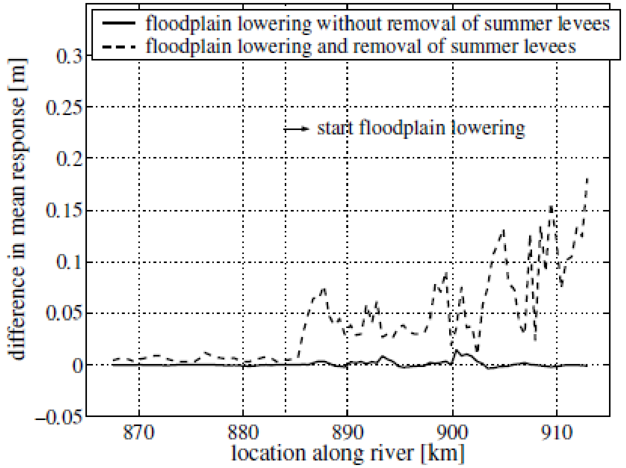
- **1.5 m** lowering in BRWL
- Incision mitigation of ≤ 25 cm after 100 years, incision downstream of measures





WWF, Ruimte voor Levende Rivieren (2021)

- **2m** lowering in upper WL
- On average, erosion-mitigation of ~15-20 cm.



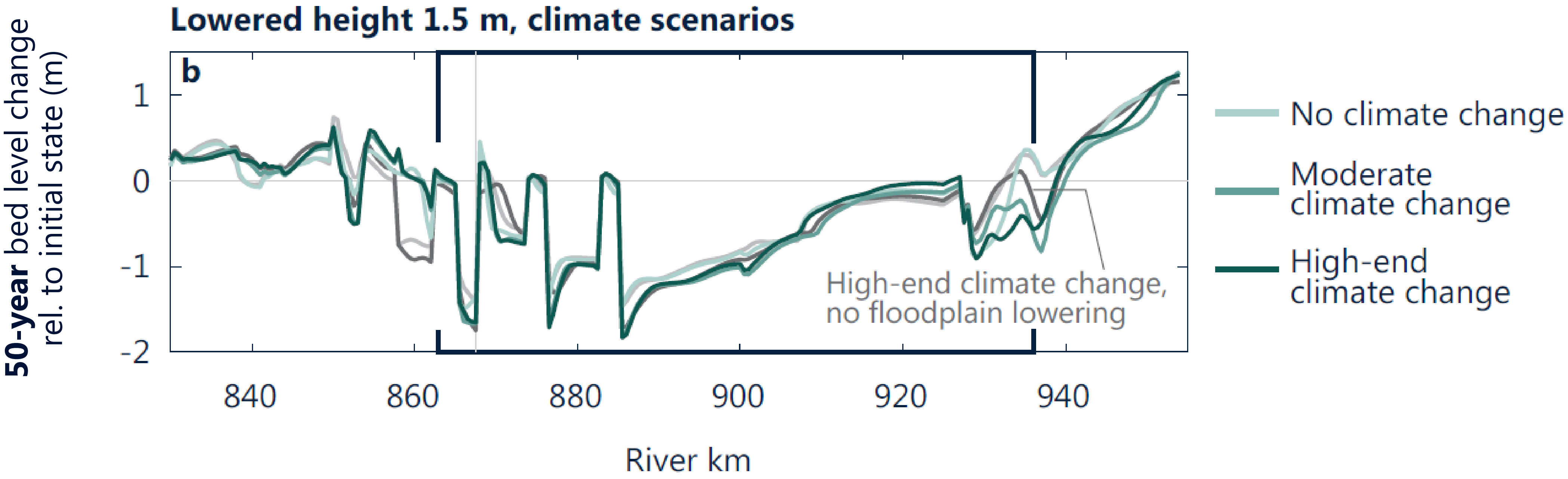
(c) Difference in mean morphological response with respect to reference situation

Van Vuren (2005)

- **1.5 m** lowering in upper WL
- Incision mitigation of ≤ 15 cm after 100 years

Floodplain lowering Bovenrijn-Waal – climate change

› Negligible effects when considering climate change

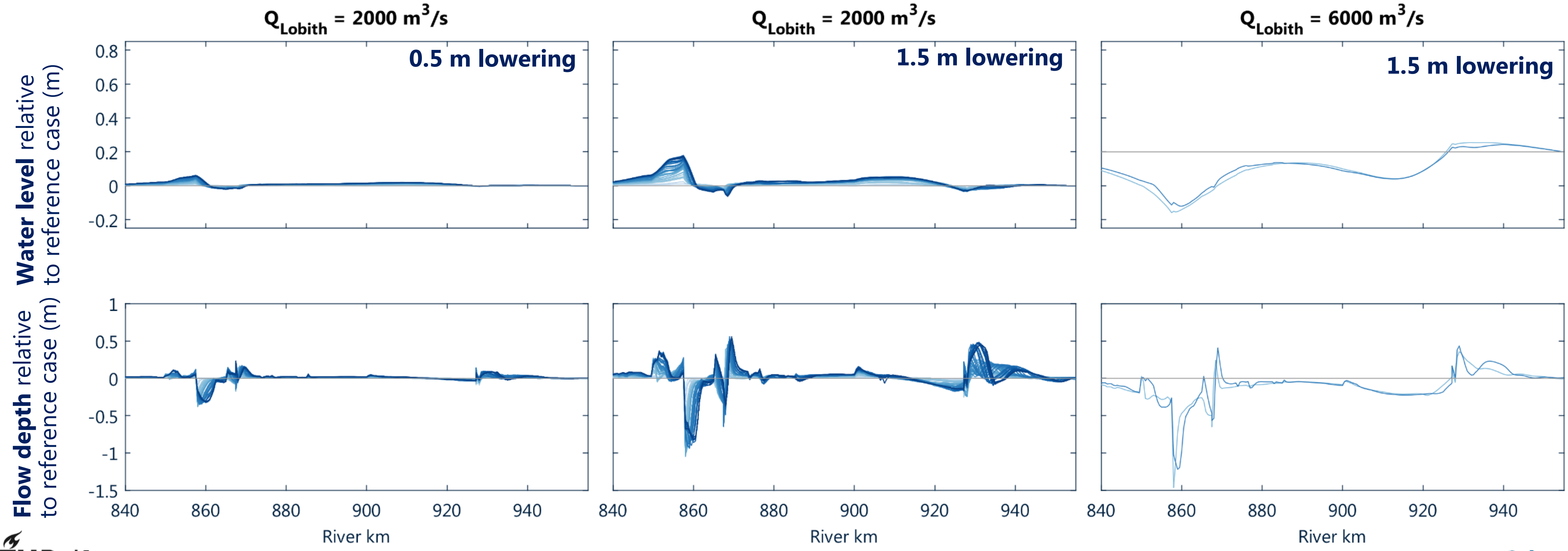


Effects on water level and flow depth – selected test cases

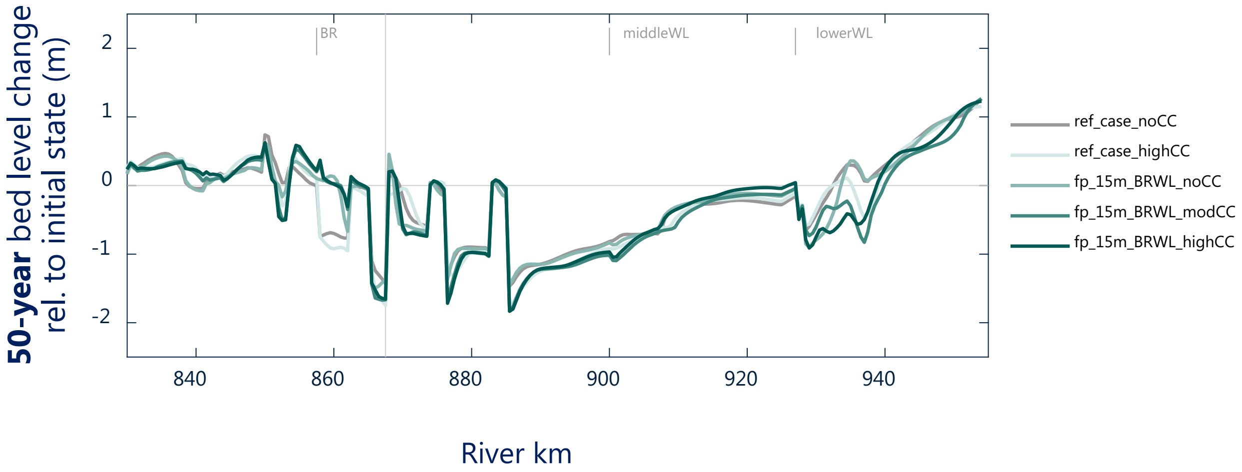
- Considered **discharges**: 1000, 1500, 2000, 4000, 6000 m^3/s
- Lowered reach: Bovenrijn-Waal
- Lowered **height**: 0.5, 1.5m
- **Climate scenarios**: no climate change (reference), high-end climate change

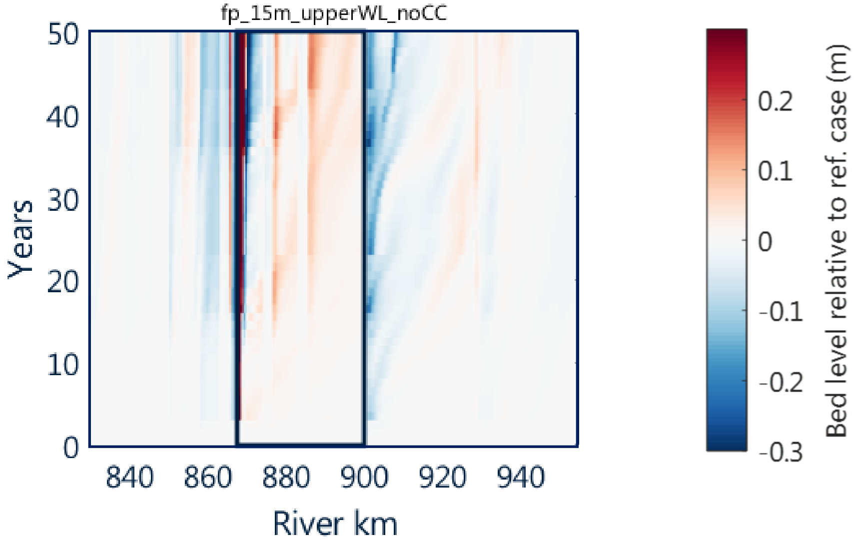
Effects on water level and flow depth – summary

- For **low discharges (inactive flooplains),** hydrodynamic changes are determined by changes in bed level →in the zones of reduced incision, **water level is slightly higher**. Flow depth changes are small.
- For **high discharges (active floodplains)**, hydrodynamic changes are determined by the floodplain lowering measures. **Water levels and flow depth decrease.**



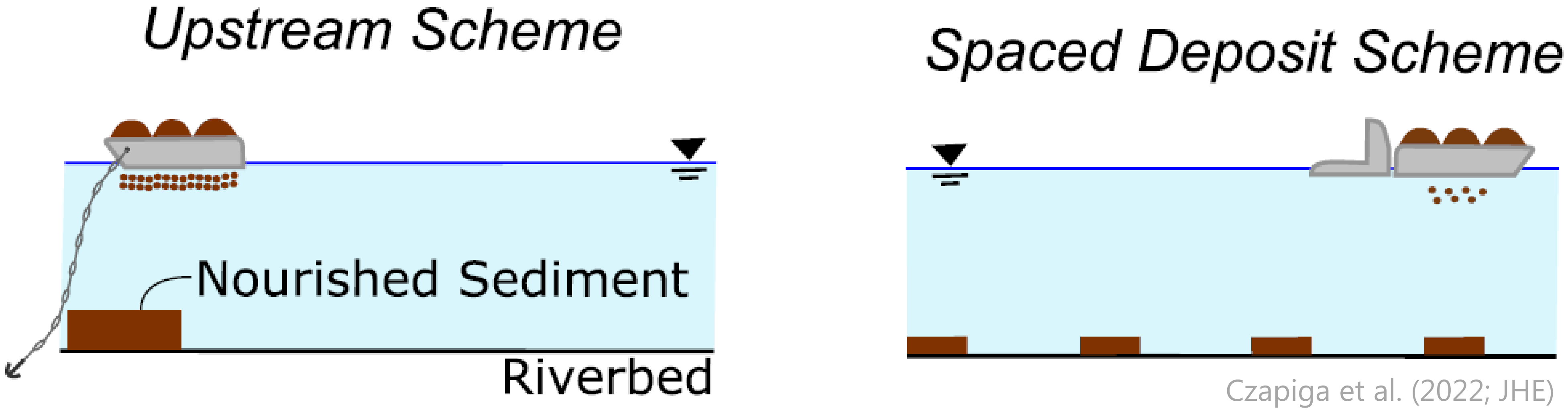
Floodplain lowering - conclusions





- Floodplain lowering can be **beneficial for flood risk** (decreased water levels) but has **negligible** effects on **large-scale morphodynamic change**, especially considering climate scenarios (~0-20 cm of erosion mitigation relative to the 1.5 m expected with climate change).
- Floodplain lowering mildly reduces incision over the lowered area, but also results in a **downstream-migrating erosion wave** downstream of the measure.
- Our results **agree with previous studies** (Ruimte voor Levende Rivieren, 2021; Van Vuren, 2005)

Sediment nourishments

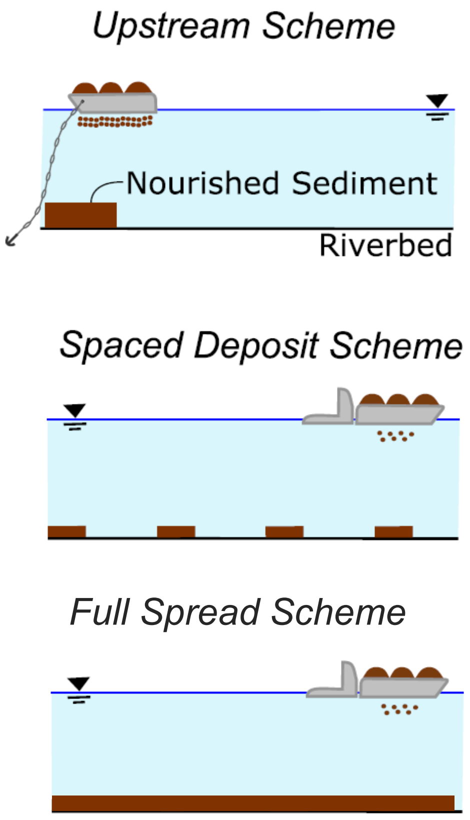


Czapiga et al. (2022; JHE)

Sediment nourishments – test cases

Building up on Czapiga et al. (2022), Liptiay (2023), we focus on system behavior and add climate scenarios

Czapiga et al. (2022; JHE)

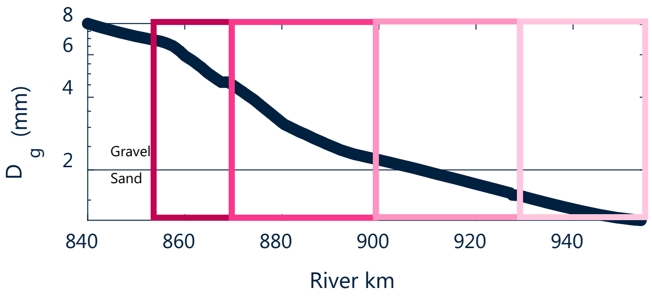


A) Hump of 0.5 m x 3 km
B) 50'000 m^3/a

C) 10 km spacing
D) 20 km spacing

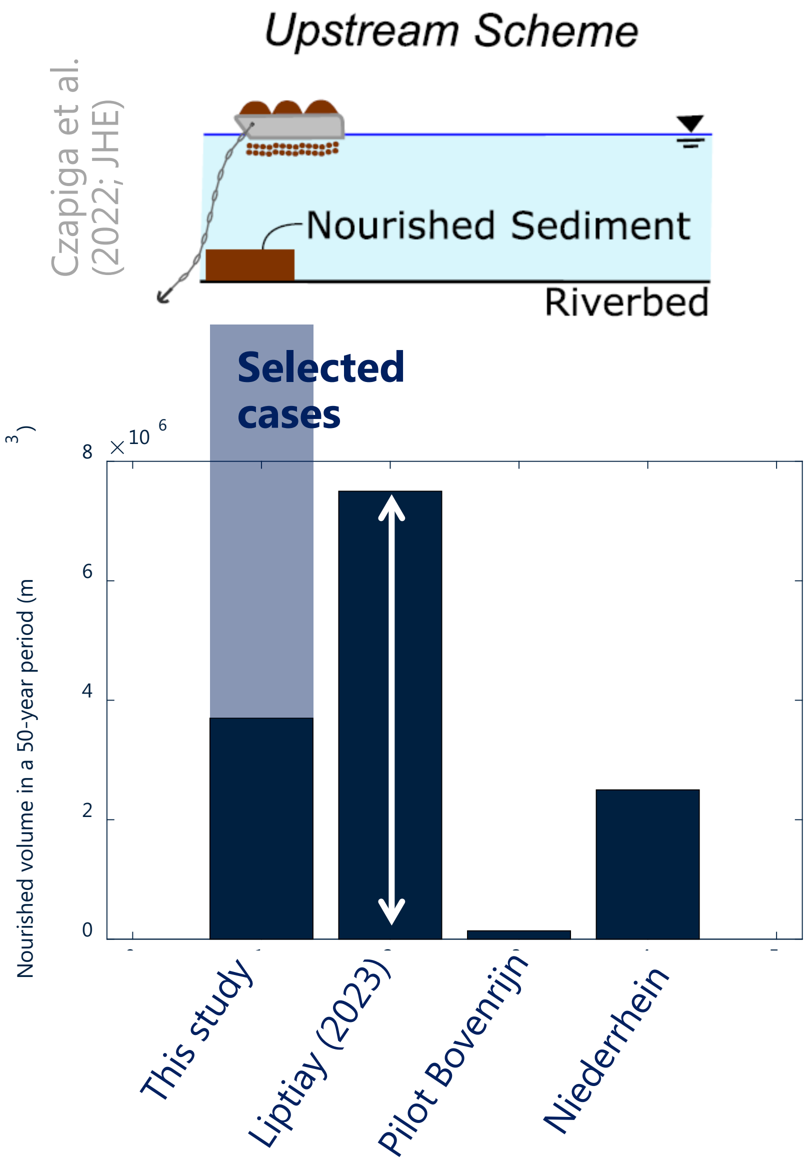
E) Entire length

- **Goal we assess**: channel bed incision mitigation
- Nourishments modeled as **humps** on initial bed elevation
- Three different **schemes**:
  - Upstream scheme
  - Spaced-deposit
  - Full spread
- Four different **grain size distributions:**
  - Mean Bovenrijn
  - Mean upper Waal
  - Mean middle Waal
  - Mean lower Waal
- Nourishment **volumes**:
  - 50000 m^3/a (Bovenrijn)
  - 70000 m^3/a
  - 150000 m^3/a (selected cases)
  - 250000 m^3/a (selected cases)
- **Climate scenario** combinations:
  - No climate change
  - Moderate climate change
  - High-end climate change



Total of 74 runs

Sediment nourishments - some orders of magnitude



Nourishments in this study

- ~ 370'000 m^3 every 5 years = hump with dimensions 0.5 m x 3 km x full river width → 70'000 m^3/a

  \+ Selected runs of 50'000, 150'000, 200'000 m^3/a

Nourishments Liptiay (2023)

- ~ 11'000 m^3 - 750'000 m^3, every 3 months, 1 year, 5 years (preferred) → (11'000-150'000 m^3/a)

Pilot nourishments Bovenrijn

- ~ 70'000 m^3 2x one-time

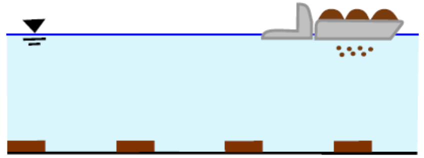
Nourishments Niederrhein

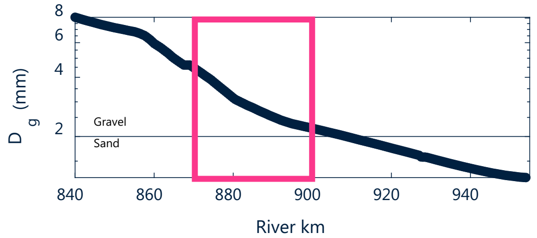
- ~ 50'000 m^3/a

Coastal sand nourishments

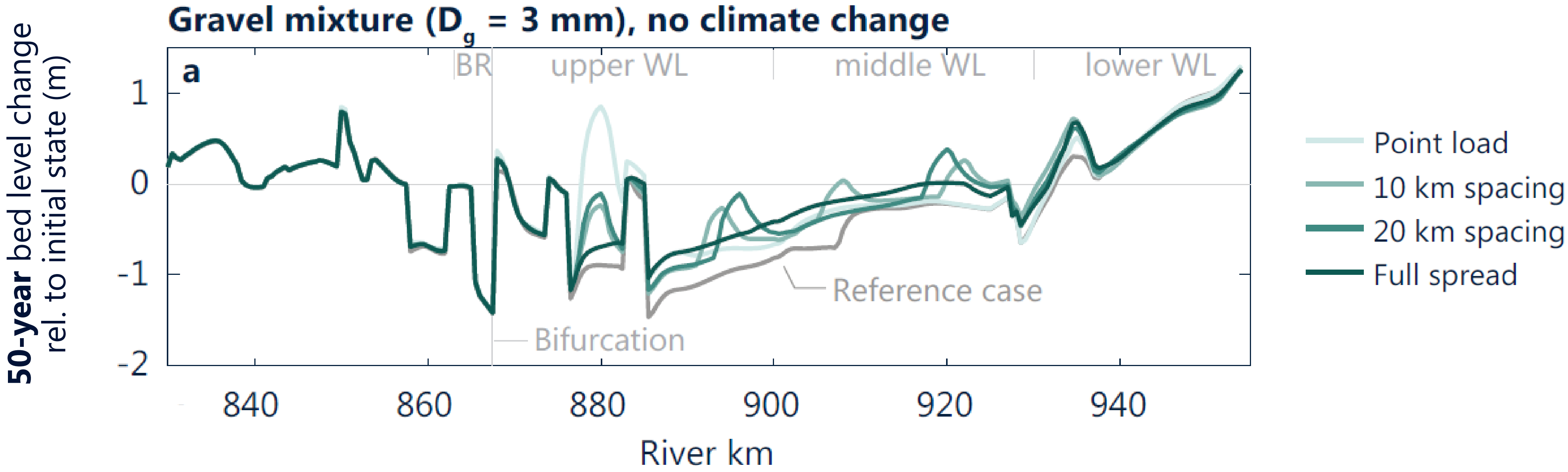
- 12'000'000 m^3/a

Effect of nourishment spreading and grain size (no climate change)

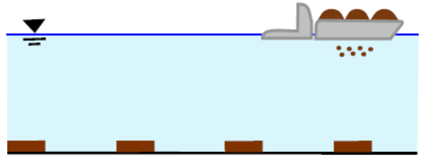


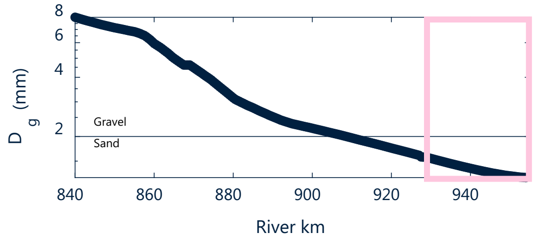


- Ongoing bed incision is not stopped but **slightly reduced**
- **Coarse** nourishments (e.g. upper Waal composition) **require spreading**

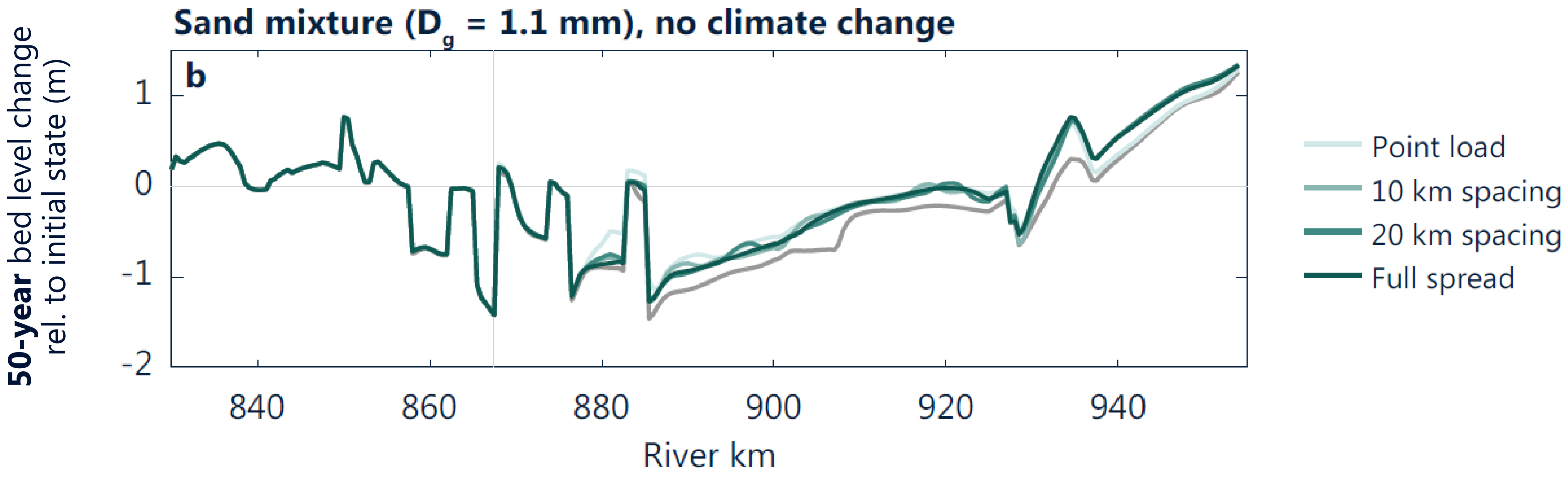


Effect of nourishment spreading and grain size (no climate change)

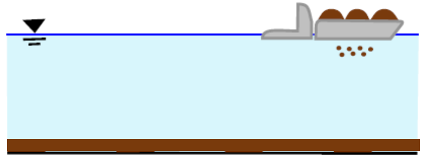




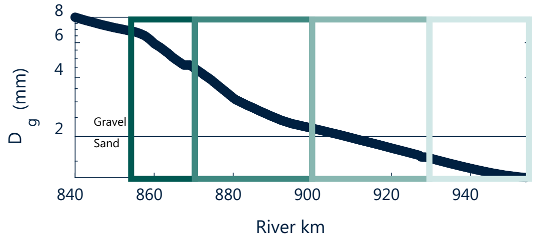
- With **finer grain sizes** (e.g. lower Waal composition), **spreading doesn't matter**

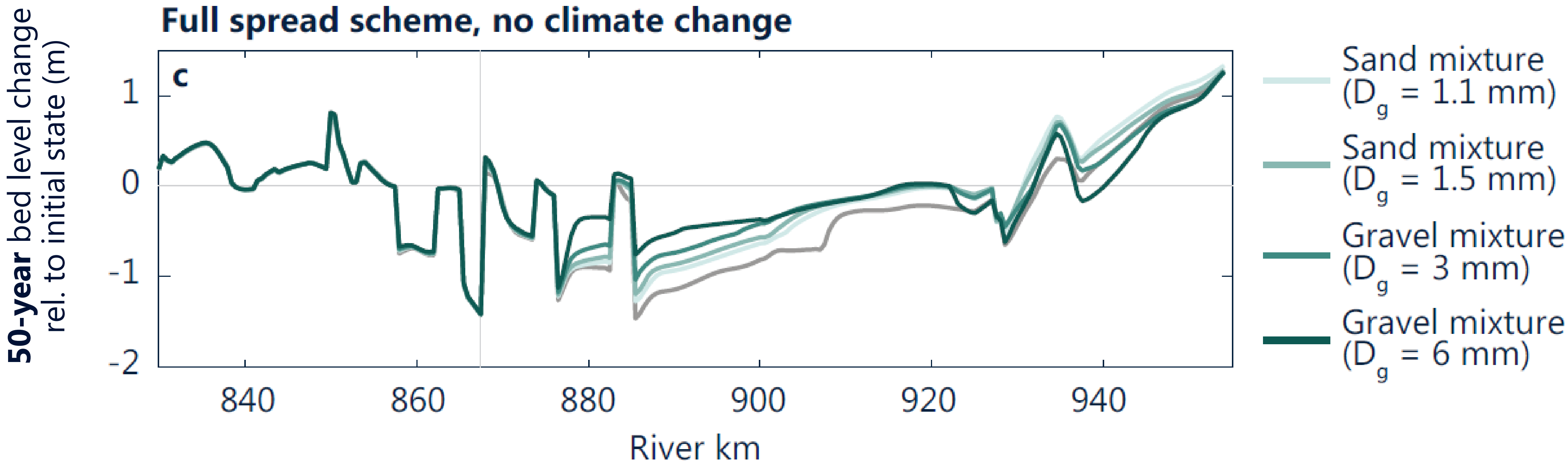


Effect of nourishment spreading and grain size (no climate change)

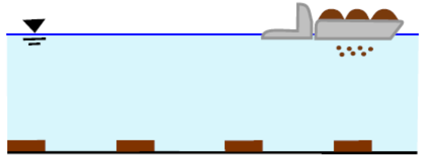


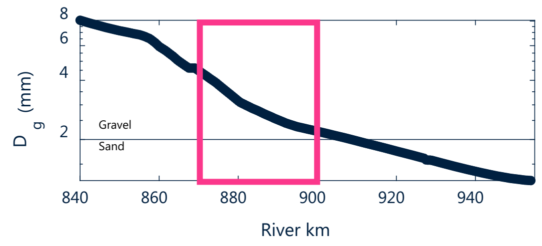
- For **spread** nourishments**, coarser** grain sizes have **higher erosion reduction** potential than finer grain sizes.





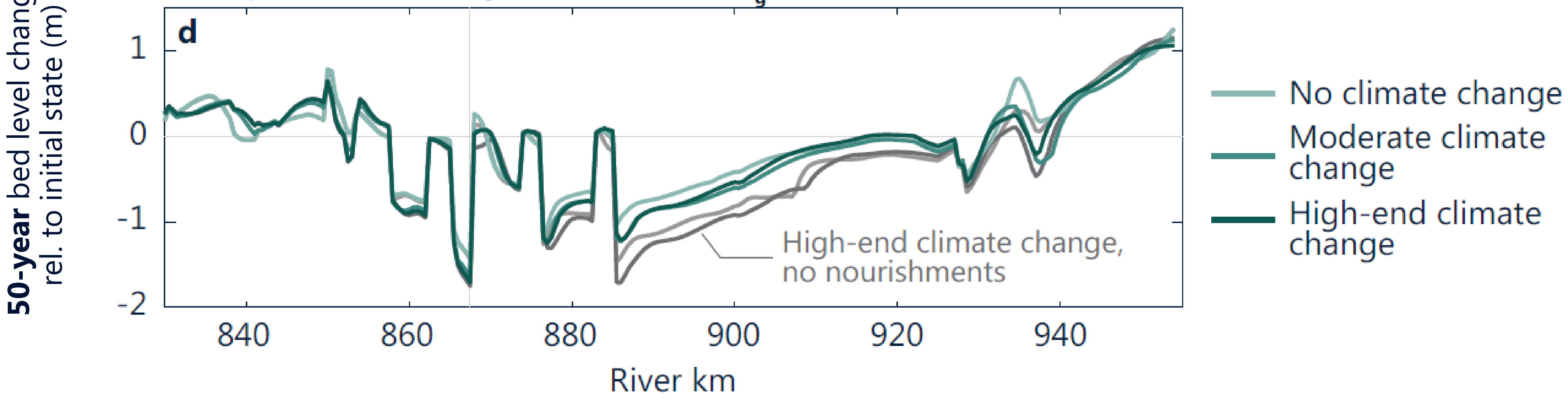
Effects of climate change



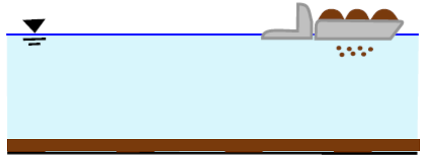


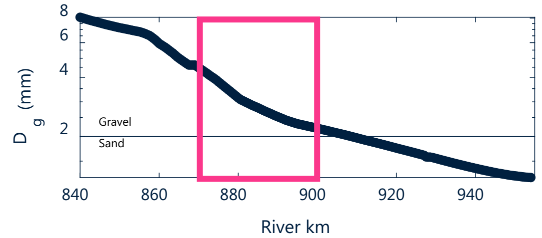
- Considering **climate change**, most **nourishment** schemes still lead to **> 1 m** of channel bed **incision** by 2050.

Full spread scheme, gravel mixture (D_g = 3 mm), climate scenarios

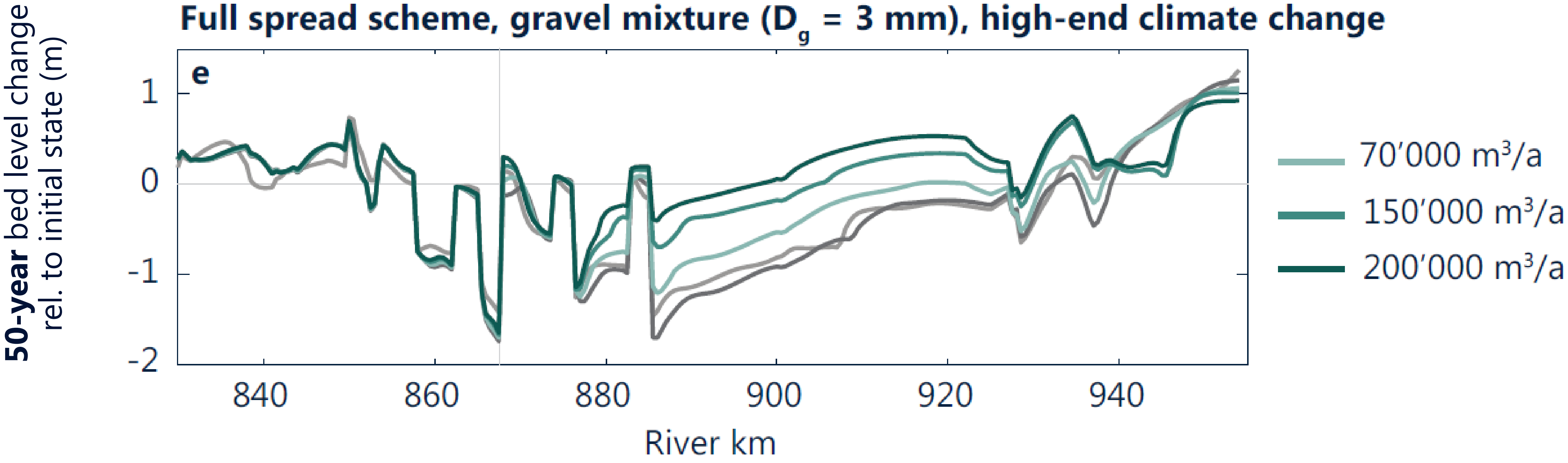


Effect of nourished volume – no climate change

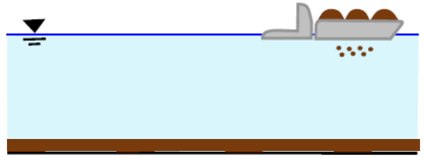


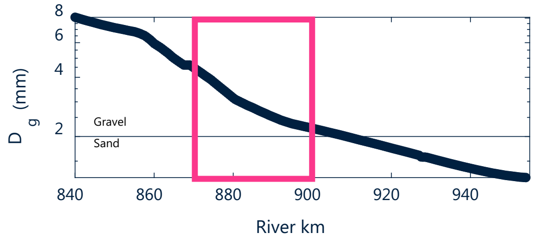


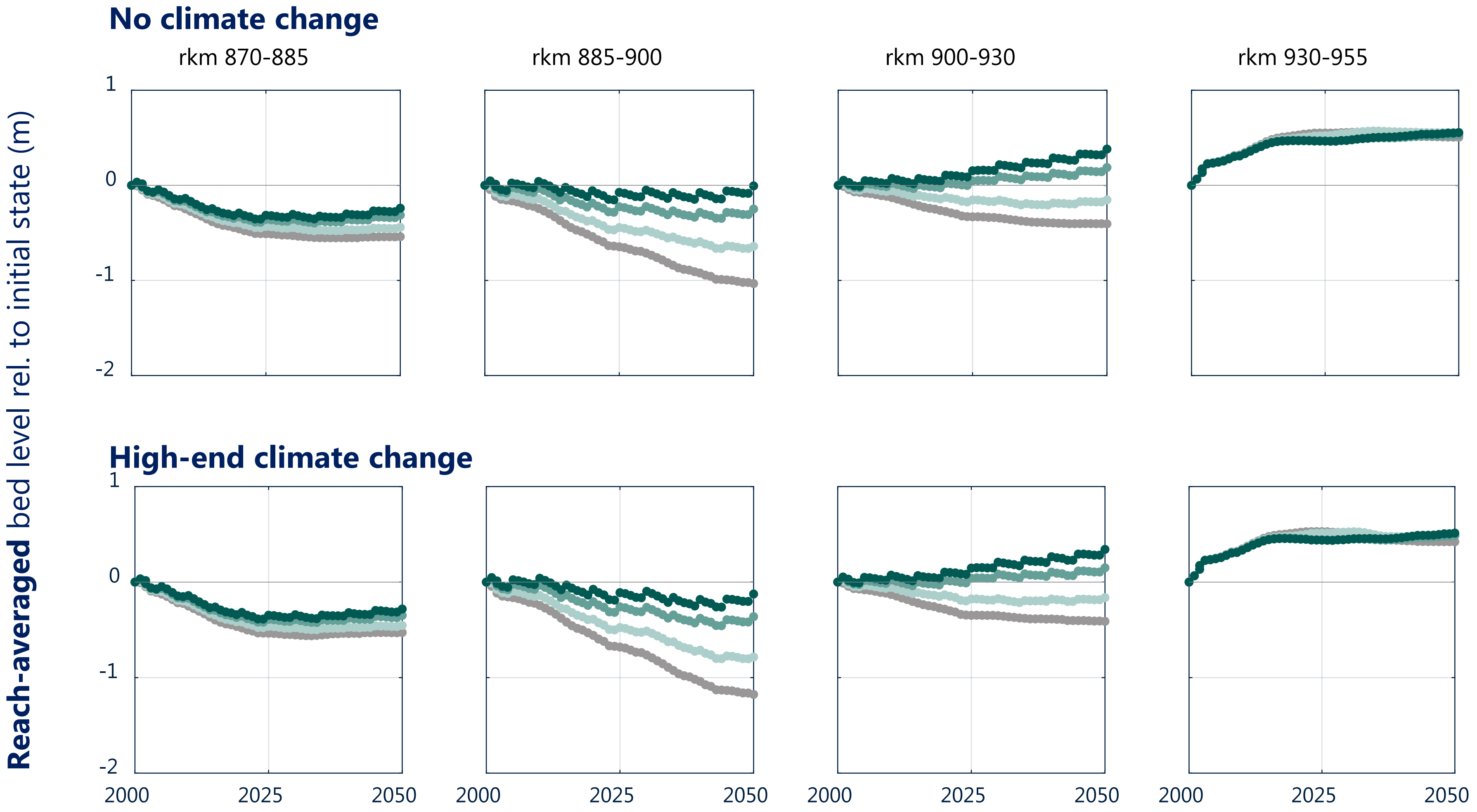
- Volumes of **150’000 -200’000 m³/a** largely reduce incision by 2050 over most of the domain, but also lead to **aggradation in the middle Waal.**



Effect of nourished volume – temporal evolution up to 2050



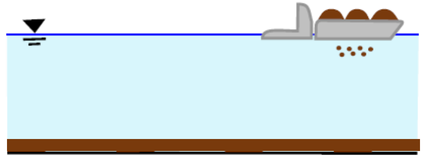


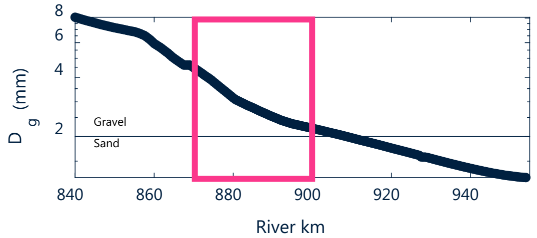


- Note **enhanced aggradation in the lower Waal** for large nourishment volumes
- Consider the use of **optimized nourishment schemes**

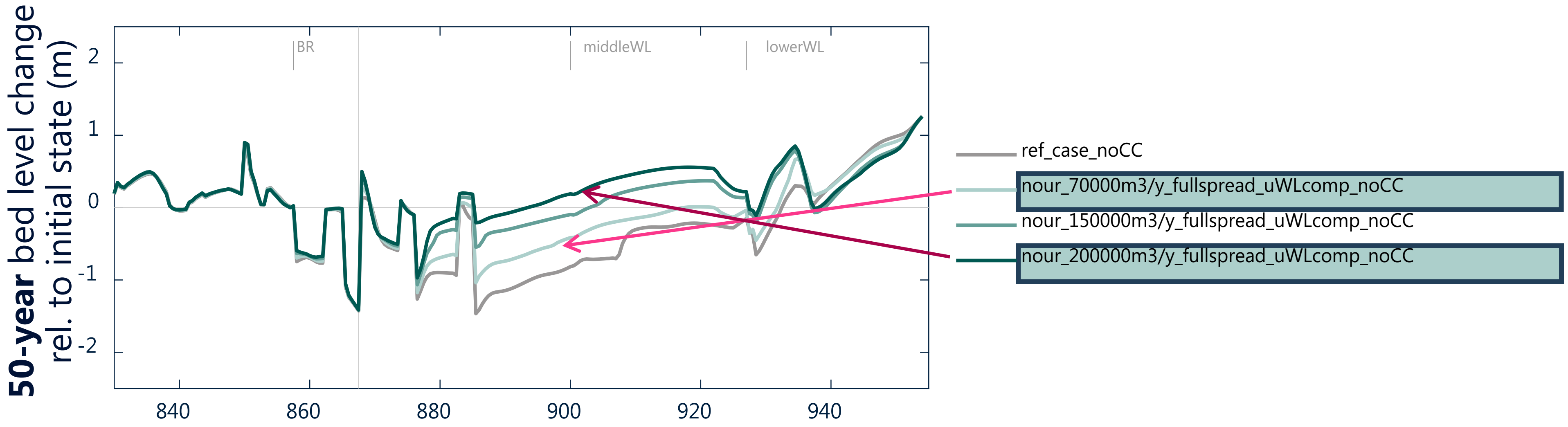
Consider spread-out nourishments exclusively in the upper Waal to limit downstream incision

Effects on water level and flow depth – selected test cases

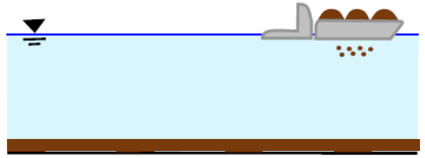


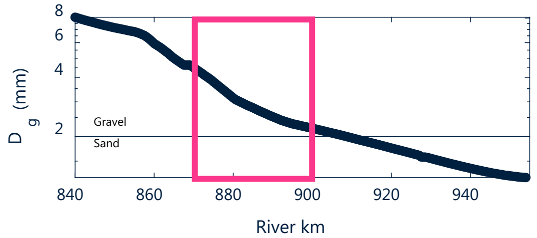


- Considered **discharges**: 1000, 1500, 2000, 4000, 6000 m³/s
- Nourishment **scheme**: full spread, upper Waal mixture
- Nourished **volumes**: 70’000 m³/a, 200’000 m³/a
- **Climate scenarios**: no climate change (reference), high-end climate change

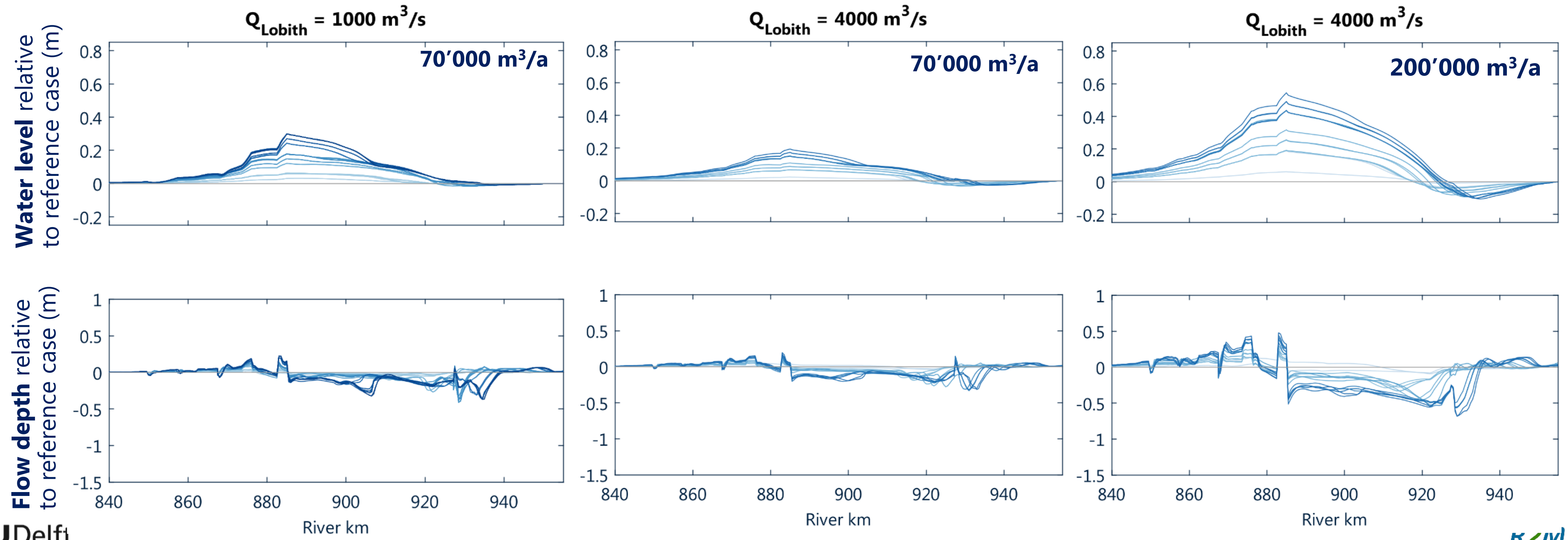


Effects on water level and flow depth – summary



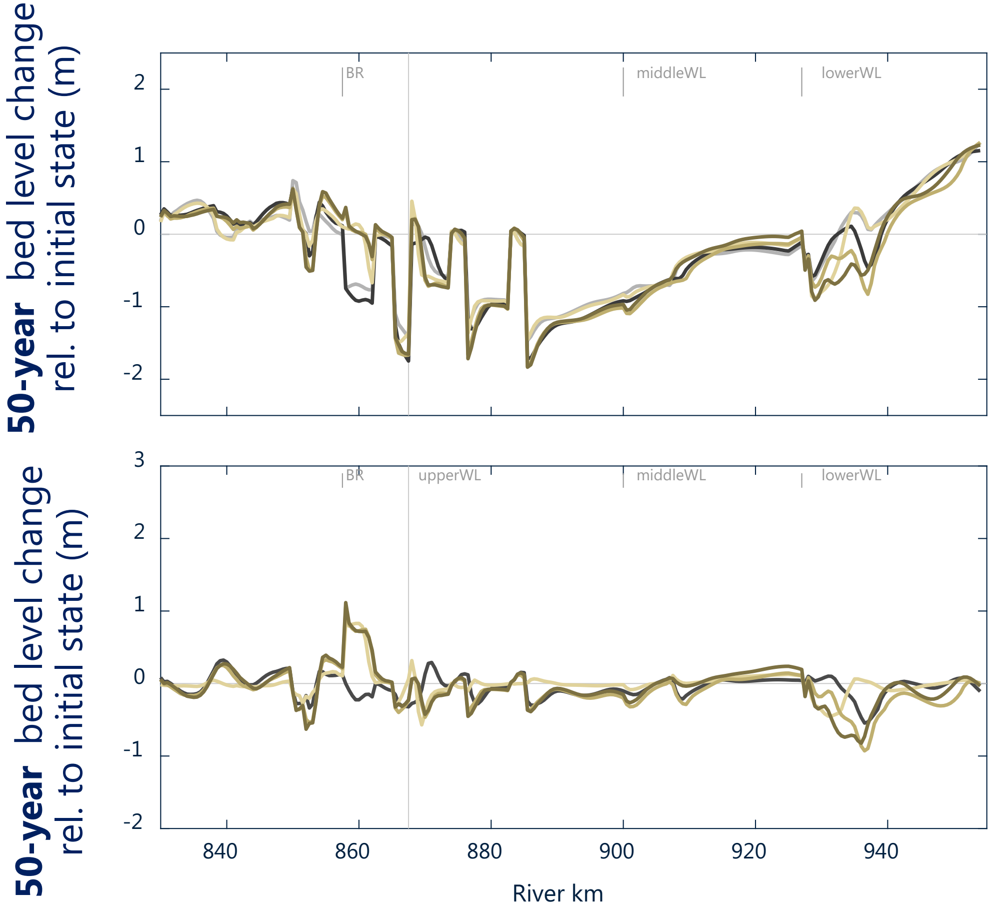


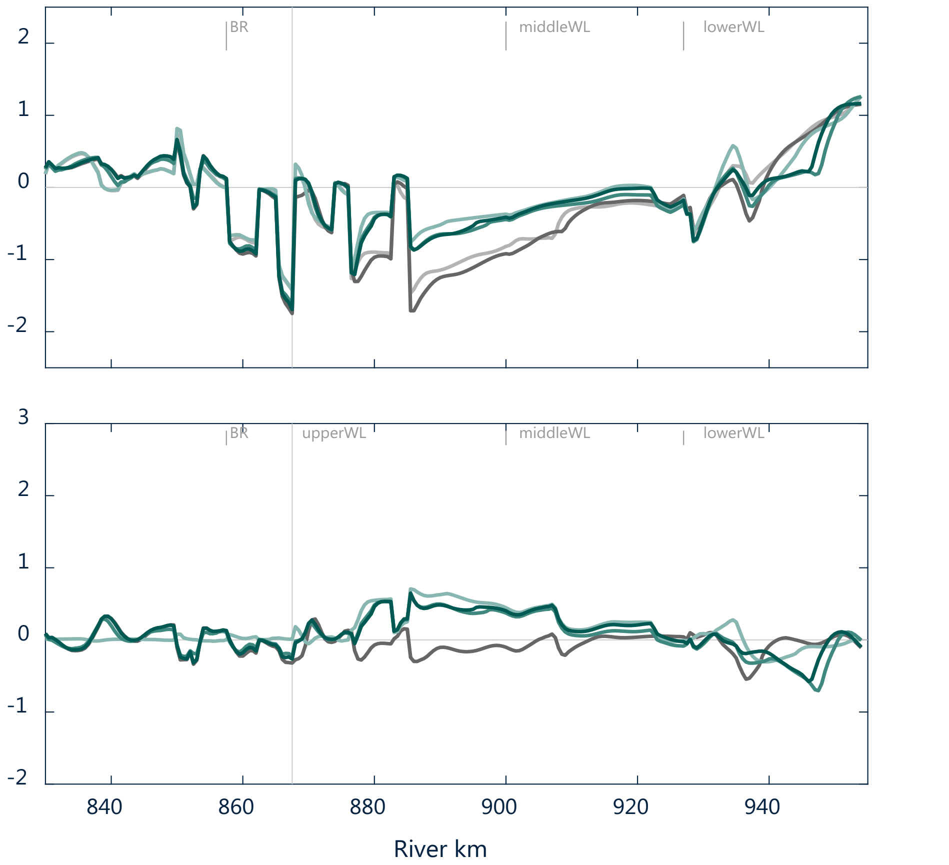
- Sediment nourishments lead to **reduced erosion** and thus to **higher water levels**
- The reduced erosion is associated with a larger channel slope, leading to **smaller flow depths**
- These effects are more pronounced for
  - **Larger volumes** of nourished sediment
  - **Smaller discharges**
- These observations hold for the different climate scenarios

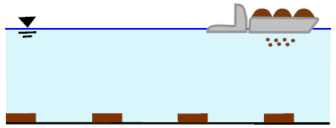


Nourishments vs floodplain lowering

Nourishments have more potential than floodplain lowering to reduce channel bed incision







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Conclusions

- **Floodplain lowering measures** have a limited effect on erosion mitigation
  - ~ 0-20 cm of reduced erosion by 2050, relative to the > 1.5 m expected with climate change
- **Sediment nourishments have more potential than floodplain lowering** to reduce channel bed incision
- **Nourishments reduce channel bed incision** as well as increased incision due to climate change. However:
  - Halting incision requires volumes of 150’000-200’000 m^3/a
- Considering **climate change**, most nourishment schemes still lead to **>1 m of incision** by 2050
- Effect of nourishments largely depends on **parameters** (grain size, spreading, nourished volume and frequency)
- Nourishment **grain size and spreading scheme** need to be considered **simultaneously**
  - Coarser grain sizes **require** spreading
  - Largest erosion-reduction potential for spread-out coarse nourishments

Recommendations

- Systematically consider* **conceptual large-scale physics of channel adjustment** on future intervention design

  * in addition to numerical modeling efforts

- Consider the effects of **climate change*** on future channel adjustment

  * update numerical simulations as new climate scenarios become available

- Bifurcation dynamics in this study are largely simplified → improve models to better capture **bifurcation dynamics** (e.g., PhD project M.K. Chowdhury, insights from 2D analysis)

- Assess the influence of **spatial density of channel widening-type measures** (e.g., floodplain lowering, multiple channel systems)
  - Assess whether multiple, smaller-scale measures are more effective at mitigating channel bed incision than longer measures

- Assess how different **channel widening-type measures compare** to each other, in terms of physics of channel adjustment, and erosion mitigation efficiency

Thank you!

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Photo: RWS