# Unravelling and quantifying natural and anthropogenic subsidence drivers in a mega delta

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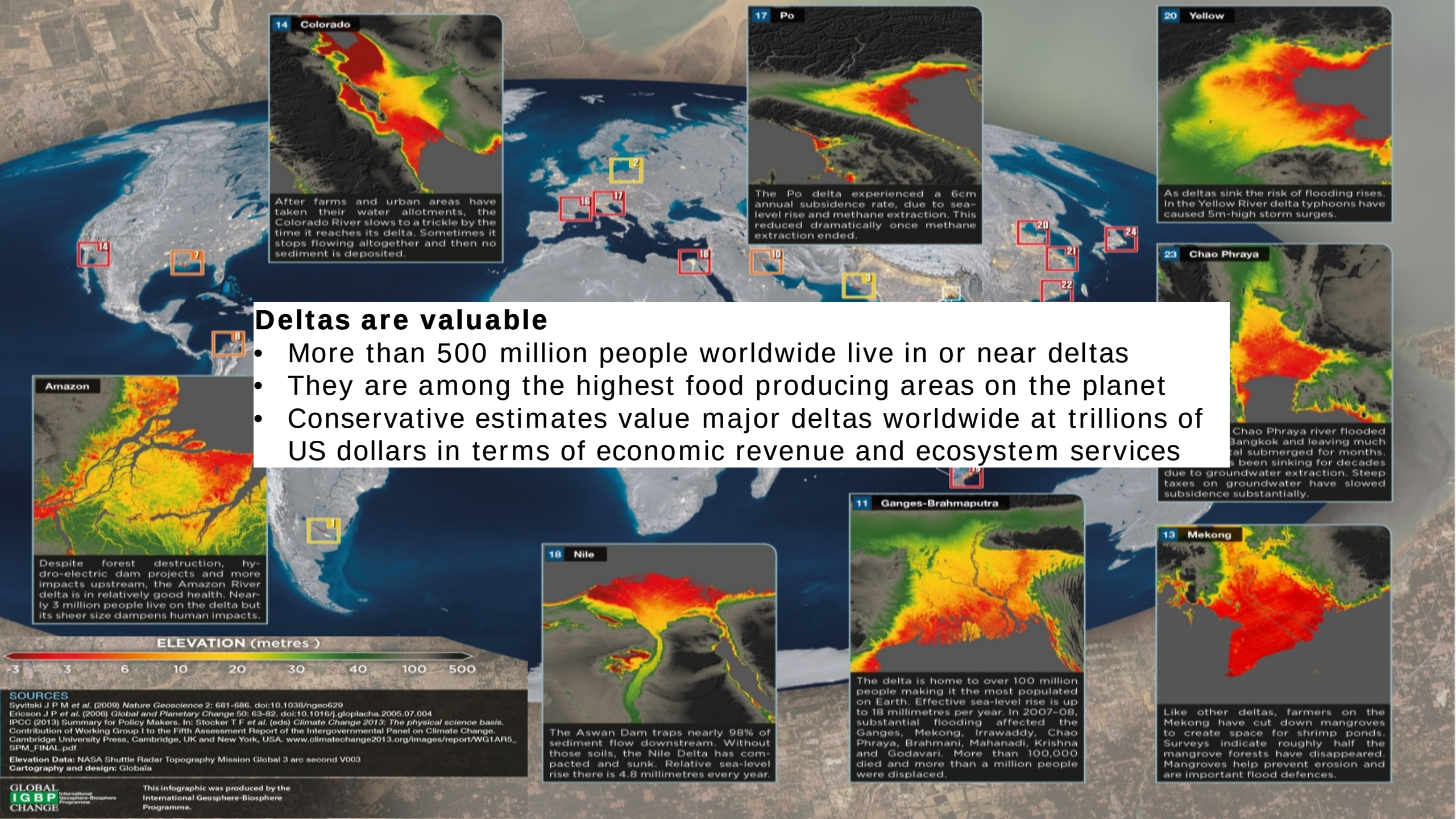
Rise and fall




## Deltas are valuable

- More than 500 million people worldwide live in or near deltas
- They are among the highest food producing areas on the planet
- Conservative estimates value major deltas worldwide at trillions of US dollars in terms of economic revenue and ecosystem services

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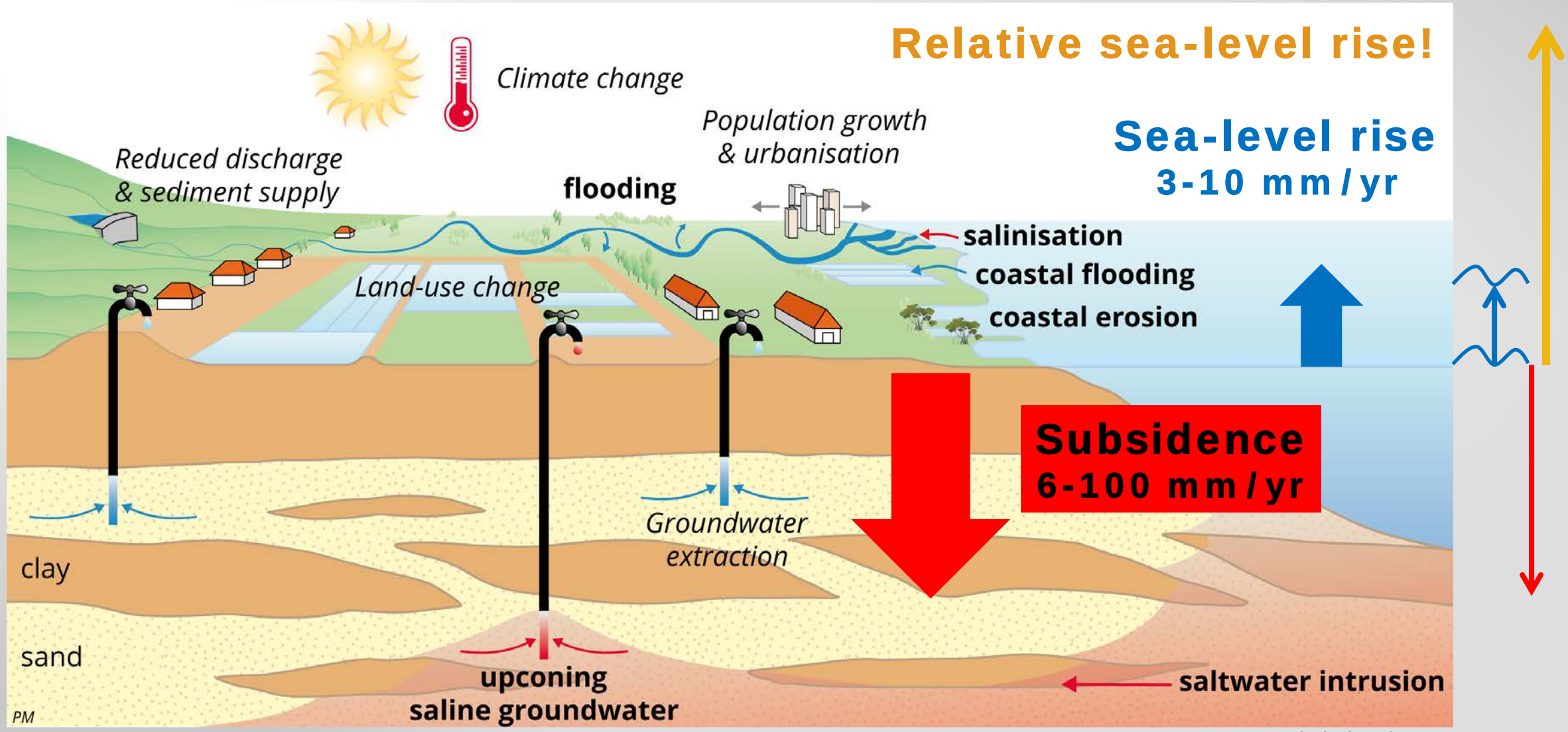
# Changes in delta systems around the world




Minderhoud, 2019

**Subsidence >> Climate-change driven SLR**

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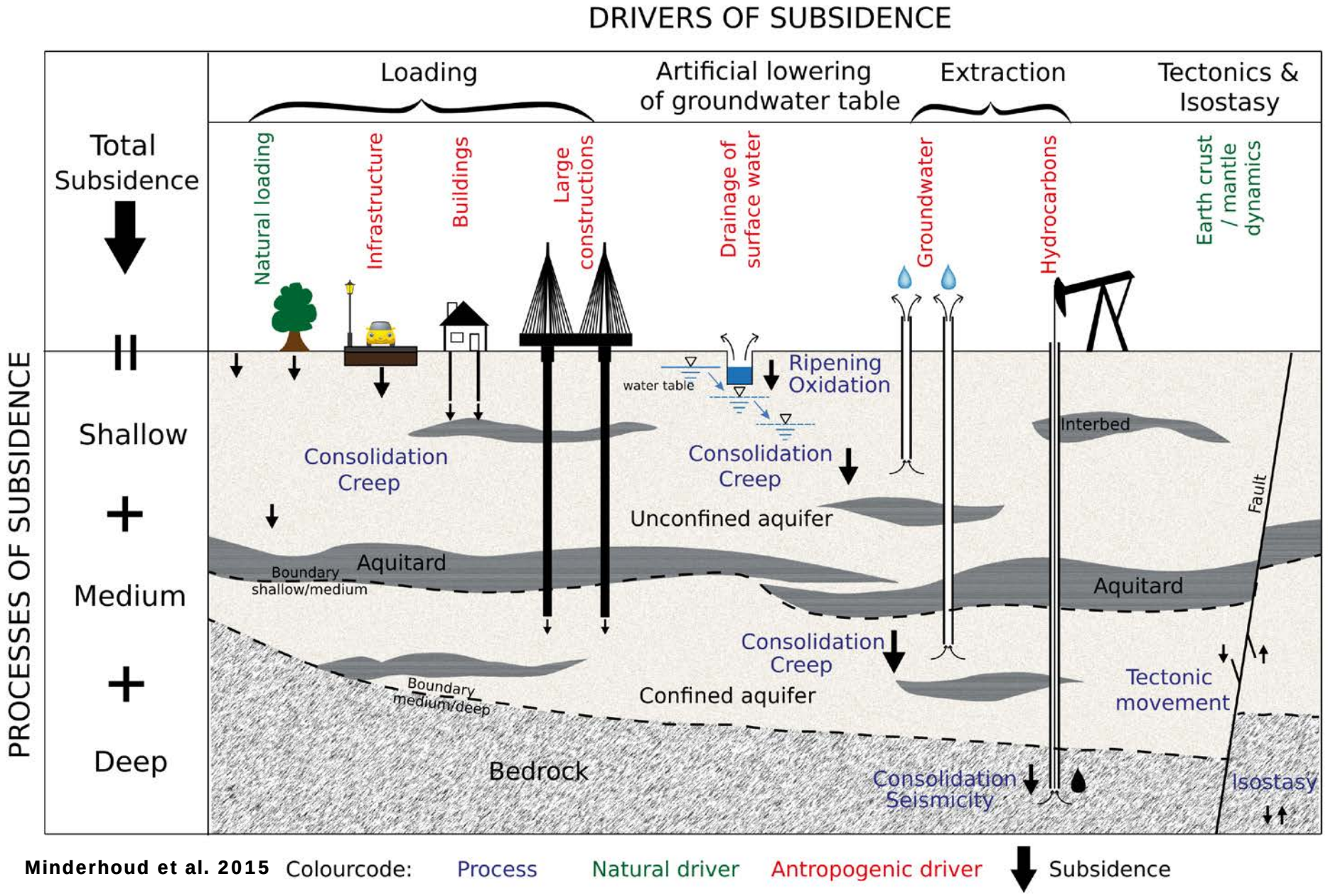
# Causes of subsidence in deltas

Land subsidence is natural process in deltas.

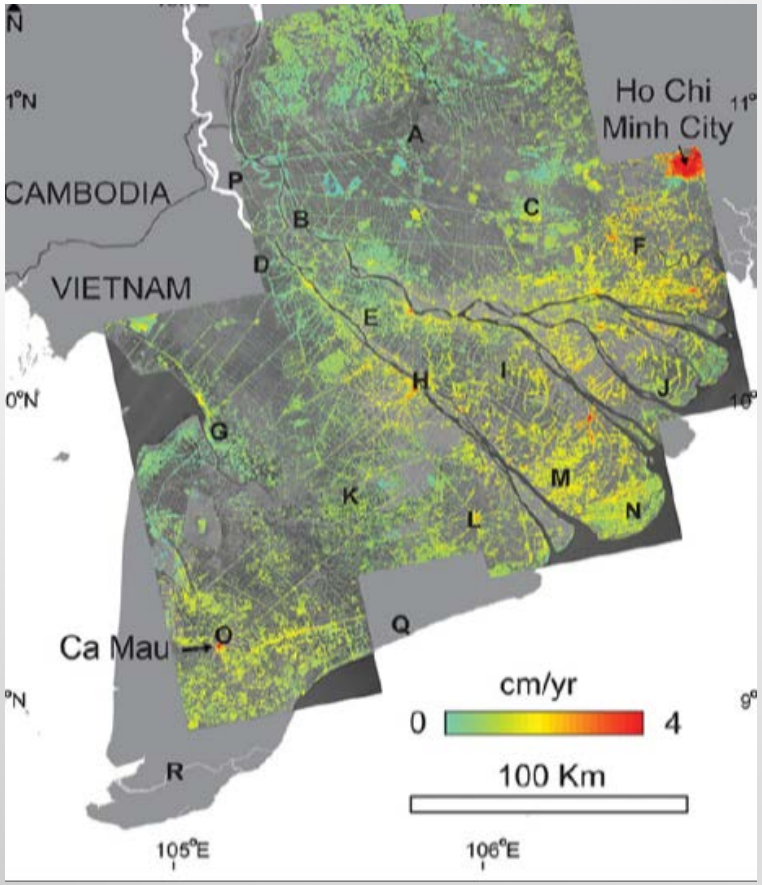
Land subsidence can be **accelerated** by human activities that increase physical loading or change the hydrogeological situation

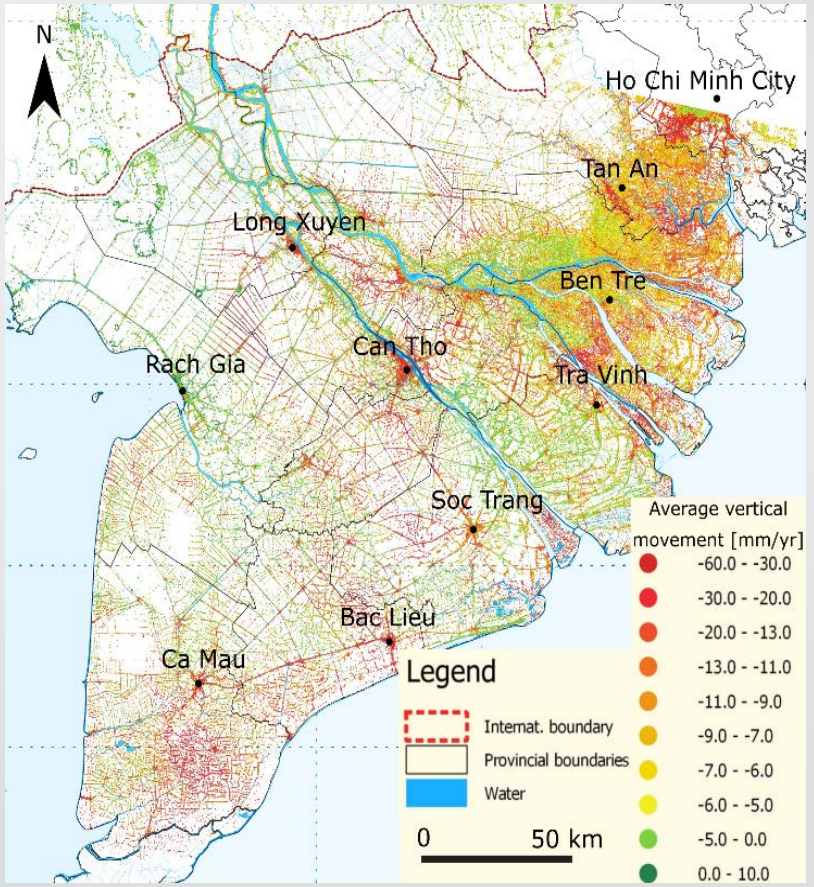
Total subsidence is the cumulative effect of all processes.



# The Mekong delta is sinking at accelerating speed

Estimated InSAR-derived subsidence rates (cm/yr)



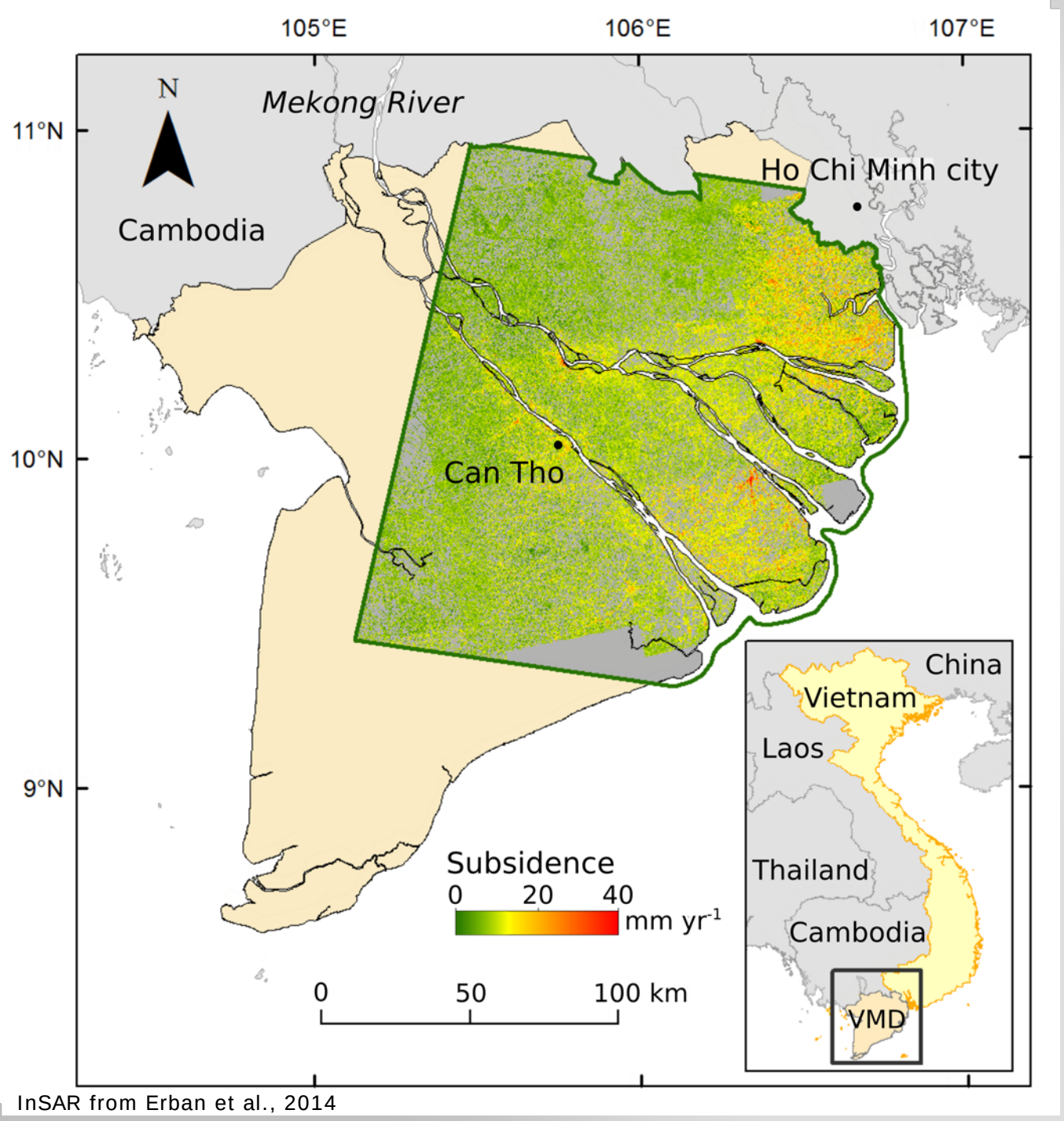


2006-2010:
Up to 2-3 cm/yr

*Erban et al., 2014. Environ. Res. Lett.*

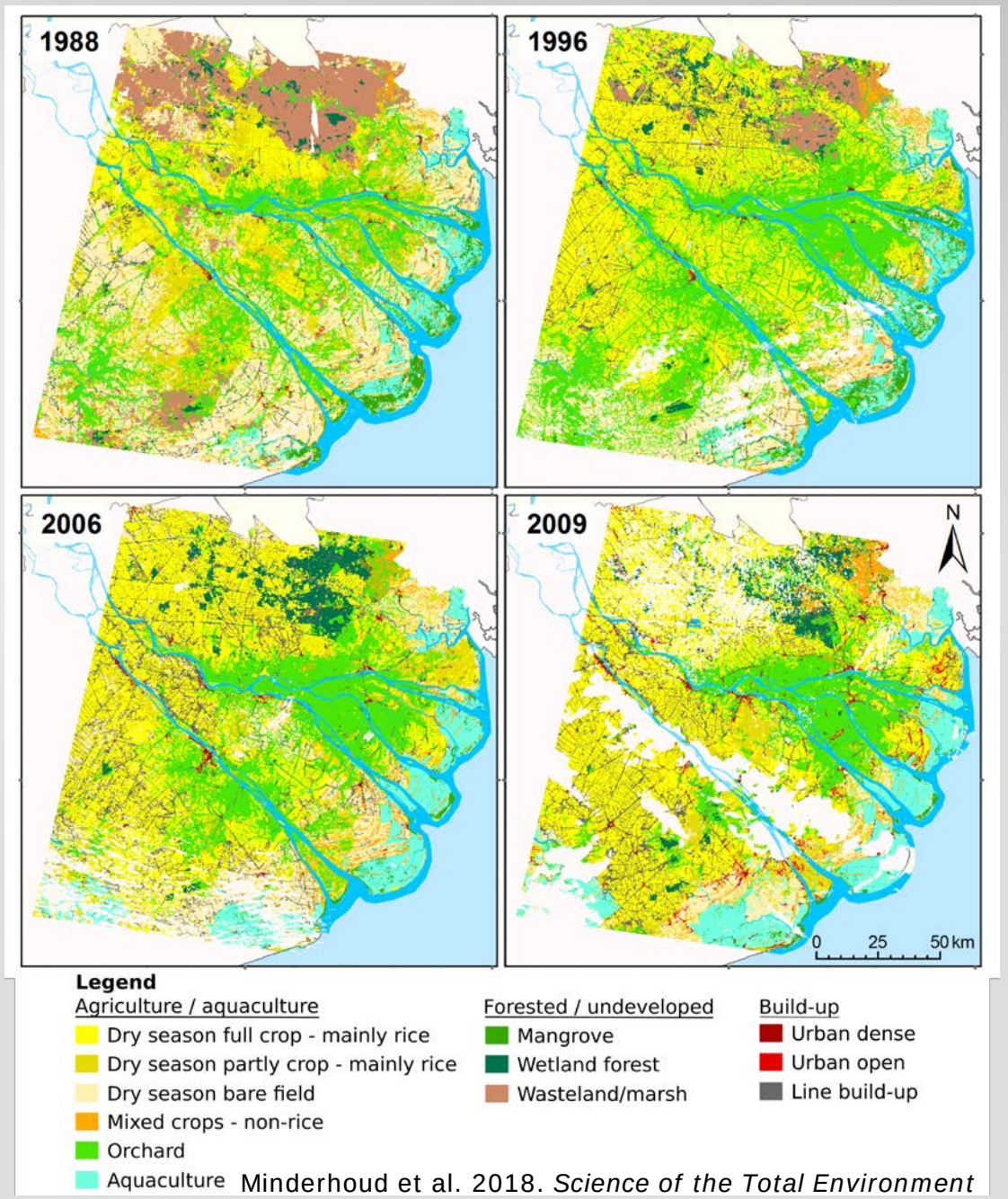
2014-2019:
Up to 5-6 cm/yr

*EU Copernicus EMSN062*
*Minderhoud et al., 2020 (IAHS)*



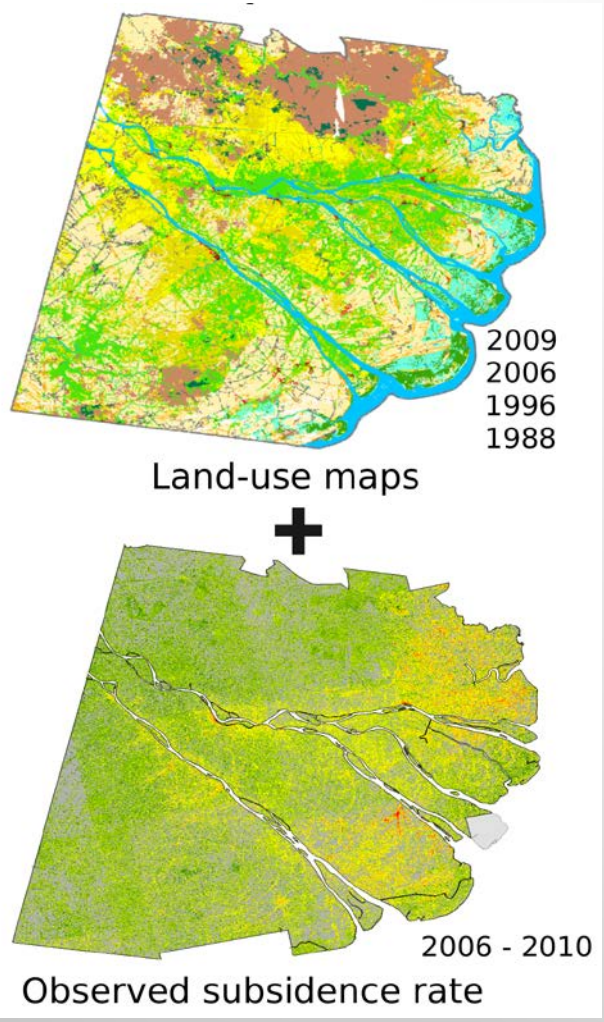

InSAR from Erban et al., 2014

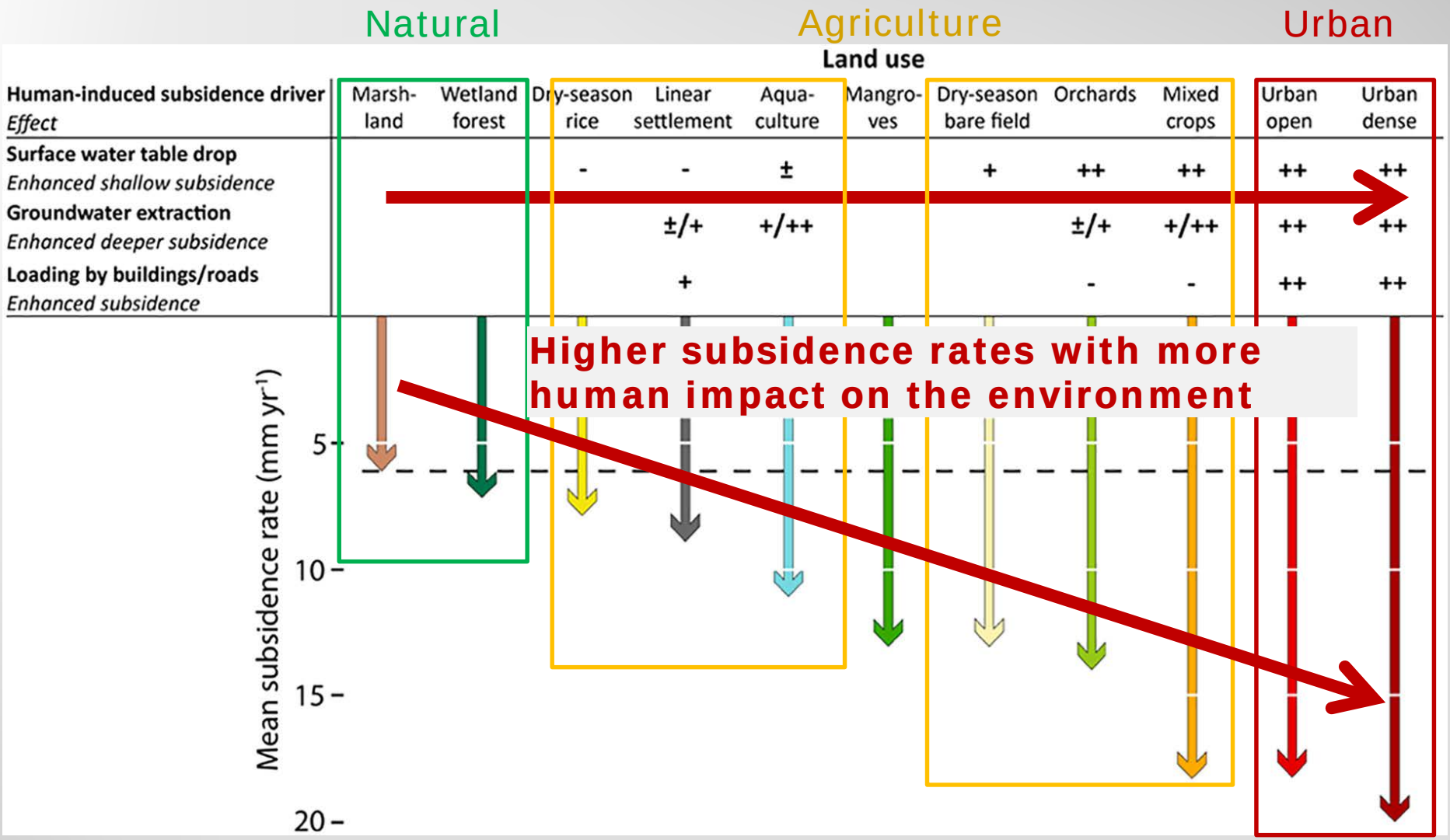
## Land-use maps




Minderhoud et al. 2018. *Science of the Total Environment*

# The relation between land use and subsidence - Evidence of human impact

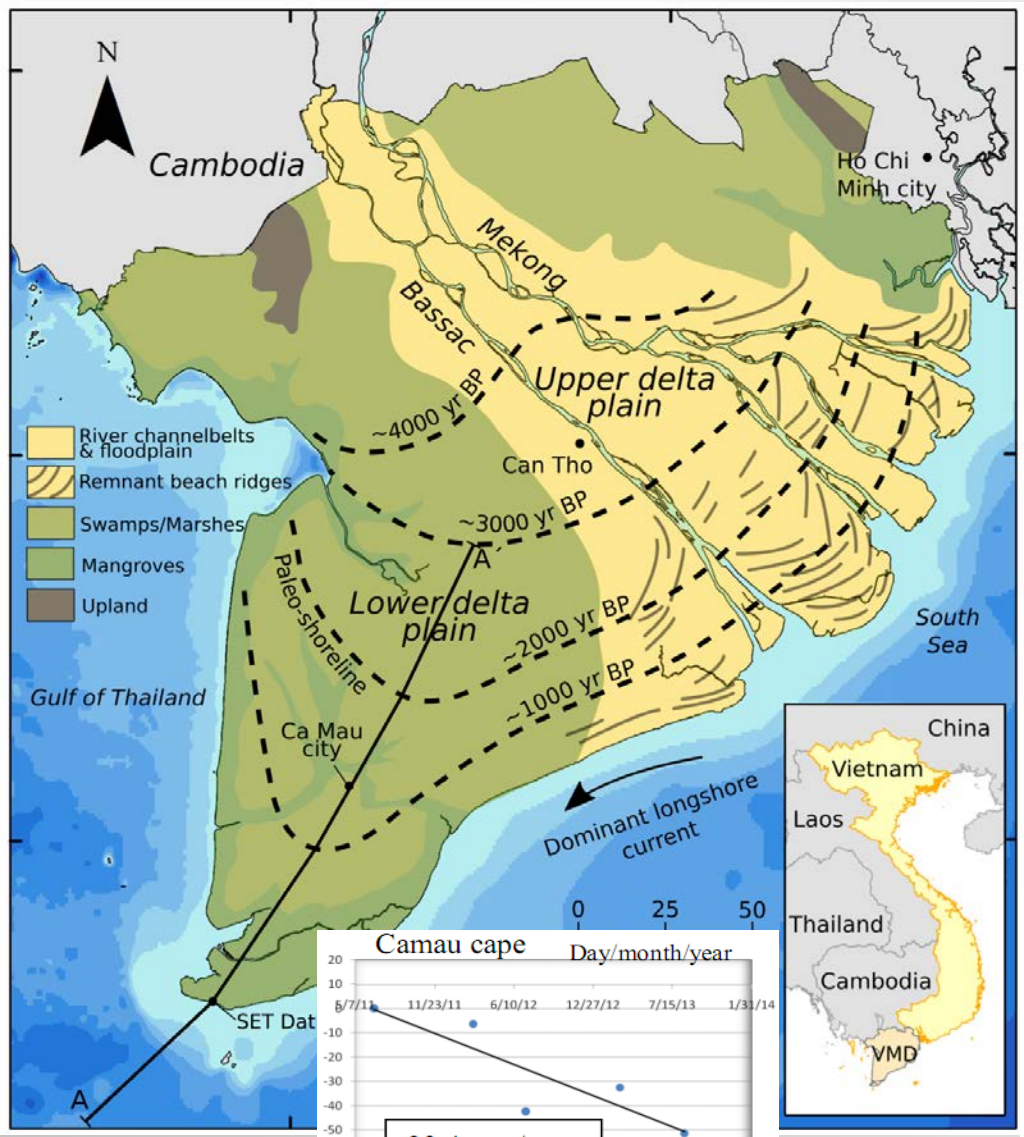



Minderhoud et al., 2018. *Science of the Total Environment*

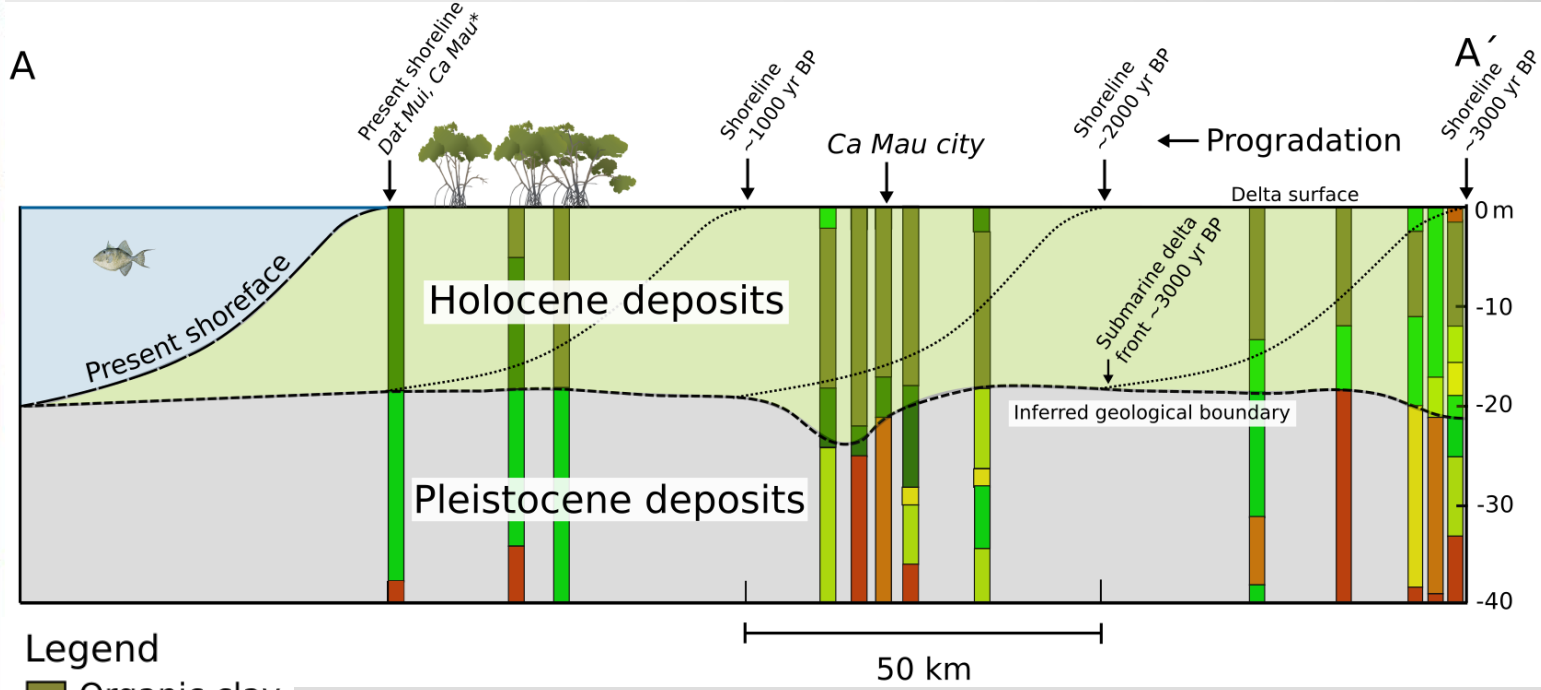
# Evolution of the Mekong delta in the Holocene

- Rapid Late-Holocene rapid transgression rates (~50 meter/yr)
- Shallow deposits of the Mekong delta are only recently deposited










Legend
- Organic clay
- Clay
- Silty clay
- Clayey silt
- Silt
- Sandy silt
- Sand

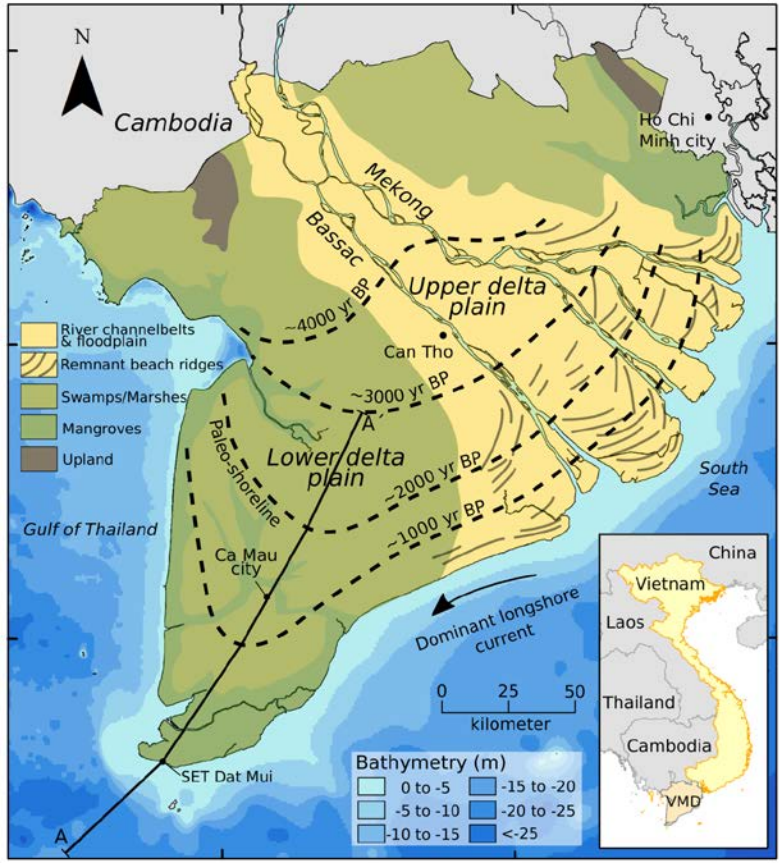
The shallow, recently deposited clays are prone to high rates of natural compaction causing subsidence

Measurement in coastal mangrove areas by R-SET show high compaction rates of Holocene strata
*(13-46 cm /yr; Lovelock et al., 2015)*

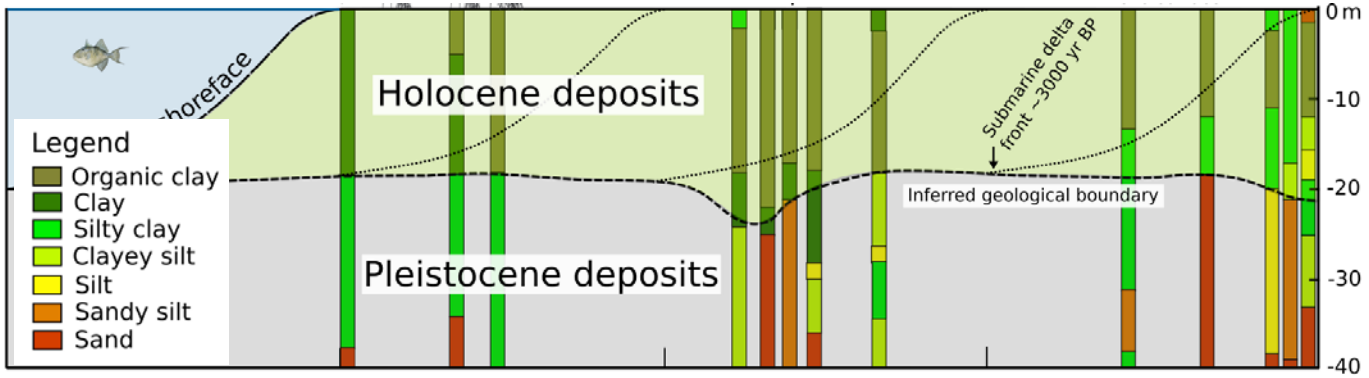
Zoccarato et al., 2018. Scientific Reports

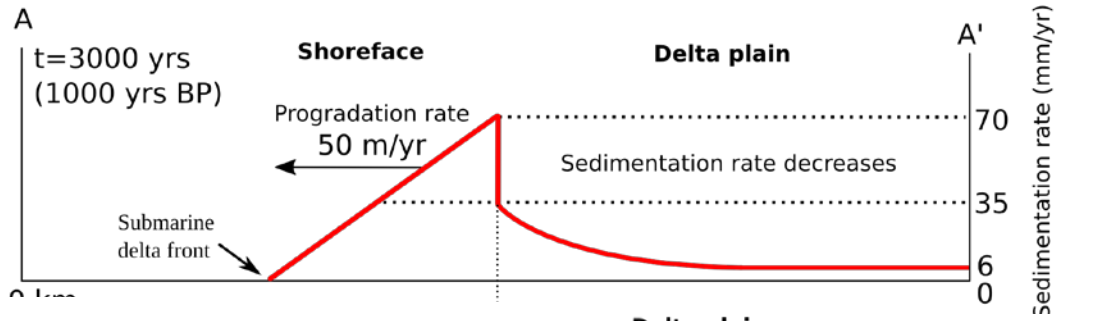
# Natural compaction following Holocene delta evolution

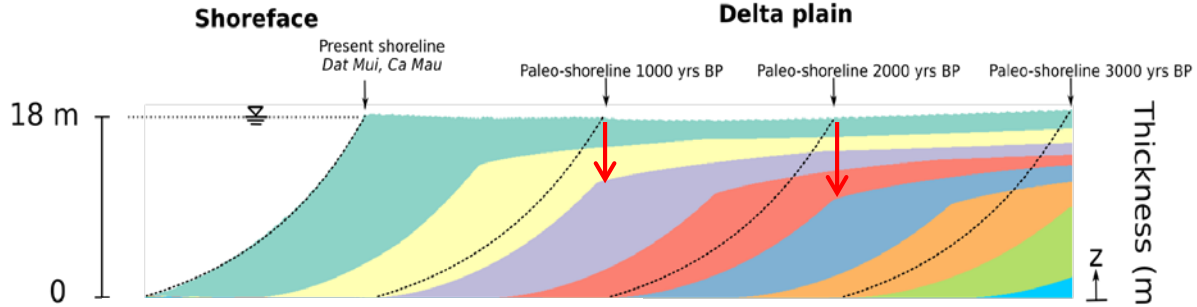
**High compaction** rates of **Holocene strata measured** *(13-46 cm /yr; Lovelock et al., 2015)*




Zoccarato, et al., 2018. *Scientific Reports*

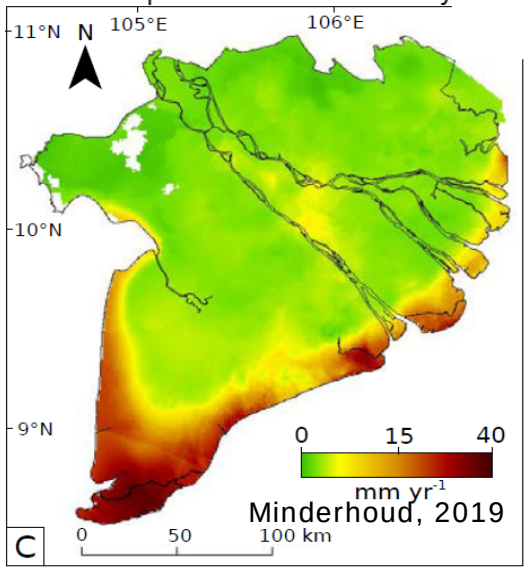



Zoccarato et al., 2018

Calculated *maximum* natura compaction of Holocene clay



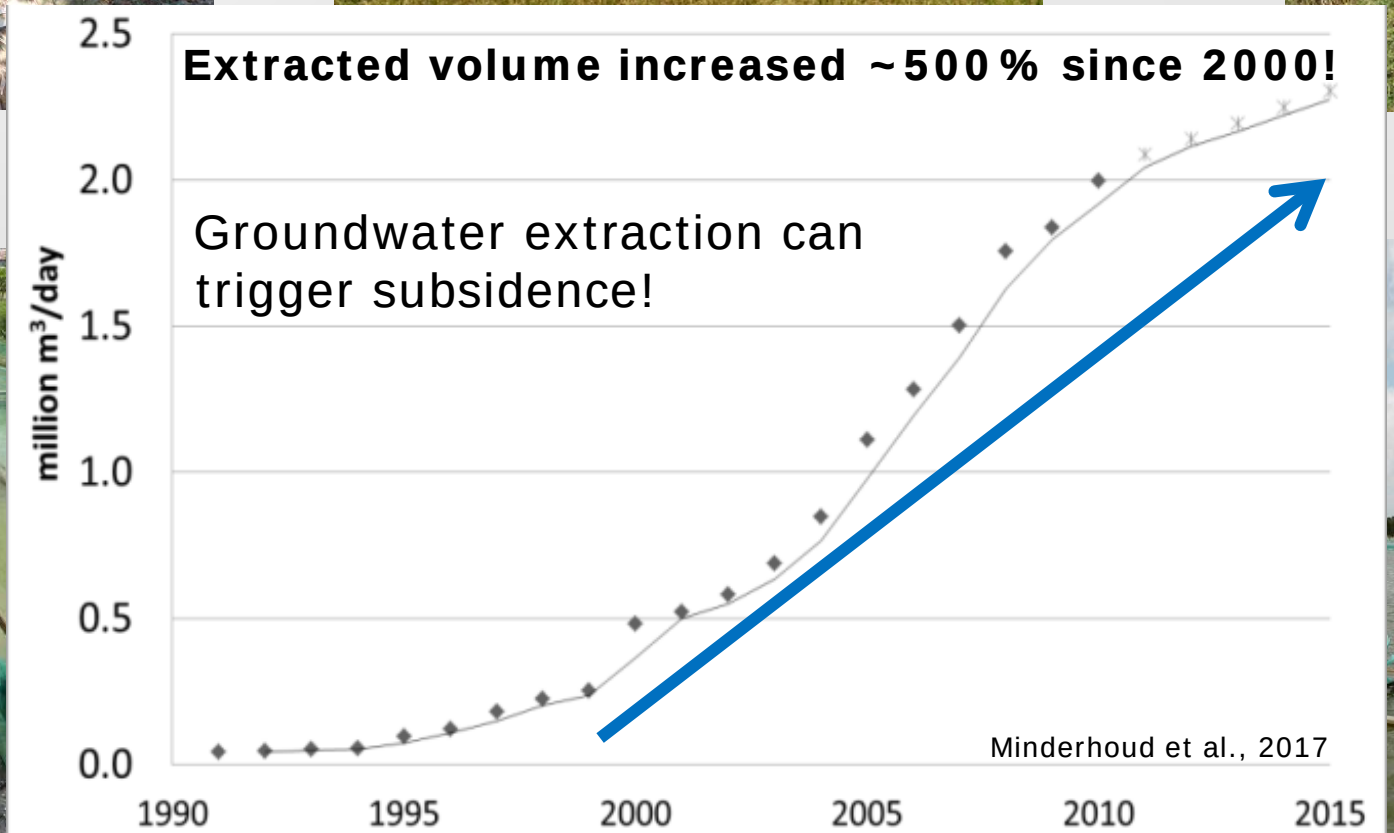

## Conclusion:

**Natural compaction** rates **at the coastline** can be as high as **~20-35 mm/yr** as result of delta evolution

# Mekong delta and groundwater extraction

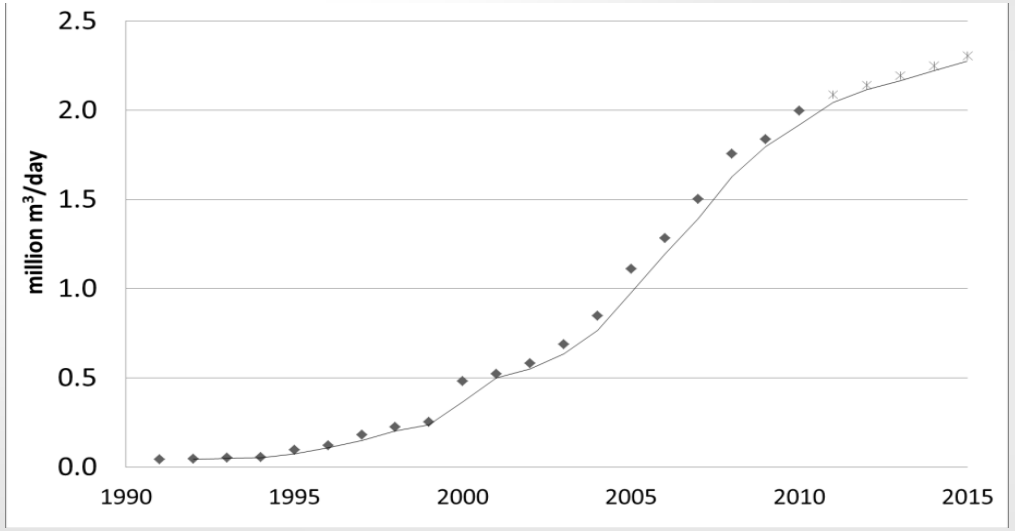




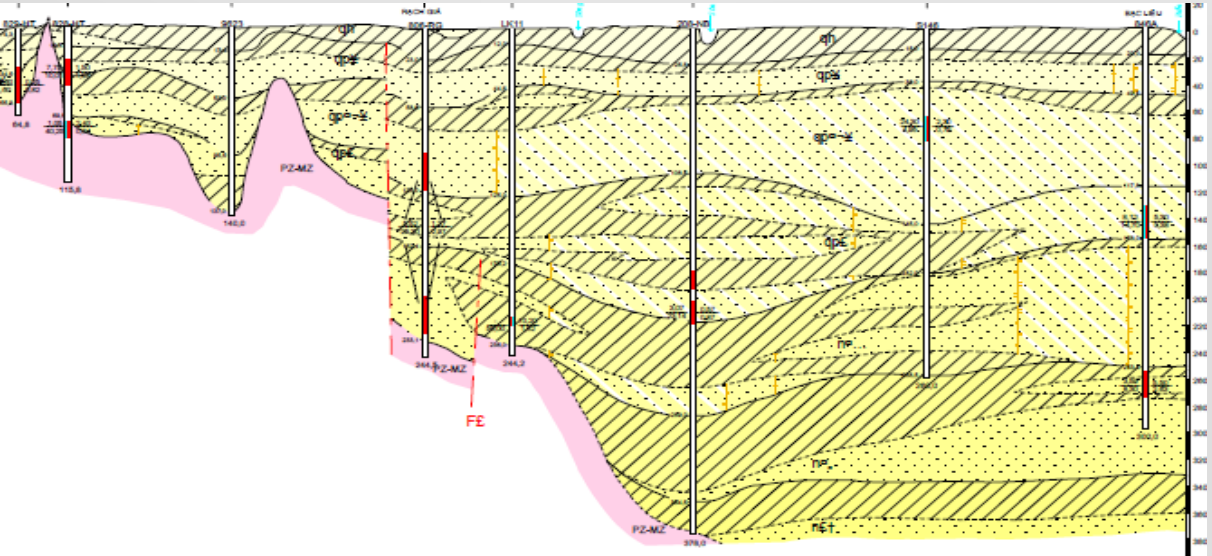



# Overextraction of confined aquifers

## Groundwater extraction in the Mekong delta

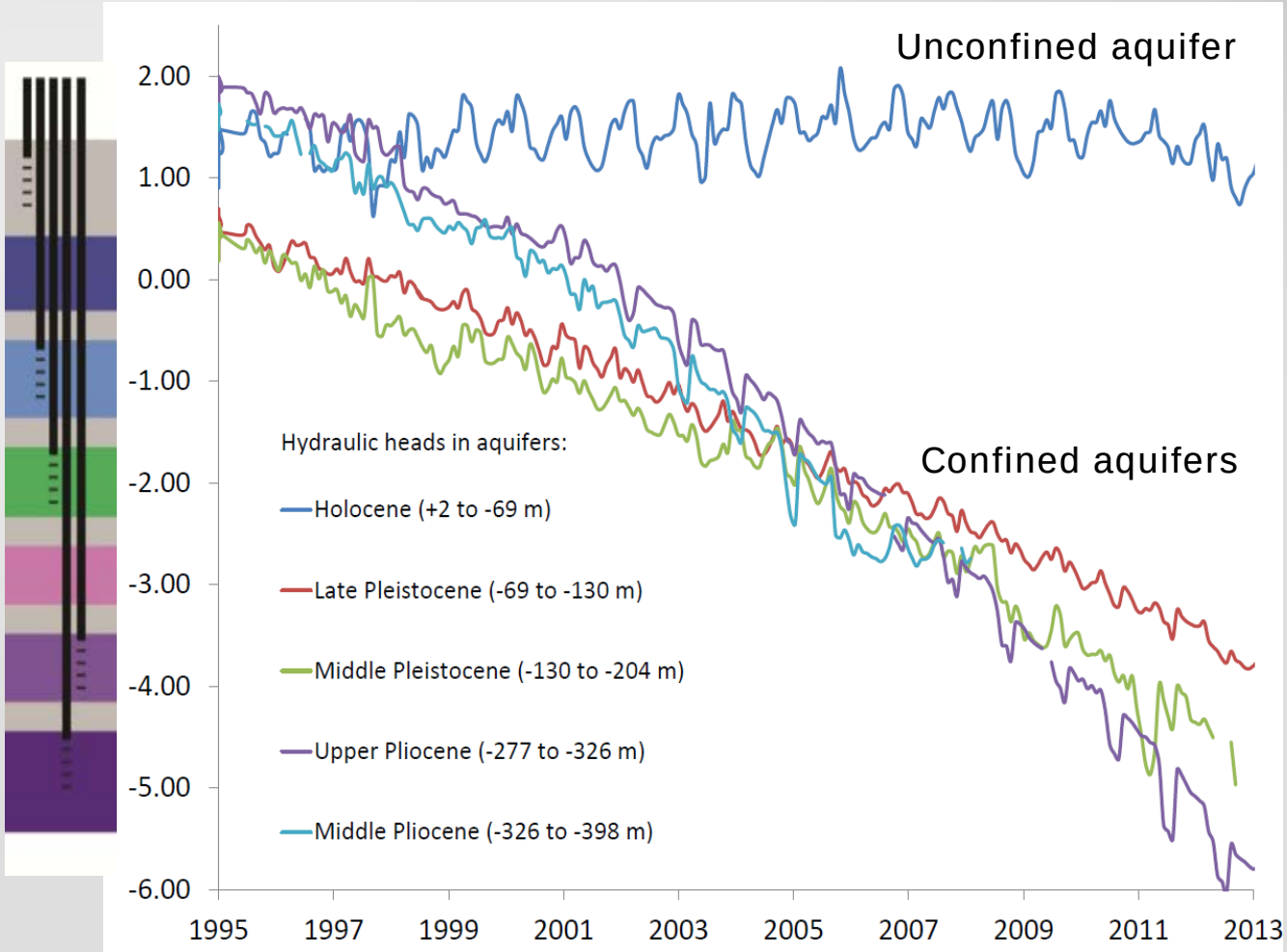



## Multi-aquifer system of the Mekong delta

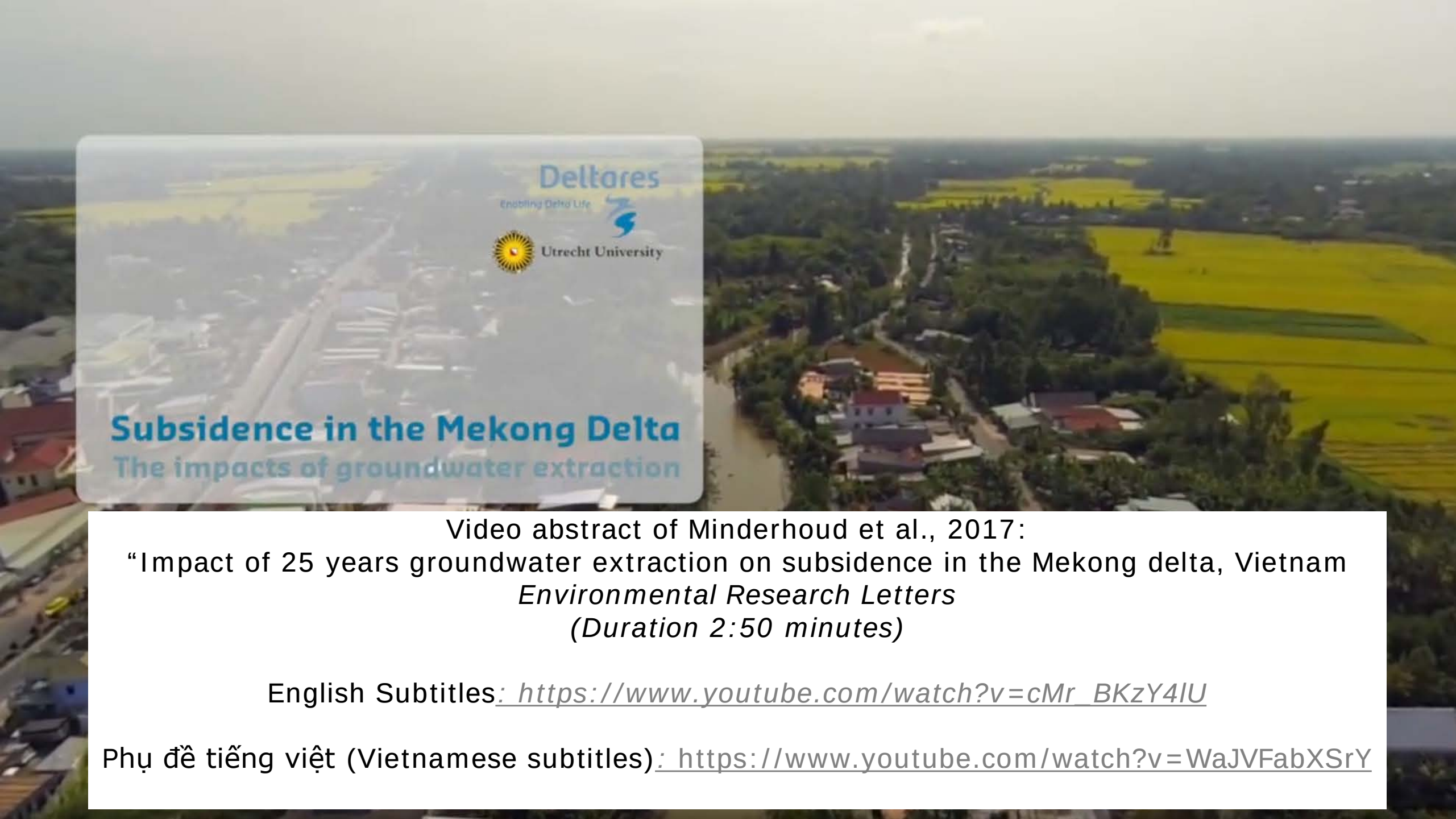


## Monitoring wells near Can Tho

Representable for the situation in the Mekong delta




Minderhoud et al., 2017




Video abstract of Minderhoud et al., 2017:
"Impact of 25 years groundwater extraction on subsidence in the Mekong delta, Vietnam
*Environmental Research Letters*
*(Duration 2:50 minutes)*

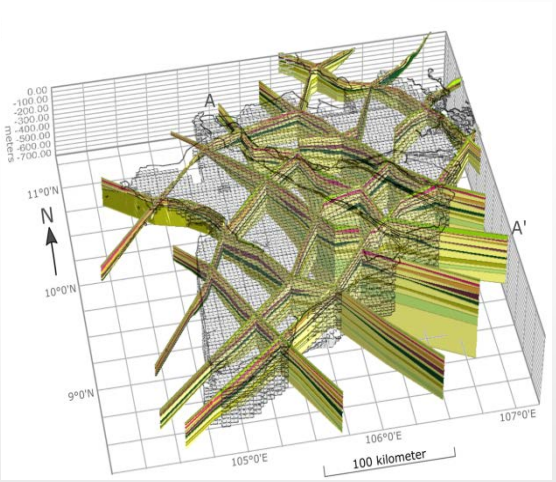
English Subtitles*: https://www.youtube.com/watch?v=cMr_BKzY4lU*

Phụ đề tiếng việt (Vietnamese subtitles)*:* https://www.youtube.com/watch?v=WaJVFabXSrY

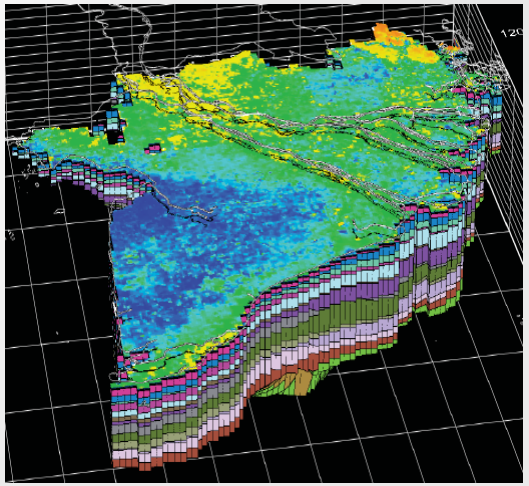
Utrecht University

# 3D hydrogeological model with subsidence module

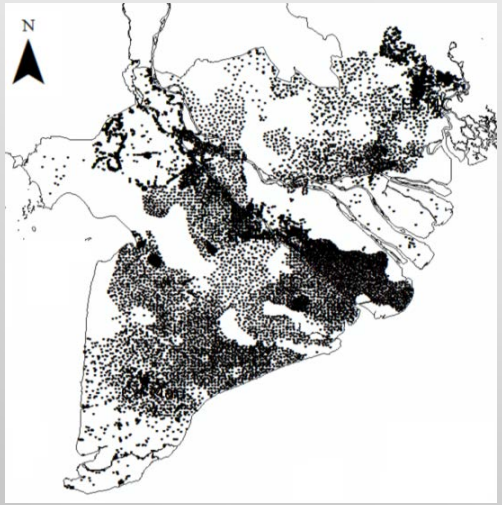
## Input data



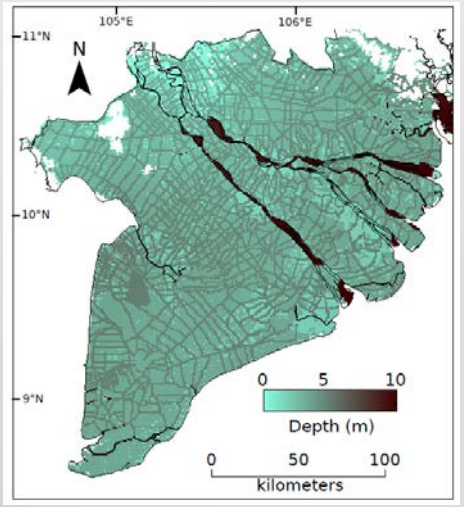

Geological borelogs and cross-sections



3D subsurface

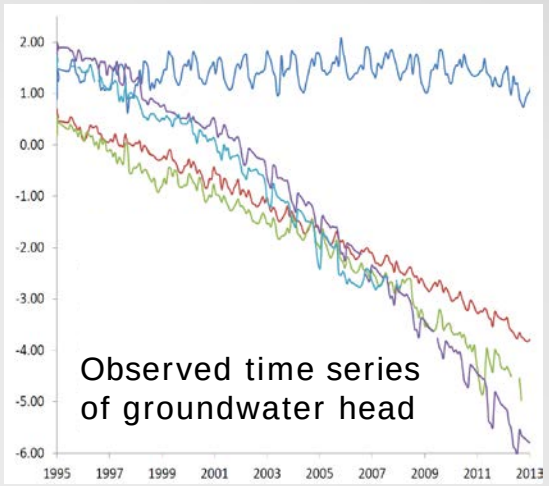


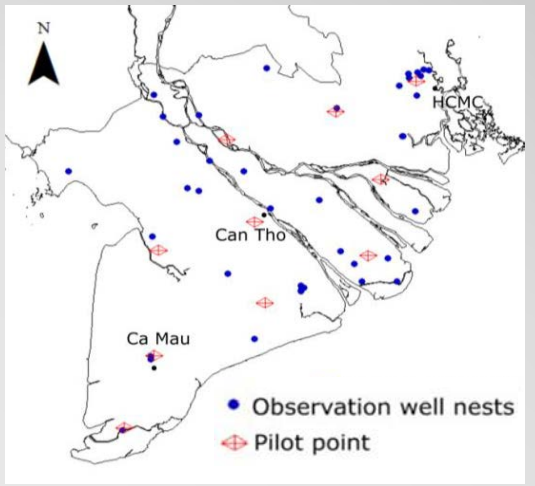

Location, depth & rate of groundwater extractions



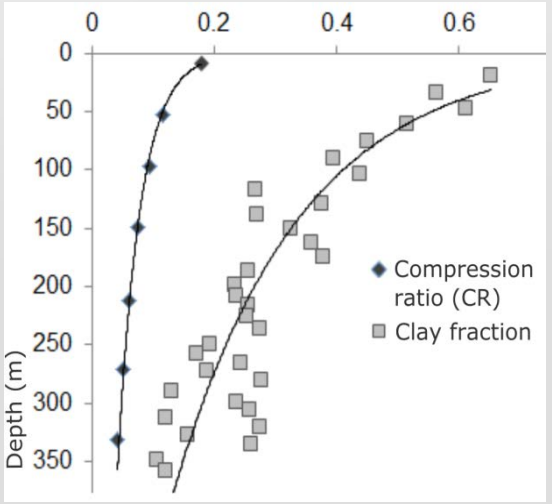

Surface water system

## Hydrogeological calibration

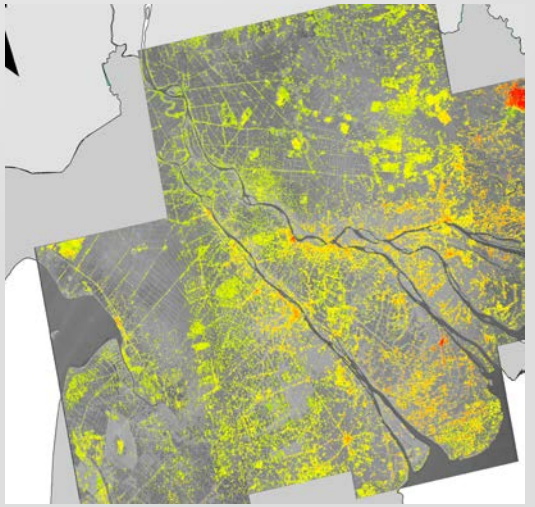



## Subsidence module




Geotechnical parameters based on field data

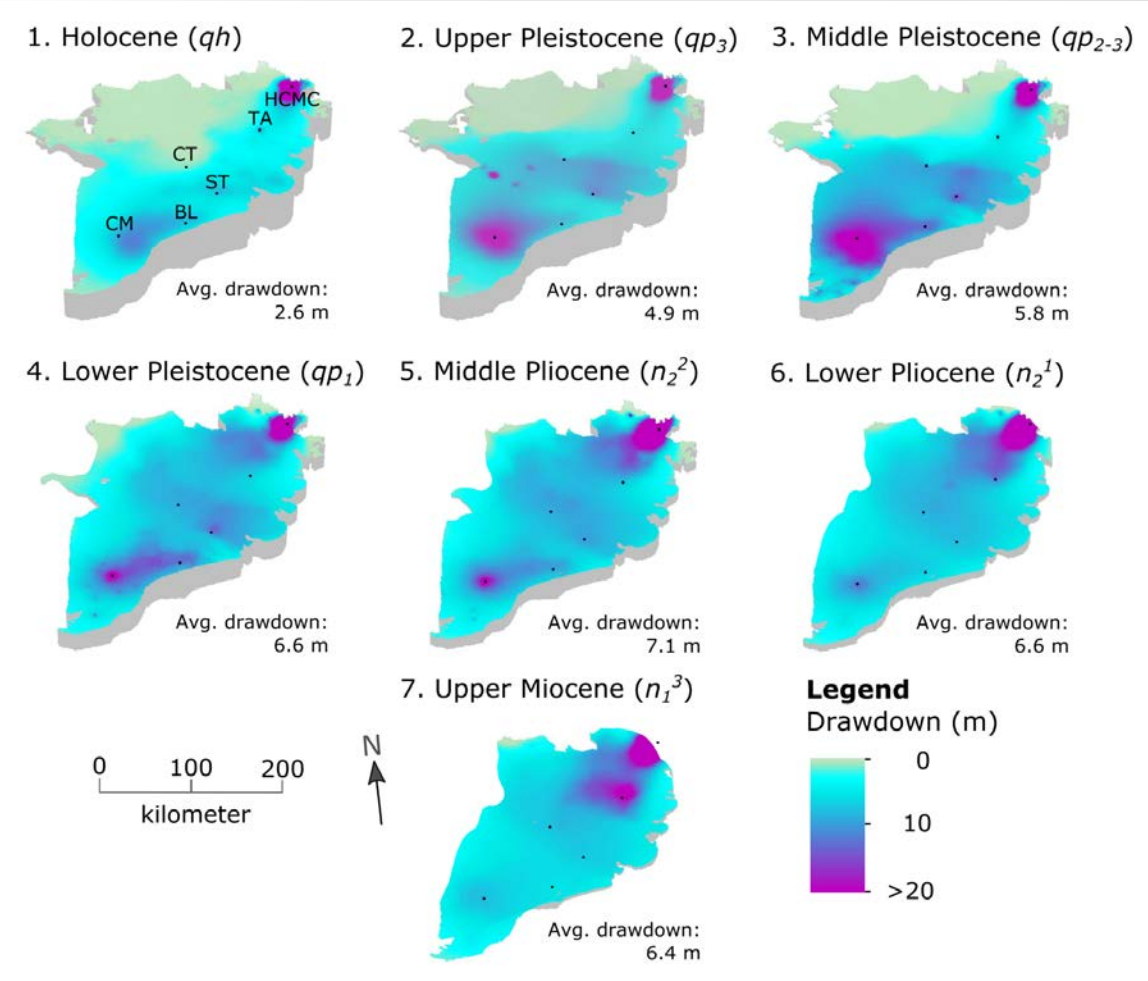


Validation: InSAR-derived subsidence (Erban et al., 2014)

Minderhoud et al., 2017 - Environmental Research Letters

# 25 years of simulated groundwater extraction

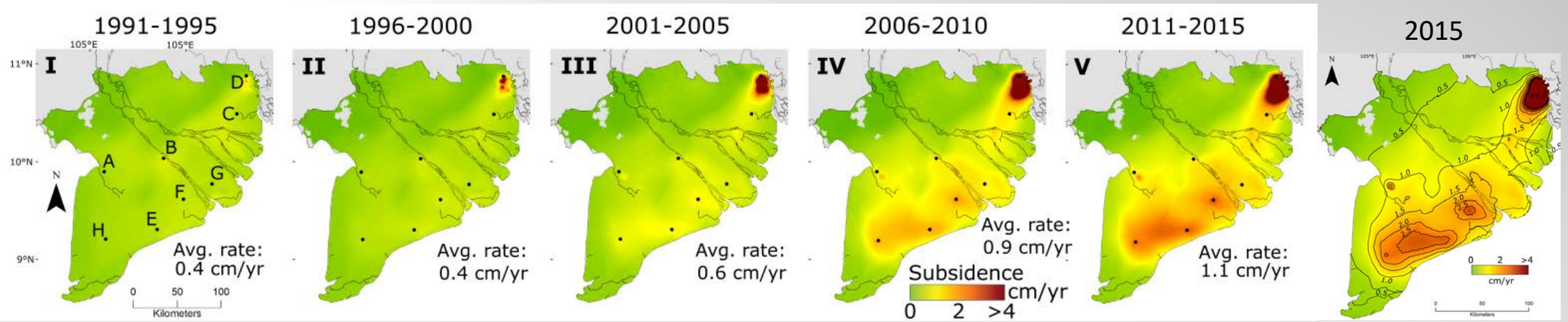
## Hydraulic head in the aquifers



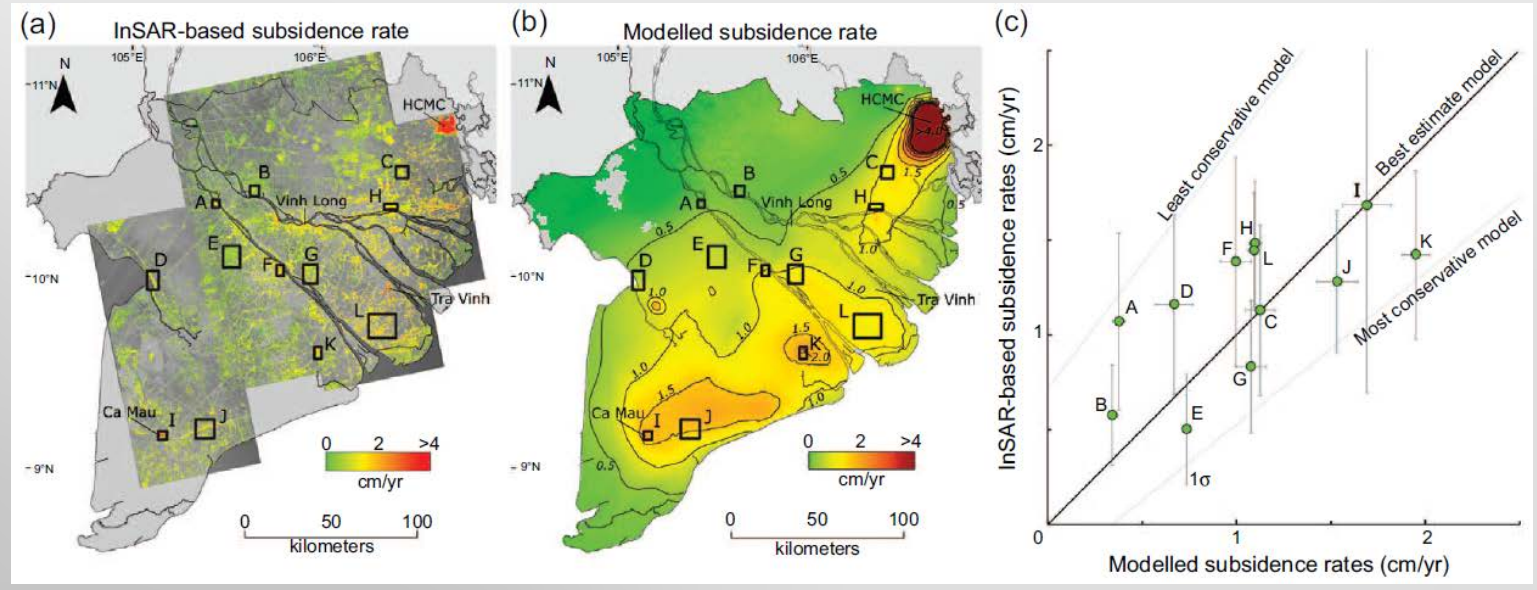

**Groundwater extraction is much larger than groundwater recharge → overexploitation**

Minderhoud et al., 2017

# Extraction-induced subsidence is accelerating!




Groundwater extraction-driven subsidence exceeds absolute sea-level rise by a magnitude!




**Most/least** conservative model: **60%/160%** of the best estimate model rates

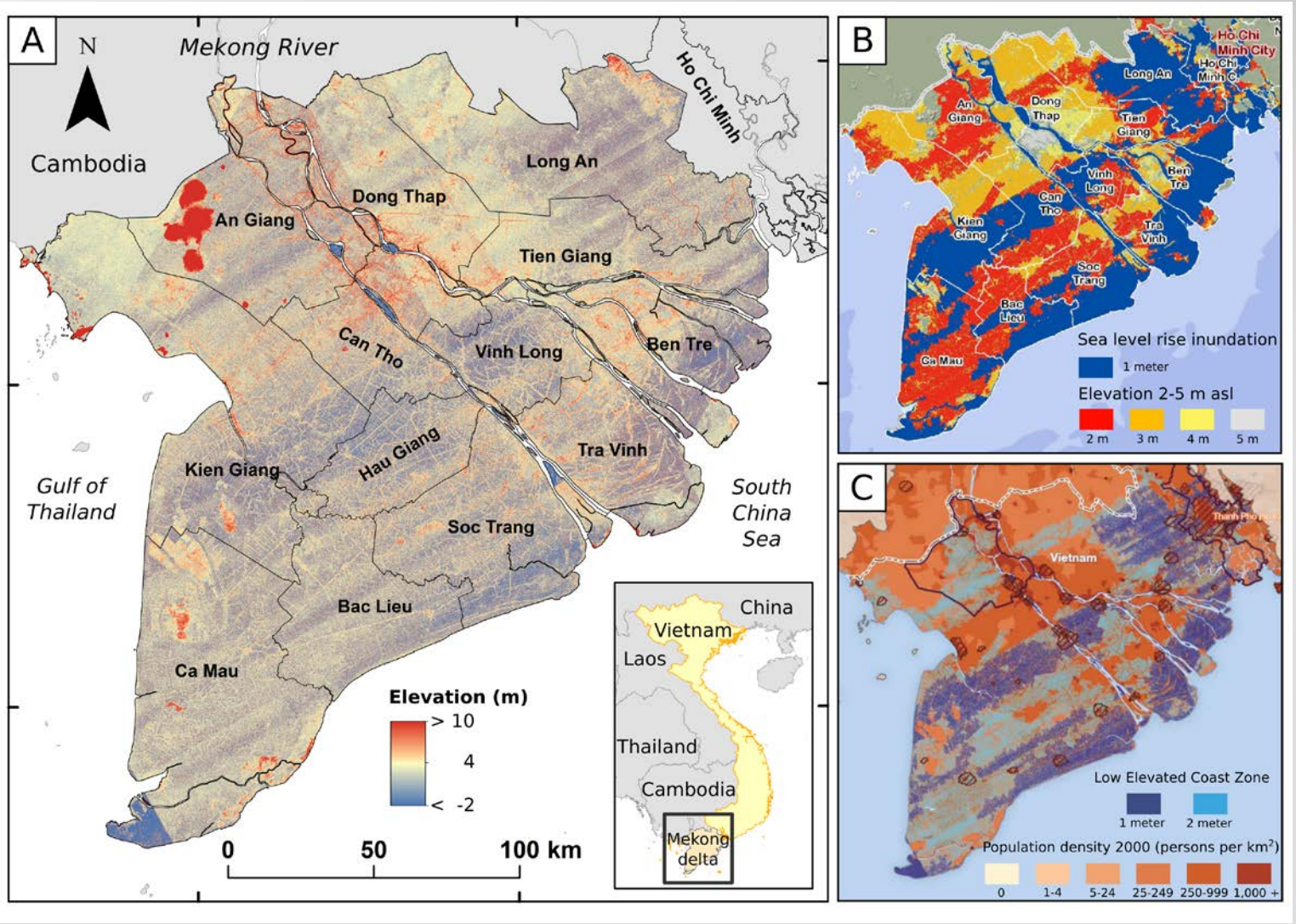
Sources of uncertainties in modeling results:

- Hydrogeology and geotechnical parameters
- Extraction data
- Geological schematization
- Layer discretization

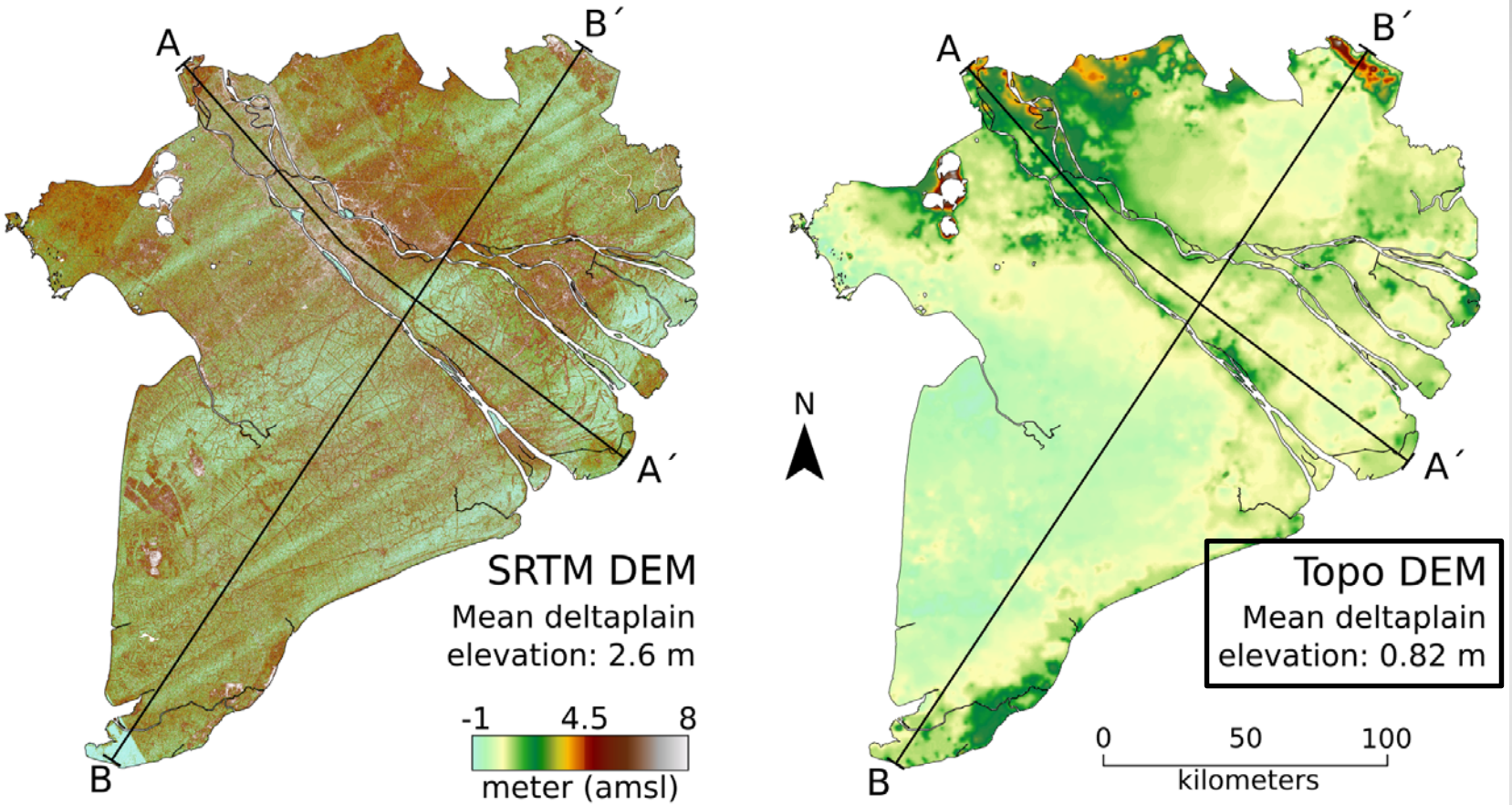
**Rates may vary for each location, but the accelerating trend is clear!**

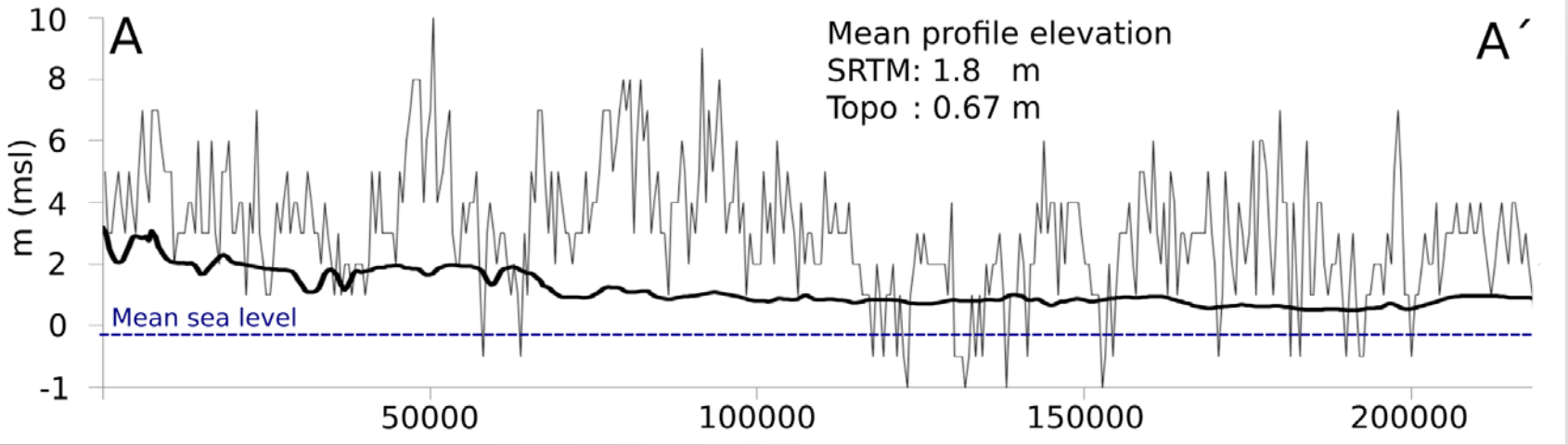
Minderhoud et al., 2017 - Environmental Research Letters

# Impact of subsidence is relative: elevation is key!




A) SRTM Digital Elevation Model of the Mekong delta.
B&C) Two examples out of many previous sea-level rise impact assessments using SRTM elevation data and erroneously assuming zero elevation (EGM96 datum) as local sea-level.




## Mekong delta much lower than internationally thought!

### Reasons:

1) SRTM DEM absolute vertical accuracy for Eurasia: 6.2 meter.

2) SRTM referenced to global GEOID (EGM96) which turns out to have an unexpectedly large vertical offset with local tidal (*Hon Dau*) datum: ~1.5 meter!

### Implications:

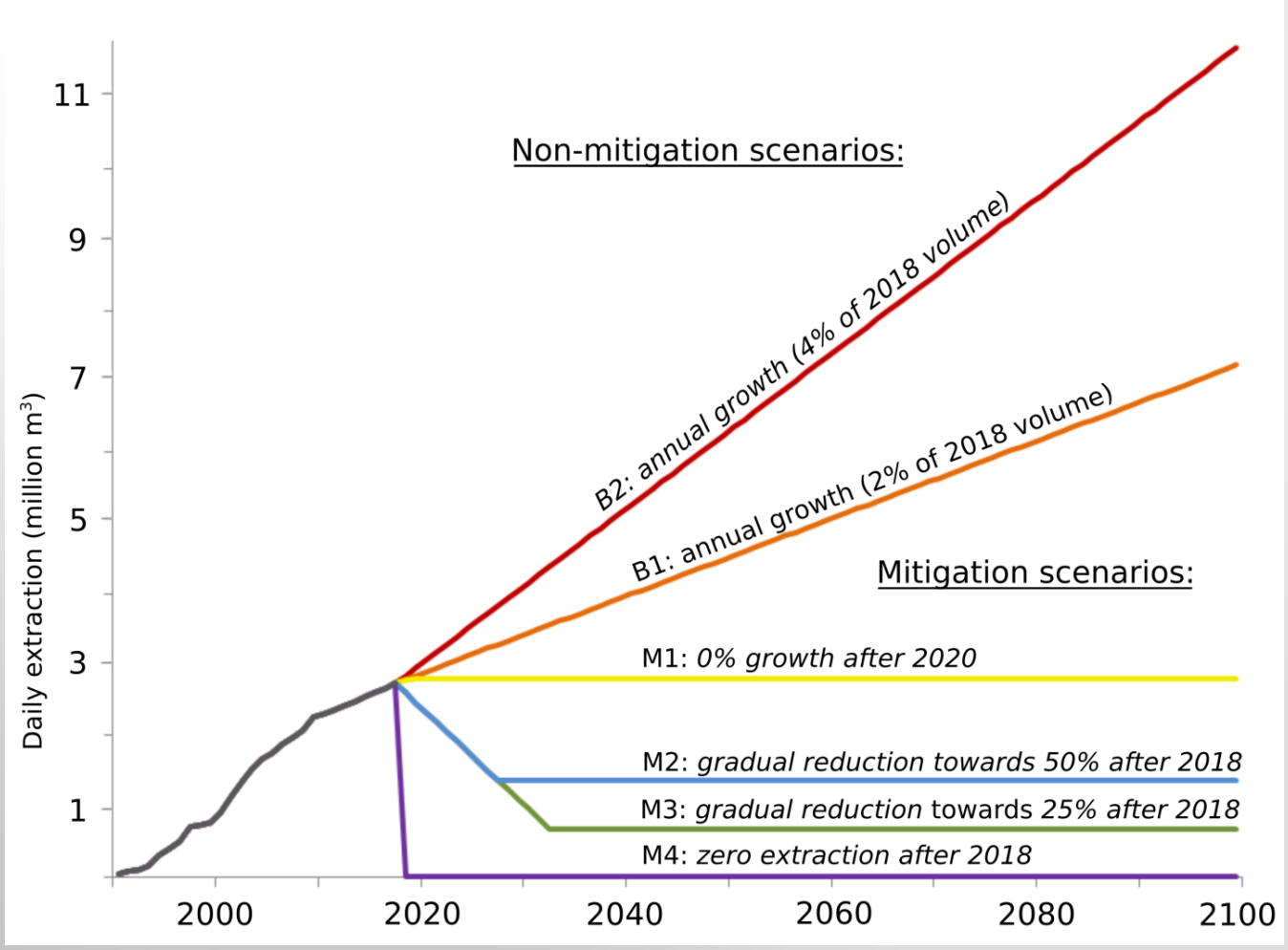
- Mekong delta is much lower elevated than international research studies assumed, so much more *vulnerably* to relative sea-level rise than previously thought

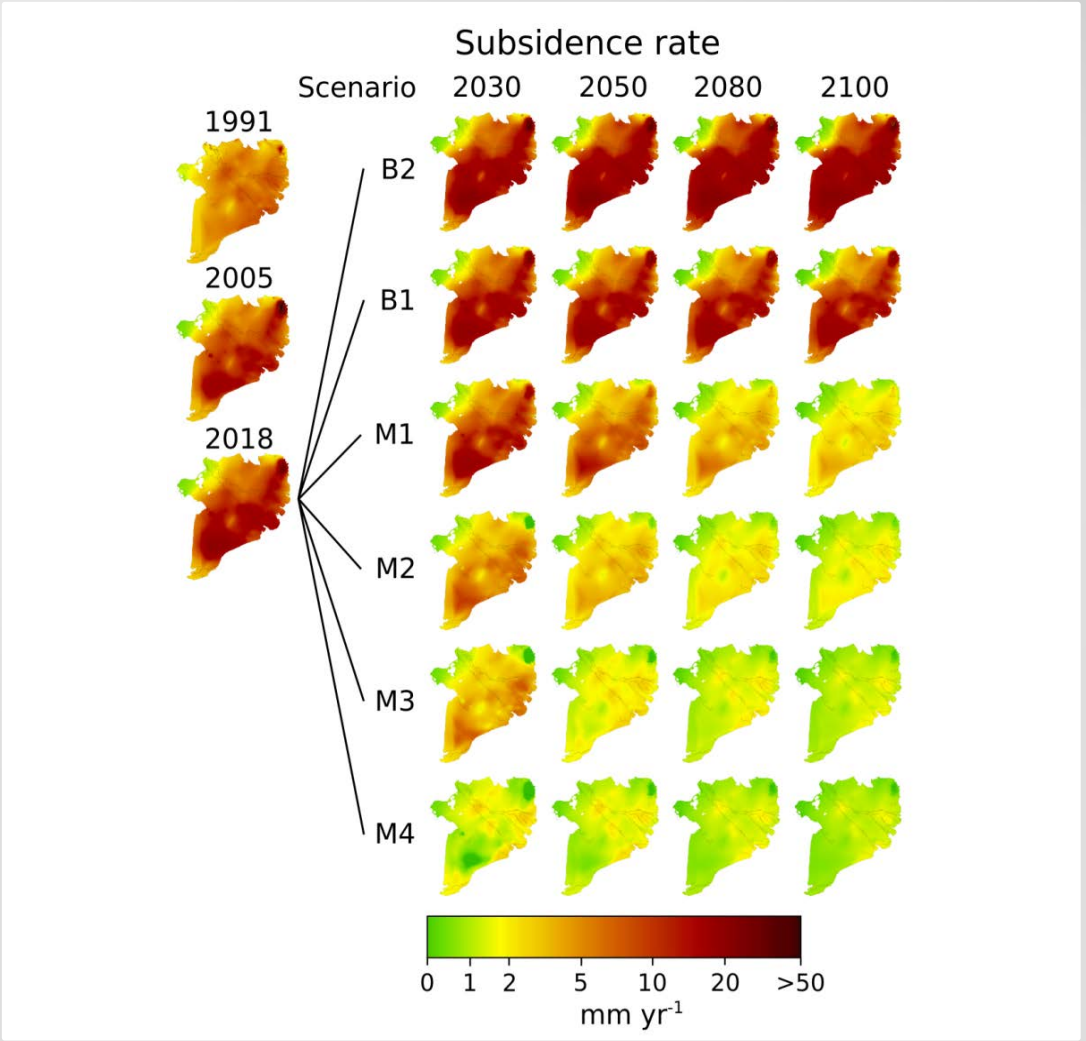
- Other deltas and coastal regions in the world potentially face similar underestimations!

Minderhoud et al., 2019 *Nature Communications*

# The future of the Mekong delta: use pathways!

## Modeling scenarios with different groundwater extraction pathways



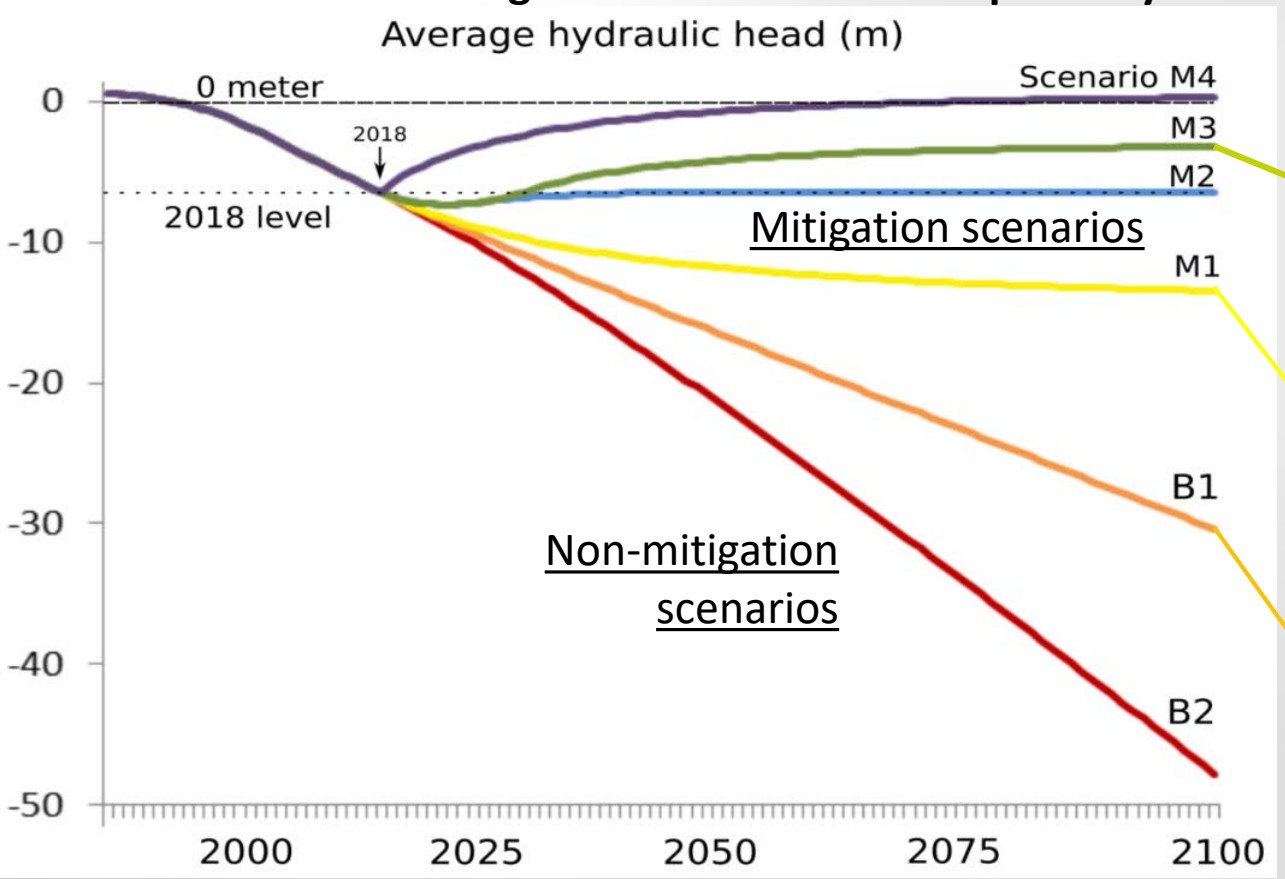




Minderhoud et al., 2020 Environmental Research Communications

# The future of the Mekong delta: use pathways!

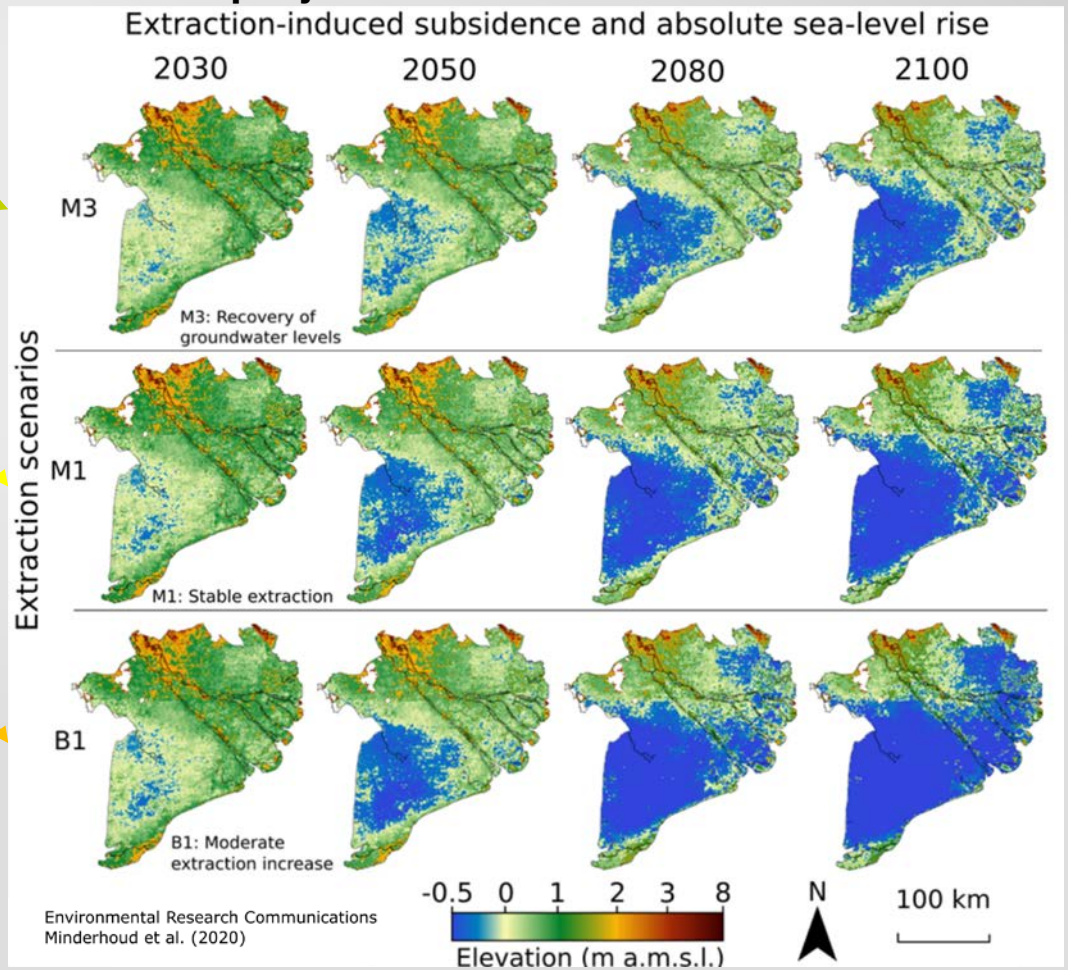
***The decisions of today will determine the status of the delta tomorrow***

## Scenarios of future groundwater extraction pathways




- Without mitigation, **extraction-induced subsidence alone** may **sink** large parts of the delta by the end of the century
- **Groundwater** in the delta is **not** a **free** resource – it is **paid** for **by elevation. Elevation**, and thus **time**, **is running out!**

## Future projected elevation of the delta




- *Elevation projections assume SLR according to RCP 4.5 projections.*
- *Elevation gain through sediment accumulation is assumed to counterbalance natural compaction*

Minderhoud et al., 2020 Environmental Research Communications

# Towards solutions

## Adequate and inclusive (ground)water management is key!

- Create **awareness** of human-driven impacts on the environment – most of the impact comes from internal rather than external factors
- Use thorough understanding of the interconnected natural system to design **mitigation** (i.e. *reduce extraction of water and sand*) and **adaptation strategies** (i.e. *prepare for consequences of relative sea-level rise and erosion*)
- Adaptive pathways – inclusive water (and sediment) management


<u>Strategies for Vietnam:</u>

- Reduction extraction of water and sand
- Find alternative water sources – surface water
- Water saving practices and smart agriculture (water efficient crops, drip irrigation, salt resistant crops).
- Smart fresh water management – save excess fresh water during wet season for dry season – subsurface storage → grow fresh water lens)

Solutions are all possible with enough and thorough system knowledge -

→ No **'one solutions fits all**' – System understanding required!

# References

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