

The existential crisis of the Mekong delta: Impact of accelerating land subsidence

Results of the Rise and Fall research program (2014-2019): Towards strategies for the subsiding Mekong Delta facing increasing salt water intrusion. Urbanizing deltas of the World (UDW NWO-WOTRO)

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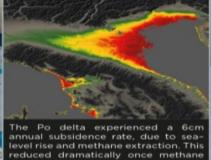
With contributions of Esther Stouthamer (UU), Gilles Erkens (Deltares/UU), Hans Middelkoop (UU), Elisabeth Addink (UU), Laura Coumou (UU), Gualbert Oude Essink (Deltares), Henk Kooi (Deltares), Laura Erban (EPA, USA), Hung Pham Van (UU/DWRPIS), Voung Tran Bui (DWRPIS).



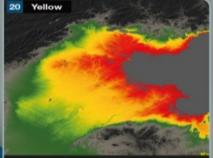


fter farms and urban areas have aken their water allotments, the Colorado River slows to a trickle by the ime it reaches its delta. Sometimes it stops flowing altogether and then no ediment is deposited.





extraction ended



As deltas sink the risk of flooding rises In the Yellow River delta typhoons have caused 5m-high storm surges

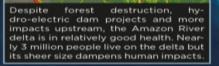
23 Chao Phraya

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

angkok and leaving much al submerged for months been sinking for decades due to groundwater extraction. Steep

taxes on groundwater have slowed subsidence substantially



ELEVATION (metres) 40 500

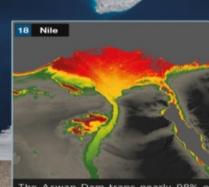
Amazon

Syvitski J P M et al. (2009) Nature Geoscience 2: 681-686. doi:10.1038/ngeo629 Ericson J P et al. (2006) Global and Planetary Change 50: 63-82. doi:10.1016/j.gloplacha.2005.07.004 IPCC (2013) Summary for Policy Makers. In: Stocker T F et al. (eds) Climate Change 2013: The physical science basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA. www.climatechange2013.org/images/report/WG1AR5. SPM FINAL pd

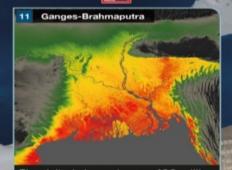
Elevation Data: NASA Shuttle Radar Topography Mission Global 3 arc second V003 Cartography and design: Globaïa



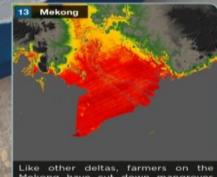
This infographic was produced by the International Geosphere-Biosphere Programme



The Aswan Dam traps nearly 98% of sediment flow downstream. Without those soils, the Nile Delta has com pacted and sunk. Relative sea-leve rise there is 4.8 millimetres every year.



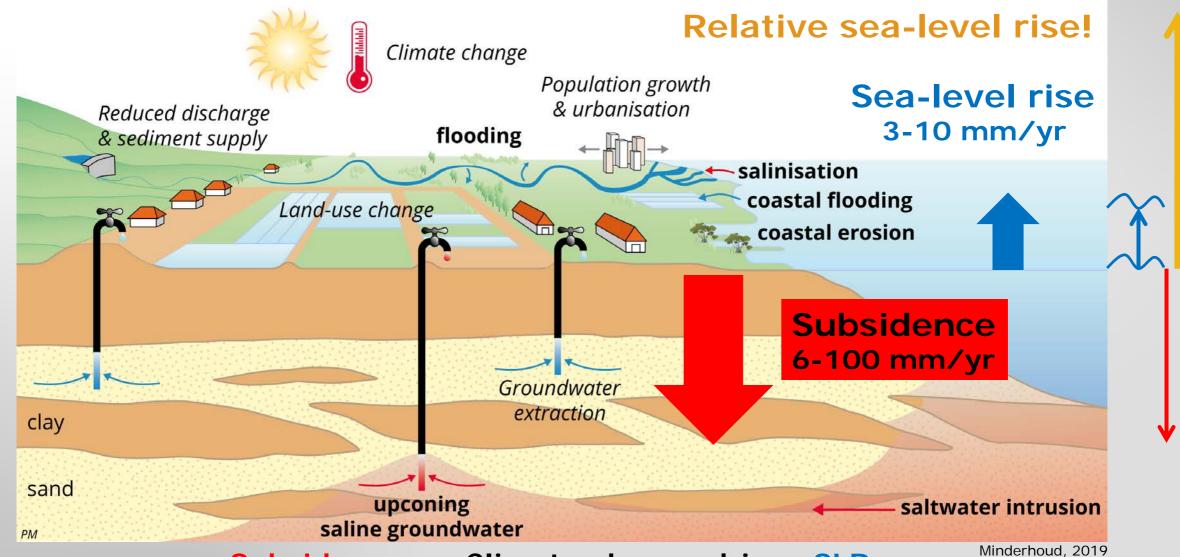
The delta is home to over 100 million people making it the most populated on Earth. Effective sea-level rise is up to 18 millimetres per year. In 2007-08 substantial flooding affected the Ganges, Mekong, Irrawaddy, Chao Phraya, Brahmani, Mahanadi, Krishna and Godavari. More than 100,000 died and more than a million people were displaced.



Mekong have cut down mangroves to create space for shrimp ponds. Surveys indicate roughly half the mangrove forests have disappeared. Mangroves help prevent erosion and are important flood defences.



Changes in delta systems around the world



Subsidence >> Climate-change driven SLR



Causes of subsidence in deltas

Artificial lowering Loading Extraction Tectonics & of groundwater table Isostasy Large Earth crust / mantle dynamics Buildings Total Natural loading nfrastructure ge of water **Hydrocarbons** Groundwater Drainage surface wai Subsidence Н Ripening Oxidation SUBSIDENCE water table Interbed Shallow **Consolidation** Consolidation Creep Creep Fault Unconfined aquifer OF Aquitard Boundary Aquitard Medium shallow/medium PROCESSES Consolidation Creep Tectonic Boundary Confined aquifer movement Deep Bedrock Consolidation Isostasy

DRIVERS OF SUBSIDENCE

Land subsidence is natural process in deltas.

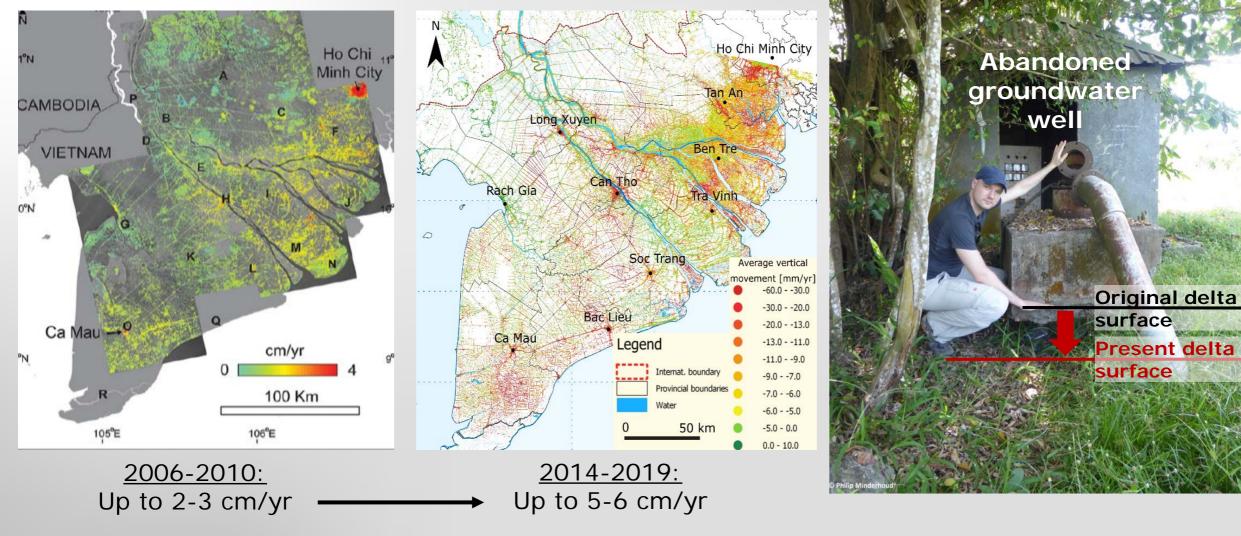
Land subsidence can be accelerated by human activities that increase physical loading or change the hydrogeological situation

Total subsidence is the cumulative effect of all processes.

Minderhoud et al. 2015 Colourcode: Process Natural driver Antropogenic driver Subsidence

Utrecht University The Mekong delta is sinking at accelerating speed

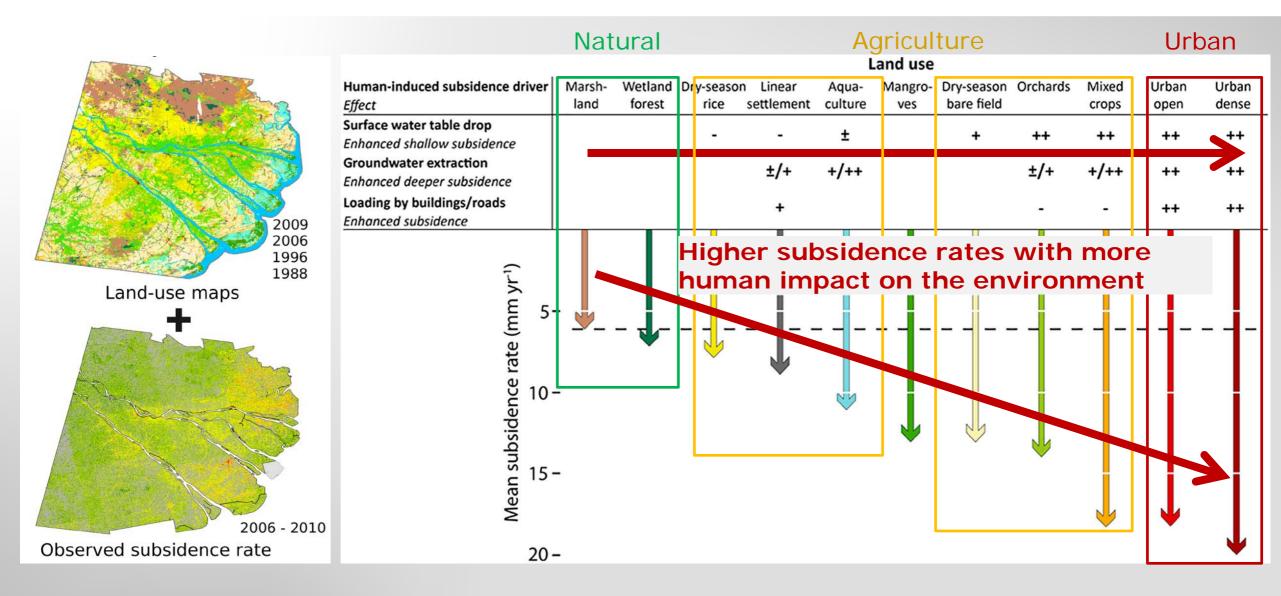
Estimated InSAR-derived subsidence rates (cm/yr)



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

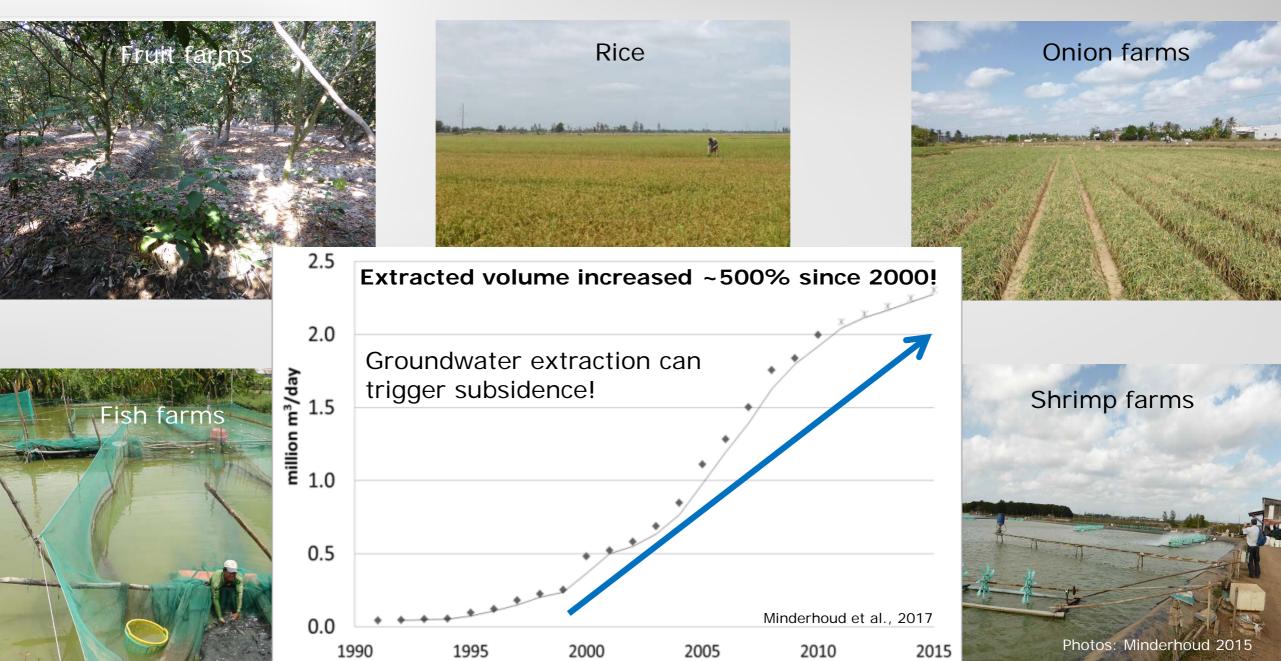
EU Copernicus EMSN062 Minderhoud et al., 2020 (IAHS)

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



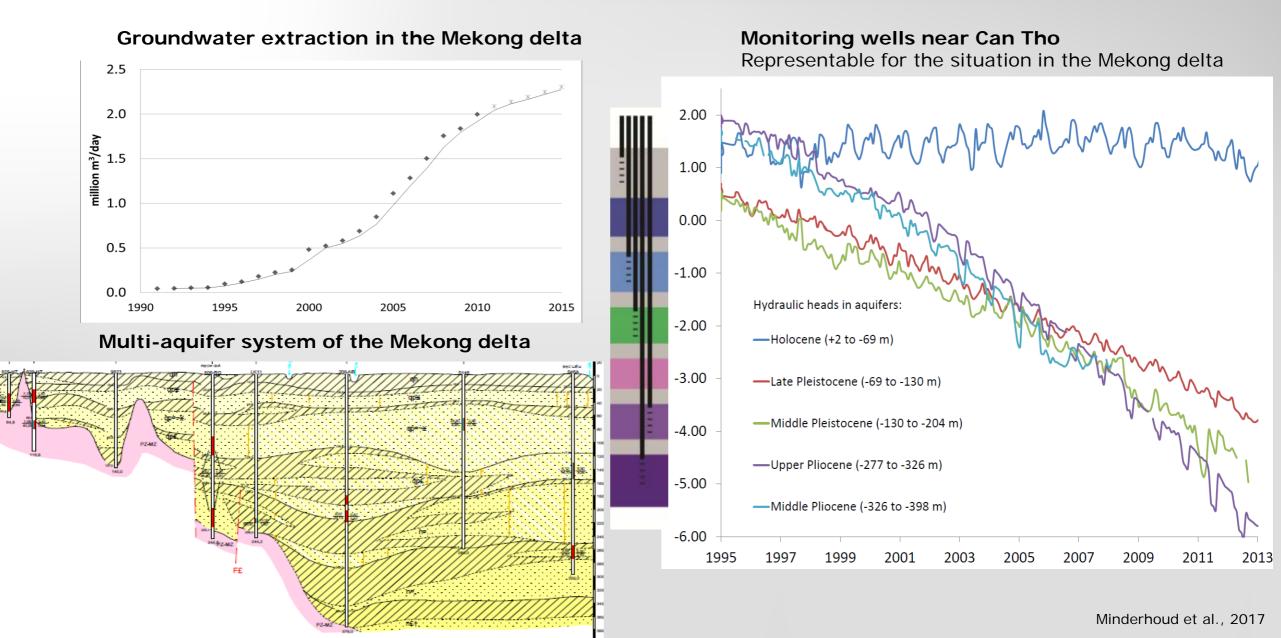


Mekong delta and groundwater extraction





Groundwater extraction and observed hydraulic heads





Subsidence in the Mekong Delta The impacts of groundwater extraction

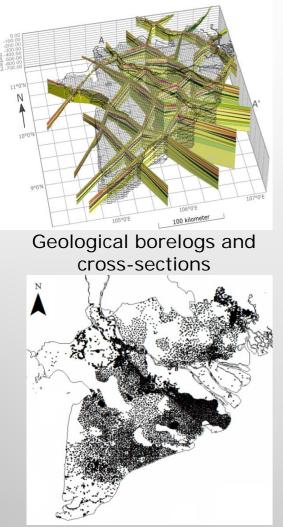
Video abstract of Minderhoud et al., 2017: "Impact of 25 years groundwater extraction on subsidence in the Mekong delta, Vietnam *Environmental Research Letters* (Duration 2:50 minutes)

English Subtitles: <u>https://www.youtube.com/watch?v=cMr_BKzY4IU</u>

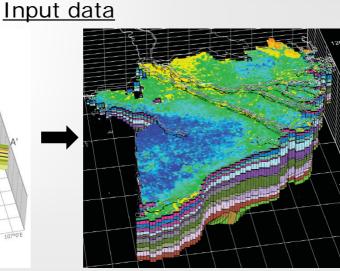
Phụ đề tiếng việt (Vietnamese subtitles): https://www.youtube.com/watch?v=WaJVFabXSrY



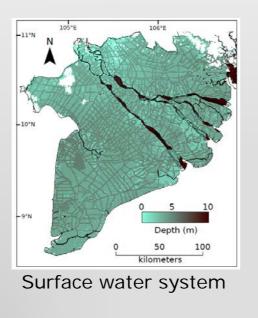
3D hydrogeological model with subsidence module

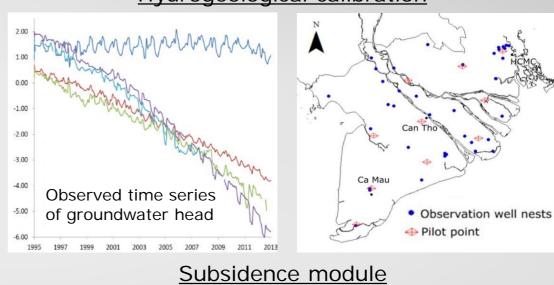


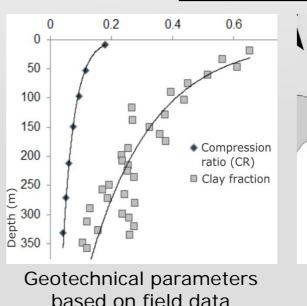
Location, depth & rate of groundwater extractions



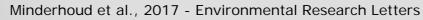
3D subsurface







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

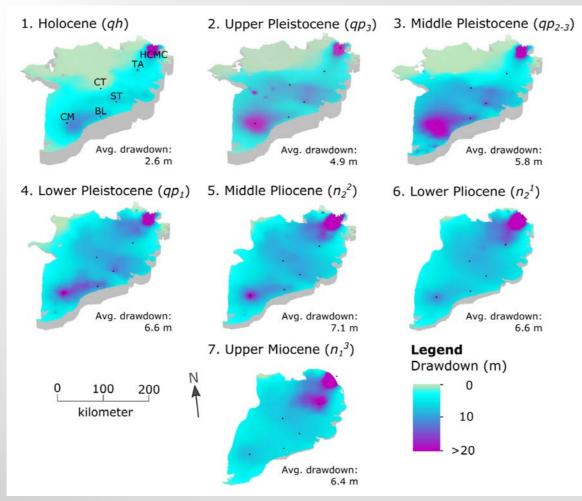


Hydrogeological calibration



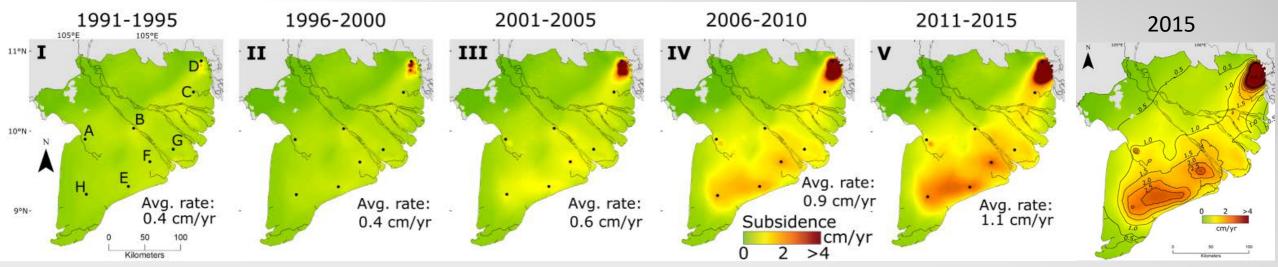
25 years of simulated groundwater extraction

Hydraulic head in the aquifers

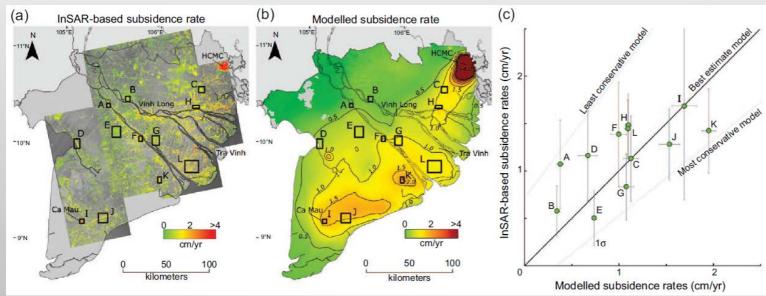


Groundwater extraction is much larger than groundwater recharge \rightarrow overexploitation

Extraction-induced subsidence is accelerating!



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



Utrecht University

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

Sources of uncertainties in modeling results:

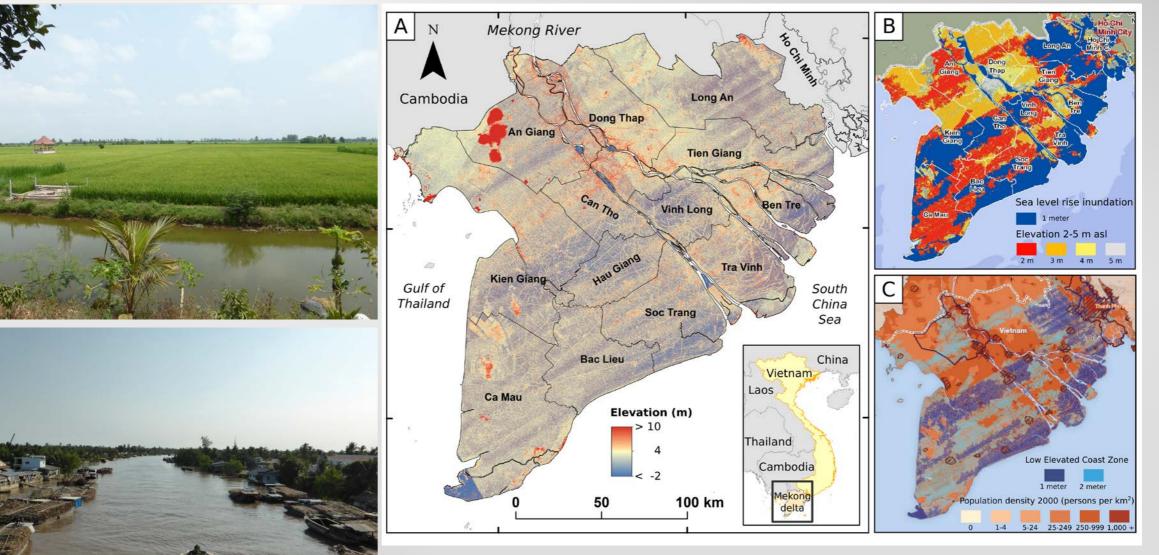
- Hydrogeology and geotechnical parameters
- Extraction data
- Geological schematization
- Layer discretization

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

Minderhoud et al., 2017 - Environmental Research Letters

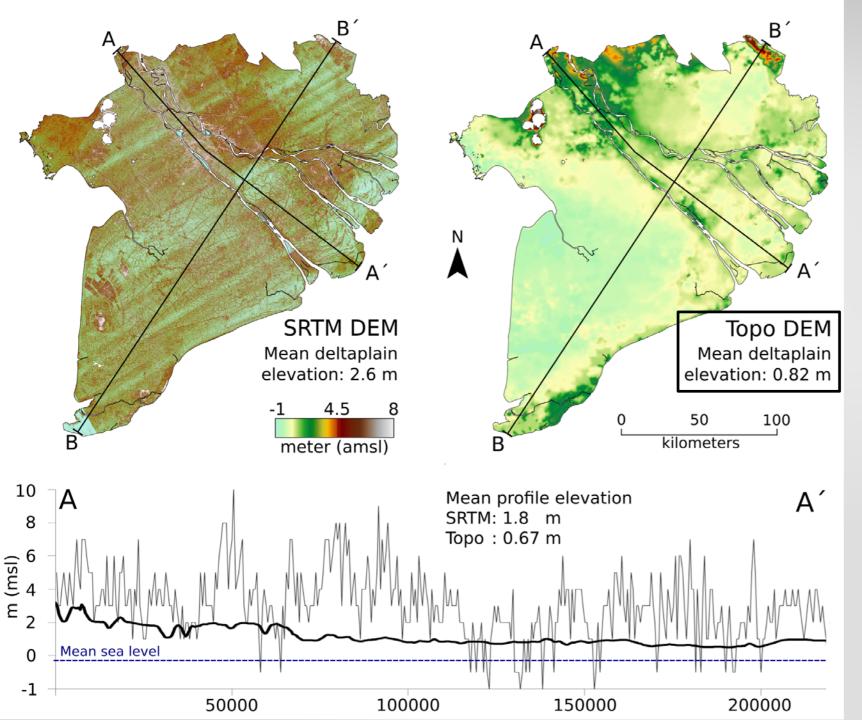
Utrecht University

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:

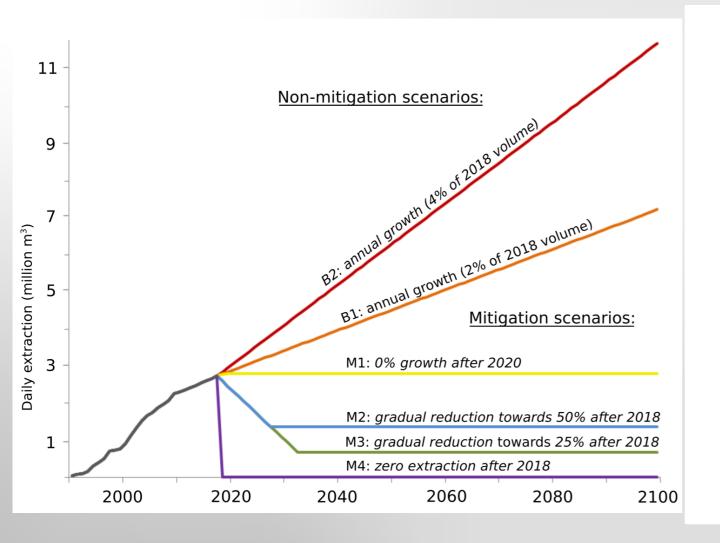
- Mekong delta is much lower
 elevated than international
 research studies assumed, so
 much more *vulnerably* to relative
 sea-level rise than previously
 thought
- Other deltas and coastal regions in the world potentially face similar underestimations!

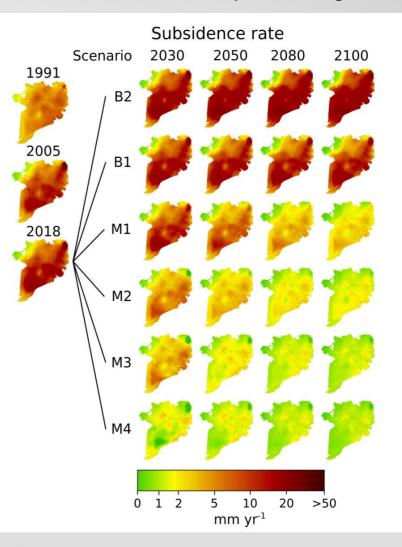
Minderhoud et al., 2019 Nature Communications



The future of the Mekong delta: use pathways!

Modeling scenarios with different groundwater extraction pathways



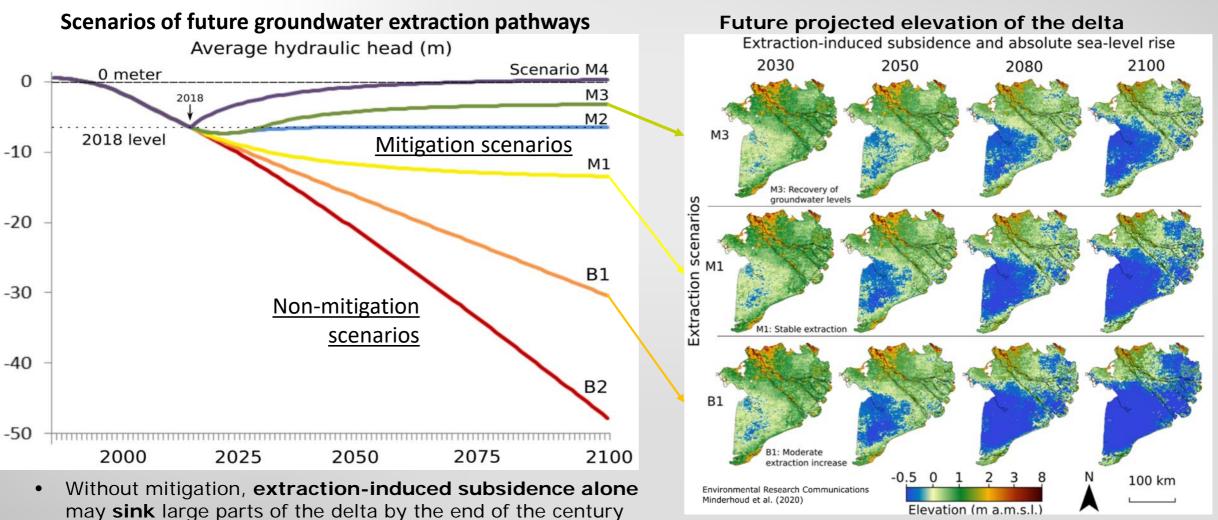


Minderhoud et al., 2020 Environmental Research Communications



The future of the Mekong delta: use pathways!

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



Groundwater in the delta is not a free resource – it is paid

for by elevation. Elevation, and thus time, is running out!

- > 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



How to deal with subsidence in Vietnam

Measure in-situ land subsidence

• Install a subsidence observation network to monitor in-situ land subsidence

There are two strategies to deal with subsidence:

Mitigate / Reduce groundwater-extraction induced subsidence:

- Strongly reduce groundwater extraction increase surface water use
- Short term, temporal solution: Change to 'smarter' extraction / artificial recharge (local solution)

Adapt to unavoidable subsidence caused by high natural compaction:

- Allow natural sedimentation as much as possible to elevate the land
- Build constructions with deep foundations

Protecting the entire Mekong delta with dyke systems will be impossible \rightarrow Difficult policy decisions to prioritise what areas to protect with dykes and polders (irreversable situation).

The hardest part is still to come





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



Strategies for Vietnam:

- 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

Erban, L.E., Gorelick, S.M., Zebker, H.A., 2014. Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. Environ. Res. Lett. 9. doi:10.1088/1748-9326/9/8/084010

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