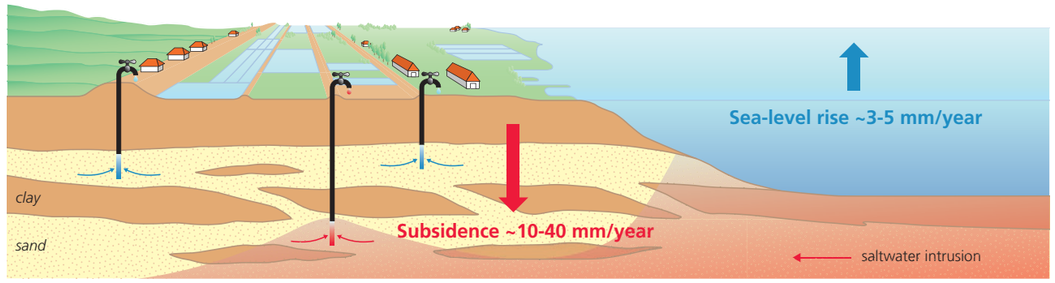


› Absolute sea-level rise and total subsidence together determine sea-level rise relative to the land surface.

Rise & Fall research program

The Rise and Fall research program aims to enhance the capabilities of individuals and organisations to develop sustainable strategies for dealing with groundwater extraction, land subsidence and salt water intrusion in the increasingly urbanizing Mekong Delta, Vietnam. The program focusses on subsurface characterization and subsidence, fresh and saline groundwater dynamics, salt water intrusion in estuarine channel networks, and governance strategies for sustainable management.

For more information see:
https://www.uu.nl/en/futuredeltas/project-rise-and-fall
http://rf.ctu.edu.vn/en/components-1/

References

Delsman, J.R. 2015, Saline groundwater – surface water interaction in coastal lowlands, VU University Amsterdam, Amsterdam, 194 pp.

Department of Surveying and mapping Vietnam, 2002. http://www.dosm.gov.vn/default.aspx?tabid=411&CateID=253

Erban, L.E., Gorelick, S.M., & Zebker, H.A. (2014). Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. *Environmental Research Letters*, *9*(8), 84010. http://doi.org/10.1088/1748-9326/9/8/084010

Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L.X., Triet, T. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, *526*(7574), 559-U217. http://doi.org/10.1038/nature15538

Minderhoud, P.S.J., Erkens, G., Pham, V.H., Bui, V.T., Erban, L., Kooi, H., Stouthamer, E. (submitted). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. Submitted to Environmental Research Letters.

Pham, V.H., Van Geer, F.C., Bui, T.V., Dubelaar, W., Van, P.D.T., Oude Essink, G.H.P. (submitted). Paleo-hydrogeological reconstruction of the fresh-saline groundwater distribution in the Vietnamese Mekong Delta since the Late Pleistocene. Submitted to J. of Hydrology.

Takagi, H., Thao, N.D., & Anh, L.T. (2016). Sea-level rise and land subsidence: Impacts on flood projections for the Mekong Delta's largest city. *Sustainability (Switzerland)*, *8*(9), 1-15. http://doi.org/10.3390/su8090959

Contact

Prof. dr. P. Hoekstra, Rise & Fall project leader, Dean of Faculty of Geosciences, Utrecht University, The Netherlands: p.hoekstra@uu.nl
Prof. dr. N.H. Trung, Dean of College of Environment and Natural Resources, Can Tho University, Vietnam: nhtrung@ctu.edu.vn

Research consortium

The Rise and Fall research program is carried out by the following consortium of universities and applied research institutes:

Researchers involved in the Rise & Fall project

Salinization of surface water: Prof. dr. P. Hoekstra (UU), Dr. M. van der Vegt (UU), **S. Eslami Arab, MSc.** (UU)
Salinization of groundwater: Dr. ir. G. Oude Essink (Deltares/UU), Prof. dr. ir. M.F.P. Bierkens (UU/Deltares), Dr. V.T. Bui (DWRPIS), Dr. ir. W. Zaadnoordijk (TNO), **V.H. Pham, MSc.** (DWRPIS/UU/Deltares)
Subsidence: Dr. E. Stouthamer (UU), Dr. G. Erkens (Deltares/UU), Dr. V.T. Bui (DWRPIS), Prof. dr. H. Middelkoop (UU), **Ph. Minderhoud, MSc.** (UU/Deltares)
Governance: Dr. C. Dieperink (UU), Dr. H. Otter (Deltares), Prof. dr. N.H. Trung (CTU), **Dr. P.D.T. Van** (CTU/UU)

This research progress report was compiled by:
Dr. E. Stouthamer, Prof. dr. P. Hoekstra, Dr. G. Oude Essink, Ph. Minderhoud, MSc. and Dr. H. Otter

NWO-UDW project number: W 07.69.105

Utrecht University

Rise & Fall research program

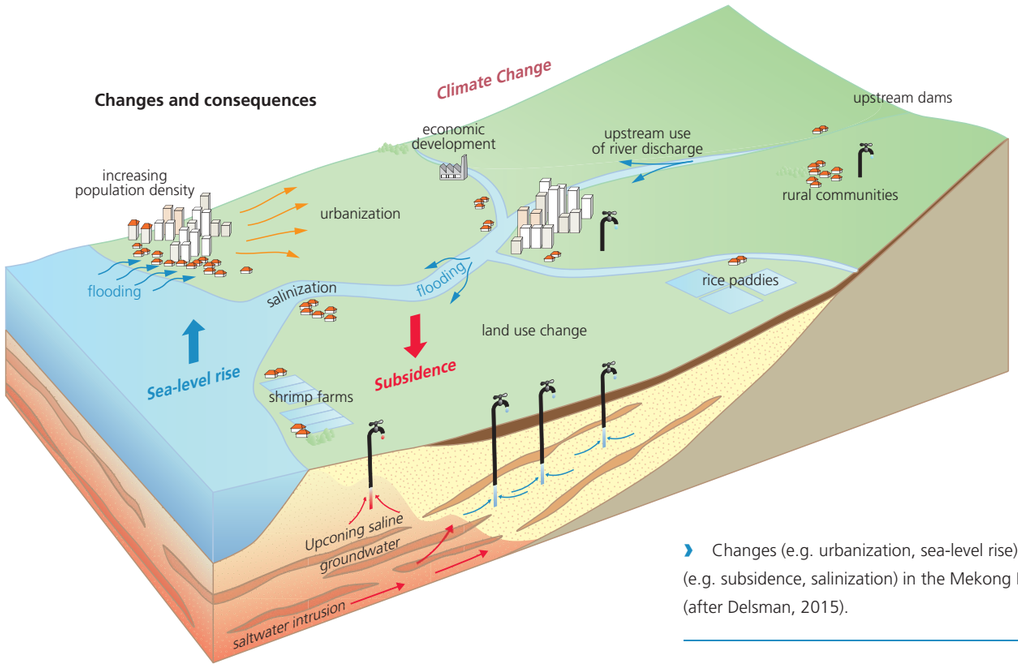
©Photo: Thue Sylvester Bording, 2017

Towards strategies for the subsiding Mekong Delta in Vietnam

The challenges: urbanization, land-use change and subsidence

The Mekong Delta in Vietnam is rapidly changing due to urbanization, land-use transformation, and intensification of economic activities. The associated increase in fresh water demand has led to:

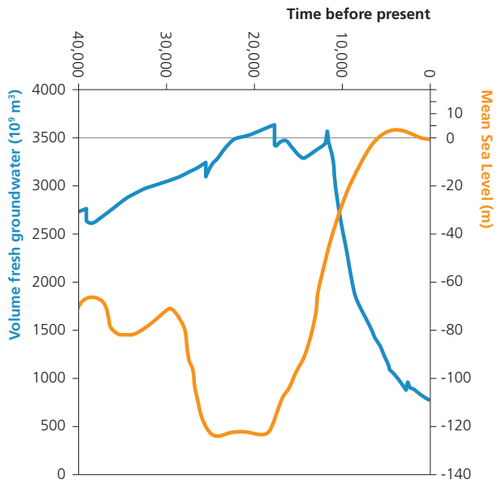
1 Large-scale extraction of fresh groundwater with rates seriously depleting the existing fresh groundwater reserves;
2 Salinization of groundwater and surface water resources;
3 Land subsidence, with current rates up to several centimeters per year, due to groundwater extraction, loading by buildings and infrastructure, and intensive drainage of the shallow subsurface;
4 Increased flood risk and flood water depth, resulting in land loss as well as damage to buildings and infrastructure.



› Changes (e.g. urbanization, sea-level rise) and consequences (e.g. subsidence, salinization) in the Mekong Delta, Vietnam (after Delsman, 2015).

Results from Rise & Fall research: Decreasing fresh groundwater reserves

Fresh water in the Mekong Delta is extracted from groundwater reserves by pumping and used for domestic, industrial as well as agri- and aquacultural purposes. In recent times the amount of fresh groundwater extraction has seriously increased. Our research indicates that nowadays extraction rates exceed the amount of natural infiltration due to rainfall or surface water. This results in a structural depletion of the groundwater reserves.



› Modelled changes in volume of fresh groundwater in the Mekong Delta during the last 40.000 years (blue line) are closely linked to the elevation of Mean Sea Level (orange line). Our 2D modelling approach shows that the fresh groundwater volume follows the pattern of Mean Sea Level but thousands of years delayed. Therefore an autonomous further decrease in fresh groundwater volume is to be expected (Pham et al., subm.).

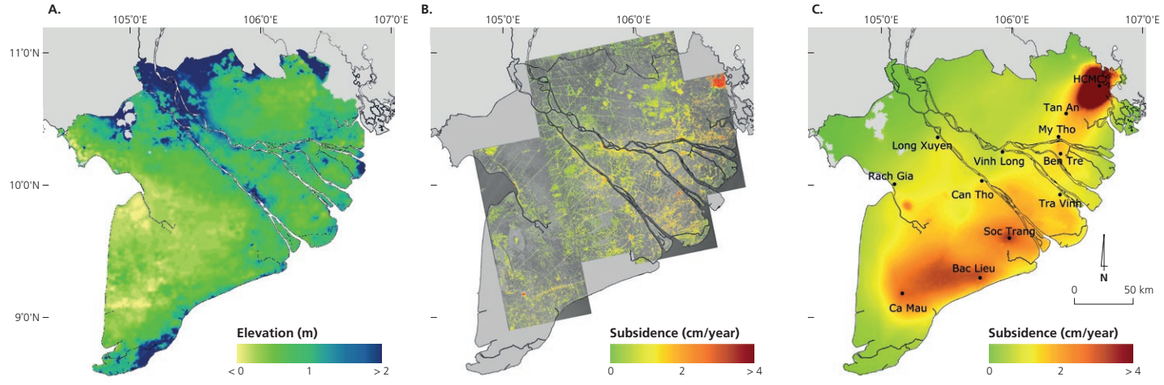
Our research has also shown that infiltration rates appear to be small due to the presence of clay layers hampering natural infiltration. The slow re-supply of fresh groundwater suggests that most of the current fresh groundwater reserves were created a long time ago, possibly as long as 20.000-30.000 years ago (Pham et al., subm.). In addition, the present extraction of groundwater is likely to enhance the intrusion of saline water into fresh groundwater reserves.

We expect that the fresh groundwater volumes will further reduce as an effect of past and current rising mean sea level as well as present day groundwater extractions. The exact amount and process rates are currently being assessed using advanced numerical 3D models.

Results from Rise & Fall research: Subsidence

Relative sea-level rise is the amount of sea-level rise relative to the land surface. It is determined by absolute global sea-level rise plus subsidence of the land surface in the Mekong Delta. Locally determined rates of absolute global sea-level rise in SE-Asia induced by climate change range from ~3 to 5 mm/yr (Takagi et al., 2016; Lovelock et al., 2015). However, our 3D numerical model shows that large areas experience subsidence rates of ~10-20 mm/yr in rural parts and ~25 mm/yr in cities and industrial areas due to serious groundwater extractions (Minderhoud et al., subm.). These subsidence rates substantially outpace absolute sea-level rise. Consequently, the threat posed by subsidence currently exceeds the threat of climate change induced sea-level rise.

Subsidence rates have steadily increased since the beginning of large scale groundwater exploitation in the 1990's (Minderhoud et al., subm.). The main drivers of subsidence seem to be the drop of pressures in groundwater reservoirs due to groundwater extraction and loading of the subsurface by buildings and infrastructure.



Towards strategies

As groundwater extraction will continue to rise in the foreseeable future; subsidence and salinization of the fresh groundwater volumes will continue as well. In this process the low-lying Mekong Delta will become even more vulnerable to natural disasters, seriously limiting future economic developments.

The first results from our Rise & Fall research program indicate that there is an urgent need to develop evidence based adaptation strategies that will counteract over-exploitation of groundwater and the associated salinization and subsidence.

› A) Surface elevation map of the Mekong delta (Minderhoud et al., subm.) created using elevation point data provided through the DWRPIS (Department of Surveying and mapping Vietnam, 2002). The surface elevation of a large part of the delta is below 1 m above sea-level, making the delta extremely vulnerable to relative sea-level rise. B) Measured, InSAR data derived, subsidence rates over the period 2006-2010 (after Erban et al. 2014). C) Modelled subsidence rates caused by groundwater extraction for the year 2015 (Minderhoud et al., subm.).

Developing adaptation strategies that lead to sustainable solutions require a joint effort of many stakeholders: local, regional and national governments, industries and non-governmental organizations as well as research institutes.

Actions for governments and other stakeholders

Governments, together with the other stakeholders, have an important responsibility to:

- Put the issues of fresh groundwater availability, salinization and subsidence on the political agenda;
- Facilitate research institutes in developing modelling tools and encourage data collection with the ultimate aim to develop evidence based strategies;
- Effectuate well-tuned governance strategies as well as a legislative framework.

Actions for research institutes

To support and encourage a well-informed decision-making process, research institutes should help develop monitoring strategies, generate data and develop databases and numerical models.
More specifically they should:

- Increase monitoring of ground and surface water quality, extraction and subsidence rates. This will enable the development of improved predictive models and water management strategies;
- Develop a centralized and open source database that stores monitoring data, including data on the subsurface architecture and geotechnical properties. These data should be used to monitor the impacts of groundwater management strategies and will aid predictive modelling;
- Develop 3D geological, hydro(geo)logical and geotechnical models. These models will enable the selection of the most effective and sustainable management strategies by determining the trade-offs of different policies.