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Conference proceedings: 4th Asia Pacific Meeting on Near Surface Geoscience & Engineering

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https://doi.org/10.3997/2214-4609.202177047

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Citation: Minderhoud, P. S. J. (2021). Modelling Mekong Delta Subsidence, Challenges and How to Improve Quantifications. 2021(1), 1–7. https://doi.org/https://doi.org/10.3997/2214-4609.202177047

Introduction

The Mekong delta is one of the largest deltas on Earth. It is densely populated and an important area for food production. Like many deltas worldwide it experiences pressures related to climate change, i.e. global sea-level rise, changes in hydrology and temperature, and anthropogenic activities, such as urbanization, land-use change and intensification of agricultural practices (Nicholls et al., 2020). This leads to overexploitation of natural resources, especially (riverbed) sand and water, which causes strong increases of natural processes in the delta such as river-bank erosion (Hackney et al., 2020), tidal amplification and salinization (Eslami et al., 2019), and extraction-induced subsidence (Minderhoud et al., 2017). The very low elevation of the delta, on average less than a meter above local sea level (Minderhoud et al. 2019), makes it very vulnerable to elevation changes and sea-level rise. Present *relative* sea-level rise in the Mekong delta is dominated by land subsidence with delta-wide average rates of subsidence exceeding 10 mm/yr and local rates going up to 60 mm/yr (EU-Copernicus, Minderhoud et al., 2020a). An increasing number of studies on subsidence have become available in recent years, from the first delta-wide InSAR observations in 2014 (Erban et al., 2014), revealing the spatial-temporal evolution and impact of land-use changes (Minderhoud et al., 2018) and ground-water extraction on subsidence (Minderhoud et al., 2017), towards recent process-based modelling of future subsidence under different water management scenarios (Minderhoud et al., 2020b) and detailed analyses of differential subsidence in urban areas (De Wit et al. 2021).

Modelling deltaic subsidence

Subsidence in a delta, like the Mekong delta, is the cumulative effect of a range of drivers and processes in the subsurface (Tosi et al., 2009, Shirzaei et al., 2021). Multiple drivers and processes can play a role at the same time. Total subsidence experienced at the delta surface depends on local hydro(geo)logical and geomechanical conditions and can be spatially highly variable within a delta. Also, subsidence processes can accelerate and decelerate with time and vary throughout the year with wet and dry seasons and variations in anthropogenic drivers. In general, subsidence due to anthropogenic drivers can be reduced or even stopped with the right mitigation strategy (Erkens & Stouthamer, 2020) while natural subsidence is unavoidable.

The use of computer models is a way to increase understanding and create physics-based interpolation and predictions beyond the spatial and temporal scale of observed subsidence. When models are properly calibrated and validated using observations, they can be used to create process-based interpolations, i.e. maps. These maps are superior to the mathematical interpolation of point measurements as they include physical processes and spatial variability in them matching the detail of the processes modelled. And this is highly relevant to create projection of relative sea-level rise, which is dominantly controlling present experienced sea-level rise by people living at coastlines worldwide (Nicholls et al., 2021). However, to date, there is no single computer model that is capable of modelling all the relevant subsidence processes occurring at different depths below a delta plain. Therefore, in contrast to measurements of total subsidence, a model is built to simulate specific processes and drivers, hence addressing only a part of the experienced total subsidence.

In recent years two different numerical models were created for the Mekong delta, each targeting distinct subsidence processes: 1) aquifer-system compaction following groundwater extraction and consequent changes in the hydrogeological situation in the delta (Minderhoud et al., 2017, 2020b) and

2) shallow, natural compaction of Holocene sediments following historical delta progradation (Zoccarato et al., 2018).

Modelling extraction-induced aquifer-system compaction in the Mekong delta

To simulate groundwater extraction and consequent aquifer-system compaction, a delta-wide 3D hydrogeological model of the Mekong delta was created based on a wide variety of datasets on geology, hydro(geo)logy and geomechanics of the delta subsurface (Minderhoud et al., 2017). Groundwater extraction was simulated using an extensive database of registered and estimated extractions and the hydrogeological model was calibrated using the time series of hydraulic head. Compaction of the aquifer system following decreases in groundwater pressure was simulated using a 1D compaction module, SUB-CR (Kooi et al., 2020). Instead of a more traditional elastoplastic approach, compaction was simulated following the isotache concept (Suklje, 1957; Bjerrum, 1967), i.e. a viscoelastic compression theory. In this approach compression is not just stress-dependent but also time-dependent, to account for long-term creep, also known as secondary compression. Karlsrud et al. (2017) also used viscoelastic computations to compute the effect of groundwater extraction for several 1D columns in Ca Mau province.

In the first publication the situation in the VMD was modelled from 1991 to 2015. The simulated results were reported for the best-estimate model run based on the parameterization the over-consolidation ratio (OCR), which plays a dominant role in the amount of compaction simulated by the viscoelastic approach. Optimal parameterization was established based on validation using InSAR-based observations from 2006-2010 and applied uniformly with depth. The best-estimate results were reported with a broad uncertainty range of about ~60% - 160% of the simulated compaction, based on the results of the least and most conservative model run. The modelling results revealed an accelerating trend of aquifer-system compaction in the Mekong delta following the increase in groundwater exploitation over recent decades (Figure 1). This trend was recently confirmed by new PSI InSAR studies on Sentinel-1 data from 2014-2019 (EMNS, Minderhoud et al., 2020b).

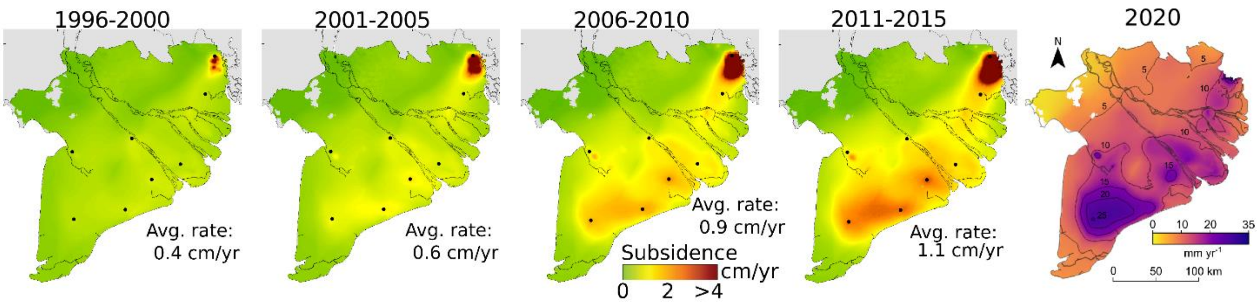

Figure 1. *Simulated annual average extraction-induced aquifer-system compaction computed by a 3D hydrogeological model for five-year periods and for 2020 (modified after Minderhoud et al., 2017 & 2020b, reproduced under CC BY 3.0).*

In a follow-up study, the model was further updated by adding an explicit surface water system and refining past extraction rate estimated based on the analysis of hydraulic head time series (Minderhoud et al., 2020b). The model was also extended to run until 2100 and using scenarios of future groundwater use, projections of aquifer-system compaction were created (Figure 2).

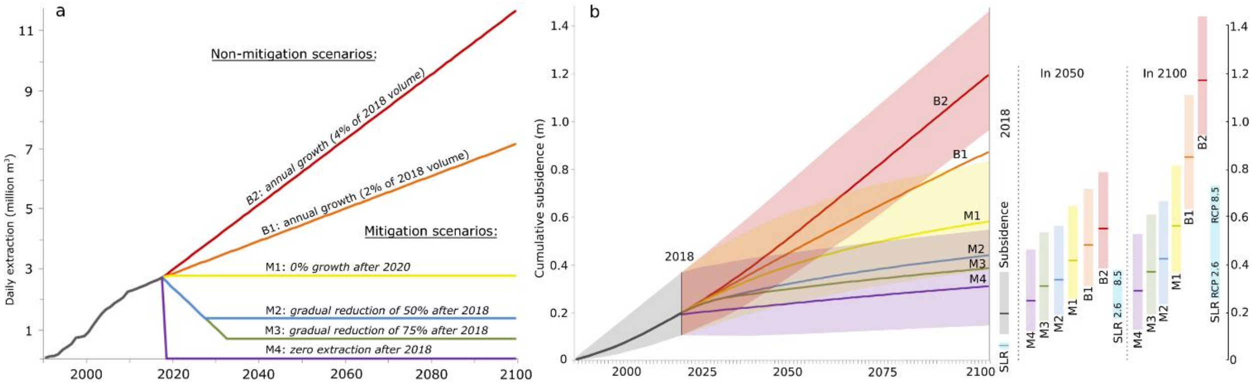

Figure 2. *a) Groundwater extraction pathways for different scenarios modelled for the Mekong delta. b) Evolution of cumulative delta-average subsidence following the extraction pathways and comparison with sea-level rise in 2050 and 2100 (after Minderhoud et al., 2020b, reproduced under CC BY 3.0).*

Modelling natural shallow compaction

Using a novel simulator, NATSUB-2D, Zoccarato et al. (2018) revealed the potential occurrence of unprecedented high natural compaction rates along the most recent (southern) coastlines of the delta, because of delayed compaction and very fast delta progradation. Natural shallow compaction was computed along a transect simulating the last 4000 years of delta progradation of the Ca Mau Peninsula. NATSUB-2D is a 2D finite-element, groundwater flow model coupled to a 1D compaction module with a deformable mesh to account for large deformations (i.e. Lagrangian approach) in the young, highly porous and compression deposits (Zoccarato & Teatini, 2017). The computed rates of tens of mm/yr matched observations of shallow compaction by surface elevation tables (SETs, Giao et al., 2014; Lovelock et al., 2015) in mangrove forests and subsidence monitoring stations (Karlsrud et al., 2020) in Ca Mau, showing large parts of the shallow near-coastal subsidence can be of natural origin. However, anthropogenic activities like drainage (Minderhoud et al., 2017) or extraction beneath the shallow layer (Karlsrud et al., 2017;2020) are likely enhancing present-day rates further. The results show the *maximum* natural compaction of Holocene clays due to delayed overpressure dissipation as the simulated clay deposits are assumed to be homogeneous. In reality, however, the subsurface may be much more heterogeneous, meaning overpressure dissipation may go faster and already happened more in the past. Also, secondary compression was not included in the computations, thereby omitting a process which may be considerably large, especially in these shallow fine-grained sediments.

Future implications of subsidence in the Mekong delta

Above-described numerical studies advanced the understanding of spatial-temporal processes and occurrence of subsidence in the Mekong delta. Combining results from various studies enables the creation of explicit maps of potential elevation evolution following certain scenarios and relative sea-level rise in the coming decades (Minderhoud et al., 2020b). This shows the great potential of using the new numerical approaches to forecast future compaction processes and quantify the contribution of land subsidence to relative sea-level rise. For the Mekong delta the analysis reveals the critical situation of the low-lying landform and the urgency of mitigation efforts to reduce future anthropogenic subsidence (Figure 3).

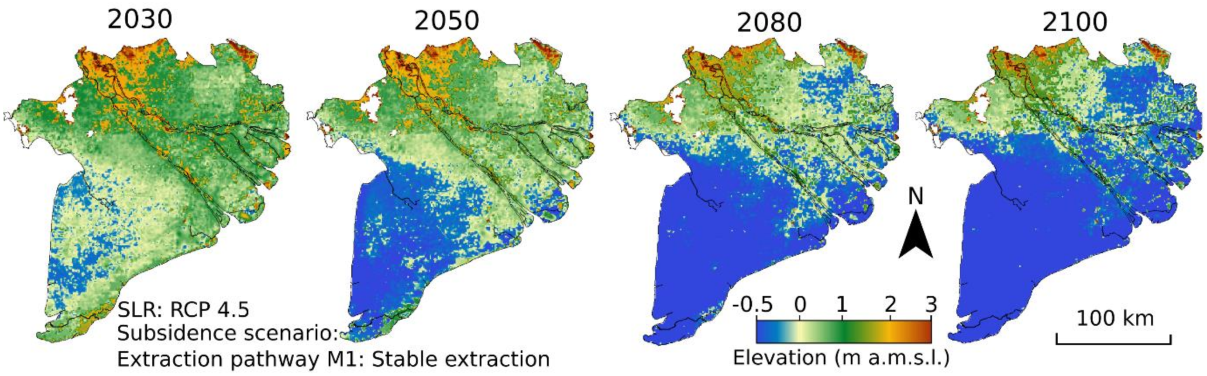

***Figure 3**. Elevation projections for the Mekong delta following extraction-induced compaction (scenario M1, stable extraction amount after 2020), sea-level rise (SLR) following RCP 4.5 and natural compaction, assuming it is no longer compensated by sedimentation due to sediment starvation and dykes (modified after Minderhoud et al., 2020b, reproduced under CC BY 3.0, elevation data from Minderhoud et al., 2019b)*

Recommendations and ongoing advances

Being the first numerical quantifications of subsidence beyond other individual 1D calculations in the Mekong delta (e.g. Karlsrud et al., 2017), there are ample opportunities to improve the above described modelling results. These improvements range from refined model discretization, both in vertical direction and timesteps, critical evaluation on the compression theories used to compute compaction (e.g. elasto-plastic vs visco-elasto-plastic), adding additional hydro(geo)logical and geomechanical data to improve subsurface representation, and improve the model calibration and validation using new observation of subsidence. Below we discuss a few specific suggestions and currently explored advances for the Mekong delta models.

Hydrogeological aquifer-compaction model:

- **Improve hydrogeological schematization and parameterization**. Two main hydrogeological aspects of the present model may considerably influence simulation results: aquifer hydraulic conductivity and vertical aquitard model layer discretization. The model was calibrated to optimally fit hydraulic head measurements, creating a deterministic model parameterization. Through stochastic modelling of the aquifer hydraulic conductivity the impact of the chosen deterministic approach on simulates subsidence is assessed. In the present schematisation the aquitards are discretized as a single layer, which make it unable to simulate delayed water pressure propagation within the aquitard. The effect is assessed by creating and comparing with several additional models in which the aquitard discretization is refined (Lexmond et al., 2021).

- **Improve geomechanical parameterization**. Measurements of geomechanical properties are increasingly sparse for deeper sediments in the Mekong delta, hence Minderhoud et al. (2017) used depth relationships to estimate values for deeper layers. In addition, the overconsolidation ratio used in the model was homogeneously applied to each model layer, with no depth-dependency. While this may be a good strategy, given measurements of OCR in the Mekong delta tend to fluctuate around a similar value, especially for deeper deposits (Hoang et al., 2016) but data also shows strong fluctuations. More and especially deeper quantifications (>40 m) of geomechanical properties of delta sediments will improve constraining model parameters.

Shallow compaction model:

- **Upgrade the model domain to 3D**. Starting from the 2D formulation (Zoccarato & Teatini, 2017), a novel numerical code was implemented to improve the spatial domain up to 3D (Xotta et al., 2021). In the new NATSUB3D code, the 1D module for shallow compaction has been coupled with a 3D groundwater flow module. The finite element code can generate a 3D tetrahedral grid that deforms over time as sediments compact. The new code allows to properly simulate sediment accretion and compaction with time, while updating the 3D mesh and recomputing the hydrogeological and geomechanical parameters dependent on strain.

- **Add creep computation to the NATSUB3D**. In addition to the existing elasto-plastic approach, NATSUB3D was upgraded to also compute compaction following a visco-elastic approach for creep (i.e. secondary compression). In this approach compaction is not only driven by load increase (i.e. stress) due to the sediment deposition, but also becomes a function of time, which causes compaction to continue also when porewater over-pressure is completely dissipated (i.e. primary compression). To this aim, the numerical model solving the groundwater equation was updated to consider the creep deformation and the numerical scheme resolving the material non-linearity was properly extended compared to the previous elasto-plastic approach. (Xotta et al., in prep.)

- **Create 3D shallow subsurface model of the Mekong delta based on paleo-sedimentation.** Sedimentation history determines the current hydrogeological and geomechanical state of the subsurface. Therefore, to properly simulate and quantify present shallow compaction using the NATSUB3D code, a new approach was developed to create paleo-sedimentation rates. It combines lithological borelogs, sediment geochronology (i.e. datings), advanced interpolation and geomechanical properties for representative lithotypes in the delta. Following the loading history of the accumulated sediments during Holocene delta evolution, a first 3D model of the sediments deposited in the last 4000 yrs was created and enables the computation of present-day natural compaction rates for the coastal part of the delta (Figure 4).

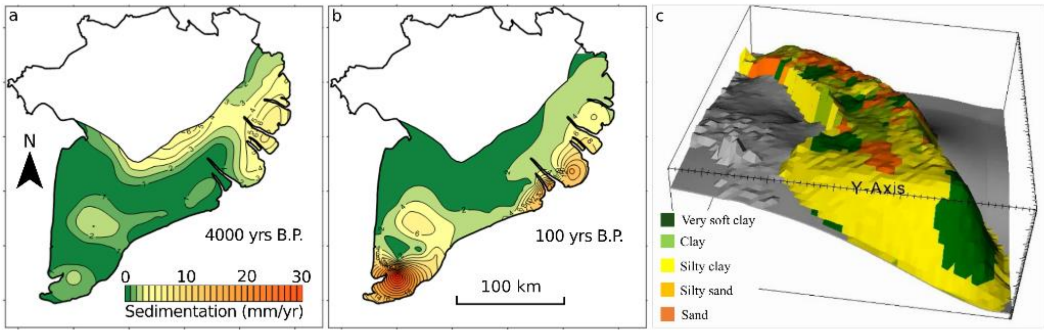

Figure 4. a-b) Maps of paleo-sedimentation rate. c) 3D view of the simulated present shape of the Mekong delta with the various lithology classes accounted for in the model (Baldan et al., in prep).

Acknowledgements
P.S.J.M. received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant No. 894476—InSPiRED—H2020-MSCA-IF-2019.

References

Bjerrum, L. (1967). Engineering geology of Norwegian normally consolidated marine clays as related to settlements of buildings. *Géotechnique*, 17(2): 81-118.

Copernicus (2019). EMSN-062: Assessing changes in ground subsidence rates, Mekong Delta, Vietnam FINAL REPORT https://emergency.copernicus.eu/mapping/list-of-components/EMSN062

de Wit, K., Lexmond, B. R., Stouthamer, E., Neussner, O., Dörr, N., Schenk, A., Minderhoud, P. S. J. (2021). Identifying causes of urban differential subsidence in the Vietnamese Mekong delta by combining insar and field observations. *Remote Sensing*, 13(2), 1–33. https://doi.org/10.3390/rs13020189

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), 084010.

Erkens, G., & Stouthamer, E. (2020). The 6M approach to land subsidence. *Proceedings of the International Association of Hydrological Sciences*, 382, 733–740. https://doi.org/10.5194/piahs-382-733-2020

Eslami, S., Hoekstra, P., Nguyen Trung, N., Ahmed Kantoush, S., Van Binh, D., Duc Dung, D., Tran Quang, T., & van der Vegt, M. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Scientific Reports*, 9(1), 18746. https://doi.org/10.1038/s41598-019-55018-9

Giao, P. H., Thoang, T. T., Thuyen, L. X. & Vu, N. H. H. (2014). Geotechnical characterization of the subsoil profile underlying the land subsidence monitoring points in Southern Vietnam Delta. *9th Int. Symp. Lowl. Technol*. 1, 429–436, https://doi.org/10.1017/CBO9781107415324.004.

Hackney, C. R., Darby, S. E., Parsons, D. R., Leyland, J., Best, J. L., Aalto, R., Nicholas, A. P., & Houseago, R. C. (2020). Riverbank instability from unsustainable sand mining in the lower Mekong River. *Nature Sustainability*, 3(3), 217–225. https://doi.org/10.1038/s41893-019-0455-3

Hoang, T. M., van Lap, N., Oanh, T. T. K., & Jiro, T. (2016). The influence of delta formation mechanism on geotechnical property sequence of the late Pleistocene–Holocene sediments in the Mekong River Delta. *Heliyon*, *2*(11). https://doi.org/10.1016/j.heliyon.2016.e00165

Karlsrud, K., Vangelsten, B. V., and Frauenfelder, R. (2017): Subsidence and shoreline retreat in the Ca Mau Province – Vietnam. Causes, consequences and mitigation options, *Geotechnical Journal of the SEAGS & AGSSEA*, 48, ISSN 0046-5828, 2017a.

Karlsrud, K., Tunbridge, L., Khanh, N. Q., & Dinh, N. Q. (2020). Preliminary results of land subsidence monitoring in the Ca Mau Province. *Proceedings of the International Association of Hydrological Sciences*, *382*, 111–115. https://doi.org/10.5194/piahs-382-111-2020

Kooi, H. and Erkens, G.: Creep consolidation in land subsidence modelling; integrating geotechnical and hydrological approaches in a new MODFLOW package (SUB-CR), *Proc. IAHS*, 382, 499–503, https://doi.org/10.5194/piahs-382-499-2020, 2020.

Lexmond, B.R., Torfs, P.J.J.F., Stouthamer, E., Minderhoud, P.S.J. (2021). The effect of vertical aquitard discretization and aquifer hydraulic conductivity on subsidence simulation of the Vietnamese Mekong Delta. *Hydrology and Earth System Sciences*, submitted.

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental research letters*, 12(6), 064006.

Minderhoud, P. S. J., Coumou, L., Erban, L. E., Middelkoop, H., Stouthamer, E., & Addink, E. A. (2018). The relation between land use and subsidence in the Vietnamese Mekong delta. *Science of The Total Environment*, *634*, 715-726.

Minderhoud, P. S. J., Coumou, L., Erkens, G., Middelkoop, H., & Stouthamer, E. (2019a). Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nature communications*, *10*(1), 1-13

Minderhoud P.S.J., Coumou L., Erkens G., Middelkoop, H. and Stouthamer E. (2019b). Digital elevation model of the Vietnamese Mekong delta based on elevation points from a national topographical map. *PANGAEA*, https://doi.org/10.1594/PANGAEA.902136

Minderhoud, P.S.J., Hlavacova, I., Kolomaznik, J., & Neussner, O. (2020a). Towards unraveling total subsidence of a mega-delta–the potential of new PS InSAR data for the Mekong delta. *Proceedings of the International Association of Hydrological Sciences*, *382*, 327-332.

Minderhoud, P.S.J., Middelkoop, H., Erkens, G., & Stouthamer, E. (2020b). Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. *Environmental Research Communications*, *2*(1), 011005.

Nicholls, R.J., Adger, W. N., Hutton, C. W., & Hanson, S. E. (2020). Deltas in the Anthropocene (p. 282). *Book. Springer Nature*.

Shirzaei, M., Freymueller, J., Törnqvist, T. E., Galloway, D. L., Dura, T., & Minderhoud, P. S. J. (2020). Measuring, modelling and projecting coastal land subsidence. Nature Reviews Earth & Environment, 2(1), 40–58. https://doi.org/10.1038/s43017-020-00115-x

Suklje, L. (1957). The analysis of the consolidation process by the isotaches method. *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering* 1 201–206.

Tosi, L., Teatini, P., Carbognin, L., & Brancolini, G. (2009). Tectonophysics Using high resolution data to reveal depth-dependent mechanisms that drive land subsidence: The Venice coast, Italy. *Tectonophysics*, 474(1–2), 271–284. https://doi.org/10.1016/j.tecto.2009.02.026

Xotta, R., Zoccarato, C., Minderhoud, P.S.J., & Teatini, P. (2021). Compaction plays a role in the evolution of depositional environments. *Journal of Geophysical Research – Earth Surface*, submitted

Zoccarato, C., & Teatini, P. (2017). Numerical simulations of Holocene salt-marsh dynamics under the hypothesis of large soil deformations. *Advances in Water Resources*, 110(October), 107–119. https://doi.org/10.1016/j.advwatres.2017.10.006

Zoccarato, C., Minderhoud, P.S.J., & Teatini, P. (2018). The role of sedimentation and natural compaction in a prograding delta: insights from the mega Mekong delta, Vietnam. *Scientific reports*, *8*(1), 1-12.