Improving Subsidence Modelling of Different Depth Domains in the Mekong Delta

P.S.J. Minderhoud[1,2,3],*, A. Guzy[2,5], S. Baldan[2], R. Xotta[2], B.R. Lexmond[4], C. Zoccarato[2], P. Teatini[2]

1 Soil Geography and Landscape Group, Wageningen University, Wageningen, The Netherlands
2 Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy
3 Department of Subsurface and Groundwater Systems, Deltares Research Institute, Utrecht, The Netherlands
4 Department of Physical Geography, Utrecht University, Utrecht, The Netherlands
5 Faculty of Geo-Data Science, Geodesy and Environmental Engineering, AGH UST, Cracow, Poland
* Correspondence to Philip.Minderhoud@wur.nl

Introduction

The Mekong delta, one of the largest deltas in the world, is densely populated and important for food production. As the delta plain is lowly elevated, less than a meter on average above local sea level (Minderhoud et al. 2019), it is vulnerable to sea-level rise and land subsidence. The delta experiences high rates of natural compaction at its coast (Lovelock et al., 2015; Zoccarato et al, 2018) while human activities associated with land-use change (Minderhoud et al., 2018), urbanisation (de Wit et al., 2021) and intensified groundwater exploitation are accelerating subsidence further (Minderhoud et al., 2017; 2020a). At present the delta experiences high rates of land subsidence, with a delta-wide average rate exceeding 10 mm/yr and local rates as high as 60 mm/yr (Copernicus, 2019; Minderhoud et al., 2020b). As a result, the relative sea-level rise in the Mekong delta is dominated by land subsidence and forms an existential threat to the delta (Kondolf et al., 2022).

Deltaic subsidence is the cumulative effect of various drivers and processes in the subsurface (Tosi et al., 2009, Shirzaei et al., 2021), that can be both of natural and anthropogenic origin (Candela & Koster, 2022). As a result, subsidence can be both spatially and temporally highly variable within a delta. Subsidence caused by natural processes is unavoidable and can only be countered by adaptation, such as managed sedimentation strategies to build elevation through sediment deposition (Dunn & Minderhoud, 2022), while human-induced subsidence can be reduced or mitigated following a proper strategy (e.g. Erkens & Stouthamer, 2020).

In recent years the number of studies on subsidence in the Mekong delta has increased considerably, from direct measurements at a few locations in the delta using relative surface elevation tables (SETs, Lovelock et al., 2015) and dedicated subsidence monitoring stations (Karlsrud et al., 2017, 2020) delta-wide InSAR estimates (Erban et al., 2014; Copernicus, 2019). These estimates, combined with land-use change detection, revealed the spatial-temporal evolution and land-use change impacts on subsidence (Minderhoud et al., 2018) and detailed analyses of differential, depth-dependent subsidence in urban areas in the delta (De Wit et al. 2021). Two different numerical models were created targeting distinct subsidence processes: 1) groundwater extraction-induced aquifer-system compaction (Minderhoud et al., 2017), consequently used to create future elevation projection under different extraction scenarios (Minderhoud et al., 2020a), and 2) natural compaction of shallow sediments following Holocene delta progradation (Zoccarato et al., 2018). This contribution provides an overview of past and ongoing numerical advances in subsidence modelling in the Mekong delta and provides an outlook for future work.

Past numerical advances

A delta-wide 3D hydrogeological model of the Mekong delta was created to simulate groundwater extraction and consequent aquifer-system compaction based on datasets on delta geology, hydro(geo)logy, geomechanics and groundwater extractions (Minderhoud et al., 2017). The hydrogeological model was calibrated using hydraulic head monitoring data. A 1D compaction module, SUB-CR (Kooi et al., 2020) was used to simulate aquifer-system compaction using a viscoelastic compression theory following the isotache concept (Suklje, 1957; Bjerrum, 1967). In the first model version groundwater extraction and consequent aquifer-system compaction were simulated from 1991 to 2015 (Minderhoud et al, 2017). The simulated subsidence was calibrated using InSAR estimates for 2006-2009 (Erban et al., 2014) and revealed an acceleration in aquifer-system compaction in the delta, which was later confirmed by InSAR estimates from 2014-2019 (Copernicus 2019; Minderhoud et al., 2020b). Consequently, the model was updated by including an explicit surface water system and the past extraction rate simulated in the model was improved based on hydraulic head analysis (Minderhoud et al., 2020a). The updated model was used with scenarios of future groundwater use to project aquifer-system compaction until the end of the 21th century (Fig. 1).

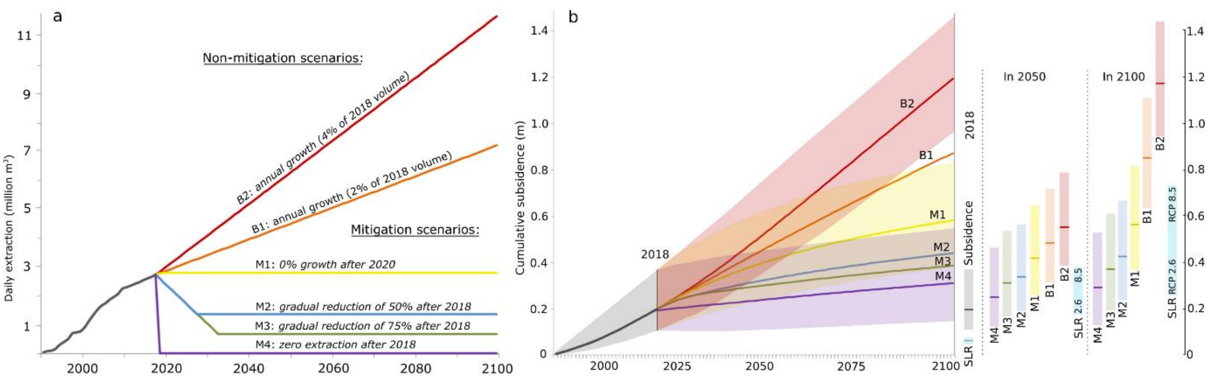

Figure 1 a) Scenarios of groundwater extraction for the Mekong delta. b) Cumulative delta-average subsidence for each modelled scenario. The results are placed in comparison to global sea-level rise as projected in various RCP scenario (IPCC) specifically for the Mekong delta (modified after Minderhoud et al., 2020a, reproduced under CC BY 3.0).

The large Mekong delta has prograded rapidly in the second half of the Holocene shoreline advances up to 50 m/yr (Tamura et al., 2020). Rapid sedimentation of fine-grained sediments is followed by high rates of natural compaction resulting from delayed dissipation of overpressure under its own weight. To simulate this for the Mekong delta, Zoccarato et al. (2018) applied NATSUB-2D, a novel finite-element, groundwater flow model coupled to a 1D compaction module with a compressible mesh, able to simulate the large deformations (with a Lagrangian approach) happening in these young, highly porous and compressible deposits (Zoccarato & Teatini, 2017). The simulation of the last 4000 years of delta progradation along a transect towards the South revealed the potential occurrence of present unprecedented high natural compaction rates at the coast, up to several cm/yr. These values match direct measurements of shallow compaction in this area with SETs (Giao et al., 2014; Lovelock et al., 2015) in mangrove forests and subsidence monitoring stations (Karlsrud et al., 2020) and demonstrated that a large part of the shallow near-coastal subsidence can be of natural origin and a product of fast delta progradation. The transect results were combined with the spatial occurrence of Holocene clays to provide a first estimate of delta-wide natural compaction following delayed overpressure dissipation assuming homogeneous clay deposits (Minderhoud, 2019).

The combined effect of extraction-induced aquifer-system compaction and natural compaction on future elevation evolution in the delta (Fig. 2) shows the critical situation and potential drowning of the Mekong delta in the near future under high rates of relative sea-level rise. It also reveals the importance of the described numerical models that enable the forecasting of future compaction and create relative sea-level rise projections to inform policymakers and steer mitigation efforts.

Ongoing advances to improve subsidence models for the Mekong delta

The described models represent the past advances in subsidence models for the Mekong delta that go beyond 1D calculations and were in revealing the high subsidence in the Mekong delta and informing policymakers (Kondolf et al., 2022). Here we describe ongoing efforts to improve these models and subsidence quantifications for the delta via code development and model advancement (Figure 3).

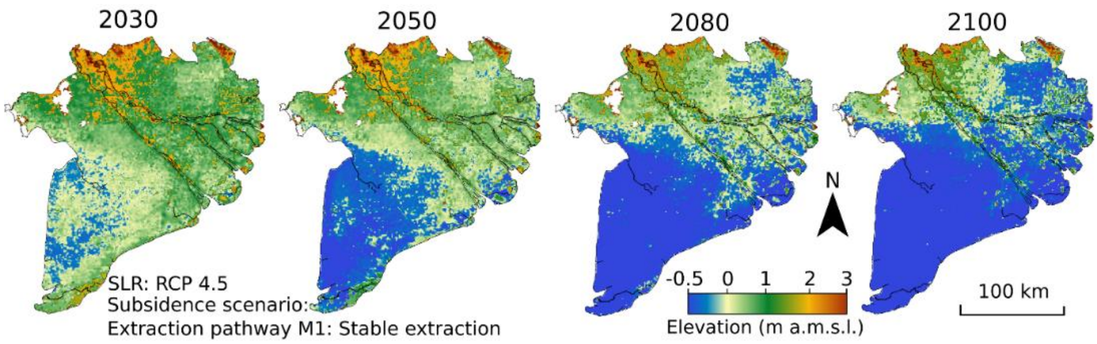

Figure 2 Elevation projections for the Mekong delta under extraction-induced compaction (scenario M1, Fig. 1), sea-level rise (SLR) following RCP 4.5 and natural compaction, assuming it is no longer compensated by sedimentation (modified after Minderhoud et al., 2020a, supplement, CC BY 3.0, elevation data Minderhoud et al., 2019b).

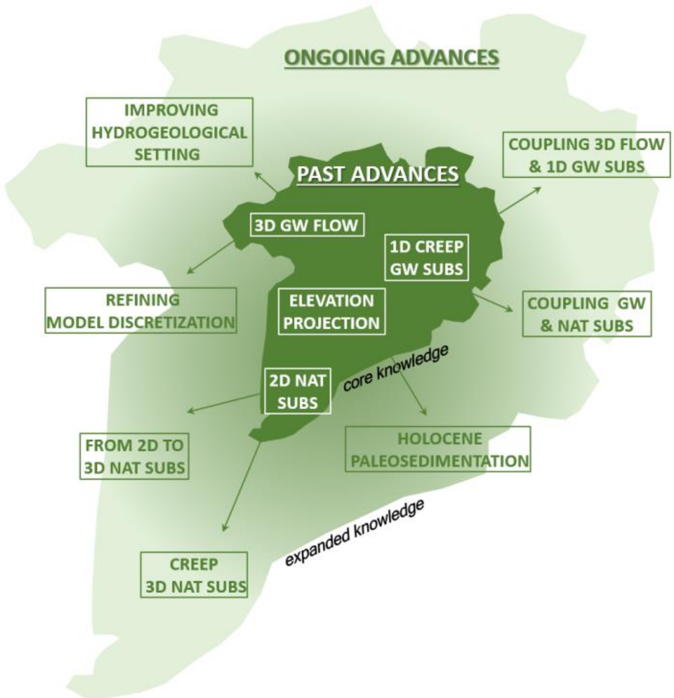

Figure 3 Past and ongoing advances in numerical modelling of subsidence in the Mekong. The modelling advances encompass both natural (NAT) and groundwater (GW) extraction-induced subsidence (SUBS), processes acting in different depth domains under different drivers.

Advances in modelling hydrogeological aquifer-system compaction

Improving hydrogeological schematization. In the present schematisation, the aquitards are discretized as a single layer, which makes it unable to simulate delayed groundwater 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., submitted).

Quantify the impact of the deterministic modelling approach on compaction. The hydrogeological model has a deterministic model parameterization, calibrated to hydraulic head time series. To determine the impact of this deterministic modelling approach on simulated compaction, stochastic modelling of hydrogeological parameters is performed (Lexmond et al., submitted).

Improve parameter consistency between hydrogeology and geomechanics. Since the groundwater model and the geomechanical module were initially parameterized and calibrated independently, there is an inconsistency between the hydrogeological model parameterization (i.e. specific storage) and the geomechanical parameterization (i.e. compression index), as Pham et al. (2022) also pointed out. To overcome this drawback, an iterative procedure is implemented to calibrate specific storage and compression index consistently for each individual layer using piezometric and InSAR records. This is accomplished with InSAR-retrieved land subsidence datasets covering the years 2006 to 2010 (Erban et al., 2014) and 2016 to 2019 (Minderhoud et al., 2020b). Since these datasets span varying time intervals, they allow for the capture of non-linear deformation behaviour and, as a result, further improvements in the accuracy of land subsidence estimations. Consequently, the recalibrated model simulates a larger decrease in hydraulic head in the most heavily pumped aquifers and thus higher values of land subsidence in vulnerable areas when compared to the initial model (Guzy et al., in prep).

Advances in modelling of natural compaction

Upgrade the numerical domain to 3D. The 2D simulator (Zoccarato & Teatini, 2017) is expanded to a 3D spatial domain, i.e. NATSUB3D (Xotta et al., 2022). The 1D compaction module is coupled to a 3D groundwater flow module and the finite element code can generate a 3D tetrahedral grid that deforms over time with sediment compaction. The new code allows for properly simulating sediment accretion and compaction with time for 3D landform evolution, by updating the mesh following compaction and recomputing the hydrogeological and geomechanical parameters dependent on the strain.

3D subsurface model development based on paleo-sedimentation of Holocene deposits. The current hydrogeological and geomechanical state of the subsurface is influenced by its recent sedimentation history which can be simulated using the NATSUB3D code. To properly simulate and quantify present shallow compaction in the Mekong delta in the NATSUB3D code, a new approach is developed to retrieve spatial and temporal information on paleo-sedimentation rates from lithological data. The approach combines lithological bore logs, sediment geochronology (i.e. datings), spatial interpolation and geomechanical parametrization of representative lithologies to create maps of paleo-sedimentation during the Holocene delta evolution. Based on these maps that represent sediment accumulation in the last 4000 yrs of the Holocene delta evolution, a first 3D lithological model was simulated that enables computation of present-day natural compaction rates for the coastal part of the Mekong delta (Fig. 4).

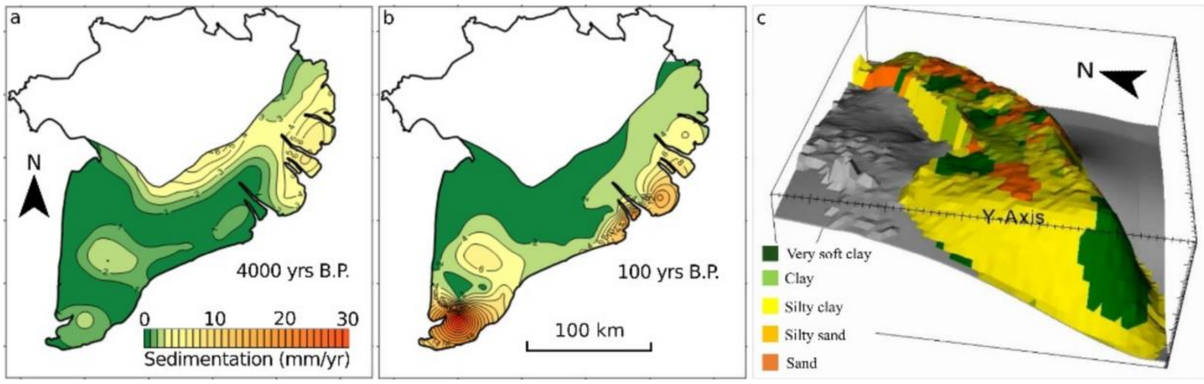

Figure 4 a-b) Example of paleo-sedimentation rate maps. Sedimentation rate maps were derived for each lithological class over 100-yr intervals spanning from 4000-0 yrs B.P. When more lithologies were deposited in the same interval, the model assumed spatio-linear mixing of the lithologies and computes hydro-geomechanical properties of the deposits according to the ratio of each lithological class. c) Simulated present 3D lithology of the Holocene deposits (4000 yr B.P to present) in the Mekong delta (Baldan et al., in prep).

Coupling aquifer depletion with shallow natural subsidence. The effect of deeper groundwater extraction on subsidence in the shallow subsurface is evaluated by linking two numerical models. The present and future effects of groundwater extraction (i.e. water level drop), computed with the calibrated 3D hydrogeological model of the Mekong delta, is used as input for the upgraded NATSUB3D model (Baldan et al., in prep.) This will allow quantifying the impact of extractions on shallow subsidence in the Mekong delta (Guzy et al., in prep.).

Adding a visco-elastic approach to NATSUB3D. In addition to the existing elastoplastic approach, a visco-elastic approach is added to the NATSUB3D code to enable the simulation of time-dependent creep (i.e. secondary compression) following the isotache approach. In this approach, compaction is no longer only driven by stress (i.e. load increase following sediment deposition), but also becomes time-dependent (i.e. creep), causing compaction to continue also in the absence of dissipation of porewater overpressure. With this update, NATSUB3D can also be applied to investigate the effect of creep compaction in young sedimentary settings (Xotta et al., in prep.).

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