Food for thoughts

This is one of three essays which are also included in the CPMD focusing in detail on related topics such as the alarming outcomes of studies on land subsidence (Essay I.), international mainstream developments in coastal spatial planning (Essay II.) and the inclusion of a better tailored climate change service into planning of infrastructure (Essay III.). These are considered important topics in the near future and should find their reflection in coming planning. The essays were written by experts in their fields who are also familiar with the special conditions in the Mekong Delta.

Essay I.

Delta subsidence and groundwater system in the Mekong Delta – state of knowledge and uncertainties

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i. Hydrogeological situation and groundwater use in the Mekong Delta

During the Cenozoic and Quaternary, the rapid uplift of the Proto-Himalaya mountain chain and related subsidence of adjacent tectonic basins resulted in the mobilization of large amounts of material, which was collected by e.g. the tributaries of the Mekong River (Wagner et al., 2012). Ongoing tectonic subsidence of the Mekong basin, high erosion rates and multiple cycles of marine transgressions and regressions lead to the deposition of an approximately 180 to over 500 m thick sedimentary basin fill (Anderson, 1978) overlaying a pre-Cenozoic basement. In general, the thickness of the sedimentary complex, or the depth of the NW trending Mekong basin, increases from the NW to the SE and from the West towards the Bassac River. During repetitive periods of transgressions and regressions strata of unconsolidated sediments developed in the Mekong basin which form a multi-layered aquifer system. It exhibits a complex alternating structure of high permeable (aquifers) and low permeable deposits (aquitards). The aquifers mainly consist of fine to coarse sand, occasionally with silty and clayey interbeds. They store and conduct groundwater and are thus the relevant layers for groundwater supply. Intercalated aquitards are generally composed of silt, clay and silty clay. They act as confining layers (of very low permeability) separating the different aquifers. Aquifers and aquitards are developed in a rather complex manner across the delta; they are sometimes discontinuous and spatially highly variable in thickness and hydraulic properties. In general, the main aquifers in the Mekong Delta range from Miocene to Holocene age (DGSM, 2004). An overview on the main geological and hydrogeological strata of the Mekong basin is given by Table 1.

Since the 1990s, groundwater has become increasingly important for domestic, agricultural and industrial demands in the Mekong delta. The shallow Holocene aquifer *qh* is mostly salty to brackish and is seldom used for water supply. It is often weakly developed and consists of intercalated lenses of sand and silty sand within the clay complex of the Q_2 and Q_1^3 aquitards. Hence, the upper 12 to 40 m of the sedimentary strata of the delta commonly consist of very soft to stiff clay with high water content (Giao et al., 2014; Hoang et al., 2016). The deeper, confined Pleistocene and Pliocene aquifers are the principle source for freshwater supply in the Mekong Delta. The most exploited aquifer is $qp_{2\text{-}3}$ followed by aquifer n_2^2.

The main share of extracted groundwater is for agriculture, aquaculture and household use in rural areas, from mostly small to medium-sized wells with pumping rates <200 m^3/day. Pumping wells with higher extraction rates need to be licensed and are commonly concentrated in urbanized areas and cities (DWRPIS, 2010). Due to the high extraction rates, the decline in groundwater levels is most severe in the densely populated areas, where localized groundwater depression cones developed. Rural areas experience a more gradual groundwater level decline, as the pumping is distributed over larger areas. However, the total volume of extracted groundwater in rural areas exceeds the volume extracted in urban areas.

Table 1: Geological and hydrogeological units of the Mekong Delta (DGSM, 2004)

System	Series	Facies and Geology [a]	Aquifer	Aquitard	Base age (Mio a BP)	Average depth below surface (m)*
Quaternary	Holocene	mQ_2^{1-2}, amQ_2^{1-2},		Q_2	0.012	9
		amQ_2^{2-3}, $ambQ_2^3$, aQ_2^3	qh			29
	Pleistocene, Upper	mQ_1^3		Q_1^3	0.126	53
		amQ_1^3	qp_3			70
	Pleistocene, Middle	mQ_1^{2-3}		Q_1^{2-3}	0.781	97
		amQ_1^{2-3}	qp_{2-3}			123
	Pleistocene, Lower	mQ_1^1		Q_1^1	1.806/ 2.588 [b]	149
		amQ_1^1	qp_1			180
Neogene	Pliocene, Middle	mN_2^2		N_2^2	3.600	212
		amN_2^2	n_2^2			242
	Pliocene, Lower	mN_2^1		N_2^1	5.332	271
		amN_2^1	n_2^1			302
	Miocene, Upper	mN_1^3		N_1^3	11.608	332
		amN_1^3	n_1^3			382

[a] ***(a) – alluvial; (m) – marine; (b) – bog, swamp***

[b] ***Quaternary base has been redefined by IUGS-ICS in 2009 to 2.58 Mio a BP, including the former upper Pliocene***

* ***Average depths derived from the 3D schematization of the delta by Minderhoud et al. (2017)***

An approximation of daily rates of groundwater extraction from 2013 and predicted rates for 2015 and 2020 are summarized by Table 2, for the coastal provinces south of the Bassac River. Accordingly, the demand for groundwater is expected to increase continuously. Direct groundwater recharge, however, is slow and limited. The shallow Holocene clays function as a rather effective seal for the deeper layers and more or less separate the surface water system from the groundwater system. Source areas for groundwater recharge, in particular to the deeper aquifers, have not yet been conclusively identified. Based on radio-carbon dating, groundwater ages are estimated to 10,000 to over 40,000 years (Dung Ho et al., 1992; Hoang and Bäumle, 2017). Fresh groundwater resources in the Mekong Delta are thus considered finite and the aquifer system is subjected to aquifer depletion. Groundwater heads are continuously declining throughout the delta (Wagner et al., 2012). Erban et al. (2014) estimated rates for groundwater level decline to 0.3-0.7 m/year over the past two decades, in the exploited aquifers in most of the delta. However, assessing the groundwater system and resources in the Mekong delta in detail is complicated by a rather limited network of groundwater monitoring wells.

Table 2: Groundwater extraction rates in m^3/day for 2013 and expected rates for 2015 and 2020 (Cao et al., 2013)

Province	*2013*	*2015*	*2020*
Bac Lieu	248,728	297,122	340,429
Ca Mau	159,118	223,920	308,237
Kien Giang	197,441	253,641	300,116
Soc Trang	244,850	323,362	396,745

Nevertheless, a permanent decline in groundwater levels and hydraulic pressure increases the risk of salt water intrusion from the sea into aquifers, and groundwater pollution in general. In order to minimize these risks and preserve the livelihood of the delta, developing and adapting water management strategies to minimize groundwater usage is a future challenge. Taking action on this issue becomes even more urgent, as recent studies conclude that groundwater exploitation also triggers land subsidence in the delta.

ii. Land subsidence and the role of groundwater extraction

Land subsidence in deltas is a natural process following compaction of sediments as they age and become buried by newly deposited sediments on top. Besides, deltas are often located in coastal zones with a downward movement of the earth's crust. Natural compaction rates and tectonic movements are usually rather small, but land subsidence can also result from anthropogenic impacts.

Figure 1 schematically summarizes drivers for subsidence and illustrates the various processes that can cause land subsidence in deltaic environments. Soft and compressible sediments at the shallow subsurface may consolidate due to the direct impact of natural or anthropogenic loading. Lowering the phreatic groundwater table can lead to compaction and bio-chemical decomposition (oxidation) of organic material by aeration of organic-rich sediments (Galloway et al., 2016). Furthermore, groundwater extraction from deeper layers has been related to accelerated subsidence in many deltas and coastal areas around the world, as explained below. The combined effect of these different mechanisms results in the total (cumulative) subsidence experienced at the delta surface.

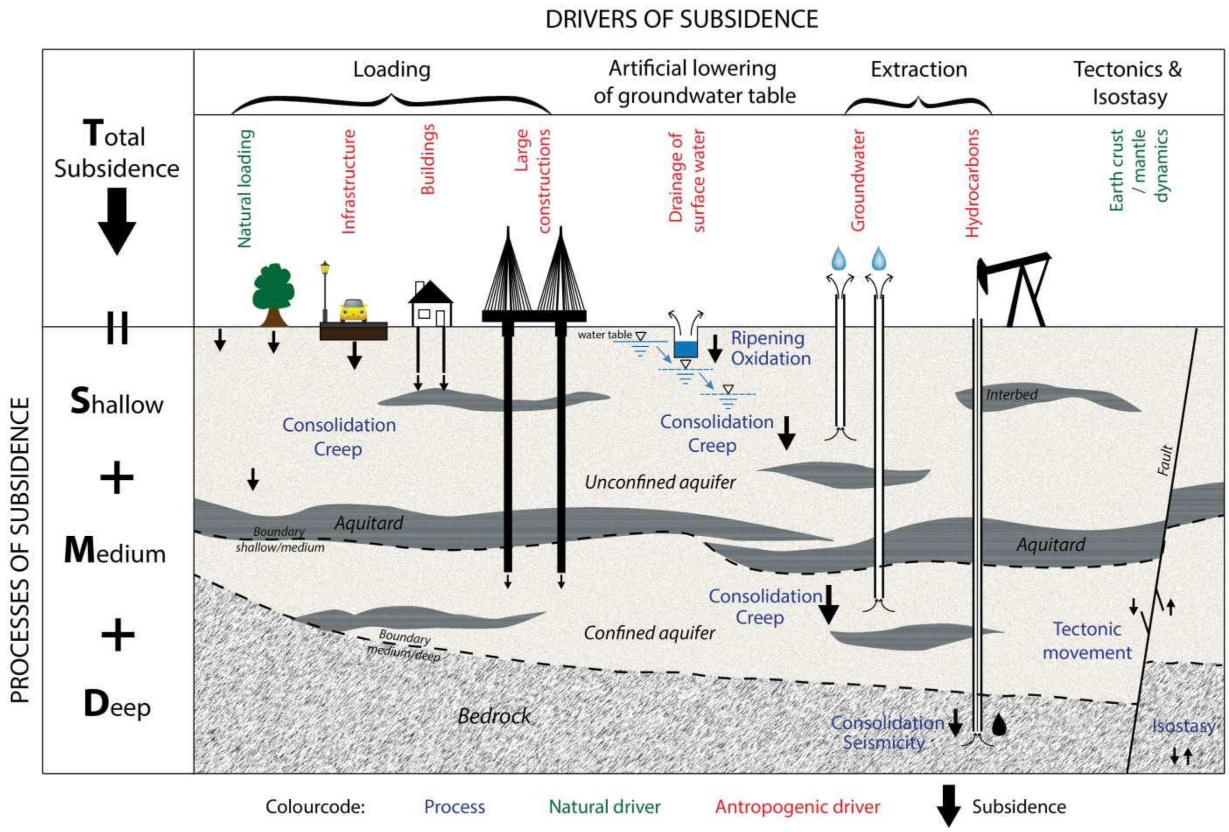

Figure 1: Schematic overview of subsidence drivers in deltaic environments (Minderhoud et al., 2015)

It is a well-studied phenomenon that a persistent drawdown of the groundwater level, i.e., a drop of the fluid pressure in a confined aquifer, can trigger subsidence (Abidin et al., 2011; Higgins et al., 2013; Phien-wej et al., 2006; Saito et al., 2007; Teatini et al., 2006). As the aquifer's pore pressure decreases, the compressible fine-grained silt and clay layers are progressively drained, and hence compact. The compaction of subsurface layers then results in land subsidence at the ground surface (Galloway and Burbey, 2011; Gambolati and Teatini, 2015). Highest subsidence rates are found in particular in densely populated areas with a large decline in groundwater levels due to excessive groundwater extraction from unconsolidated sediments; where often soft compressible clays cap deeper sand or gravel aquifers. Nevertheless, examples from Shanghai (Dong et al., 2014; Wu et al., 2010), Taipei (Chen et al., 2007) or Tokyo (Sato et al., 2006), which experienced subsidence of up to 4 m (Table 3), show that accelerated subsidence can be reduced by regulating and restricting groundwater pumping.

Table 3: Selected cases of subsidence due to groundwater pumping (as summarized by Gambolati and Teatini, 2015)

Location	*Max. subsidence (m)*	*Recent subs. rate [a] (cm/year)*	*Depth of pumping (m)*
Bangkok	2.1 (1933-2002)	2 (2005-2010)	30-300
Ho Chi Minh	0.4 (1996-2005)	4 (2010-2014)	50-240
Jakarta	4.1 (1974-2010)	26 (2007-2011)	40-240
Shanghai	2.6 (1958-2002)	1.5 (2006-2011)	10-330
Taipei	2 (1955-1991)	-0.7 (1989-2003)	50-250
Tokyo	4.3 (1900-1975)	-0.3 (1991-2005)	0-400

[a] ***Local maximum measured rate for the specified period. Negative values mean uplift.***

Several studies investigate land subsidence in the Mekong delta and its relation to groundwater extraction (Erban et al., 2013, 2014; Fujihara et al., 2016; Karlsrud and Vangelsten, 2017; Minderhoud et al., 2015, 2017). At present, satellite based InSAR (Interferometric Synthetic Aperture Radar) data is the only source of surface elevation data available in time series, allowing to estimate subsidence rates. By evaluating the corresponding time series from 2006 to 2010, Erban et al. (2014) estimated total subsidence rates between 1-4 cm/year with an average of 1.6 cm/year at considered groundwater monitoring stations throughout the Mekong Delta. If pumping continues at present rate they expect an average subsidence of about 0.88 m (0.35 – 1.4 m) by 2050. Karlsrud and Vangelsten (2017) focused on the estimation of subsidence rates in Ca Mau Province. They applied 1-D consolidation calculations for the clays in the upper 40 m in Ca Mau city, and estimated comparable subsidence rates due to groundwater pumping, between 2-4 cm/year. In the most recent study, Minderhoud et al. (2017) adopt a delta-wide approach to compute groundwater extraction-related subsidence rates in the Mekong delta using a groundwater flow model of the entire aquifer system, coupled with a geotechnical subsidence model. They found that subsidence rates steadily increased since the beginning of excessive groundwater extraction in the 1990's, with current rates of about 1-2 cm/year in rural and about 3 cm/year in cities and industrial areas, on average 1.2 cm/year.

Figure 2 shows the groundwater contour map for the intensively exploited aquifer $qp_{2\text{-}3}$. The map was interpolated from groundwater head measurements provided by the National Center for Water Resources Planning and Investigation of Vietnam (NAWAPI), but does not consider the corresponding data for Ho Chi Minh City, northeast of the delta. Furthermore, Figure 2 shows the groundwater extraction-induced subsidence rates computed by Minderhoud et al. (2017). It can be seen that the pattern of modelled subsidence rates agrees well with areas which show the lowest groundwater levels, generally due to excessive groundwater pumping, including Soc Trang, Bac Lieu, and Ca Mau Province. Note that the modelled subsidence rates by Minderhoud et al. (2017) relate to groundwater extraction-related subsidence only, and are thus somewhat lower than total subsidence rates estimated from InSAR data by Erban et al. (2014).

Besides groundwater extraction-related subsidence, Giao et al. (2014) investigated shallow subsidence in coastal Mangrove areas by surface elevation table measurements (SETs). They found subsidence rates for the shallow Holocene clays of 1.42 to 2.63 cm/year in intact mangrove forest, and a maximum rate of 3.8 cm/year on barren land of dead mangrove bushes. These latter, increased subsidence rates were attributed to the decomposition of subsoil of dead/rotten plants.

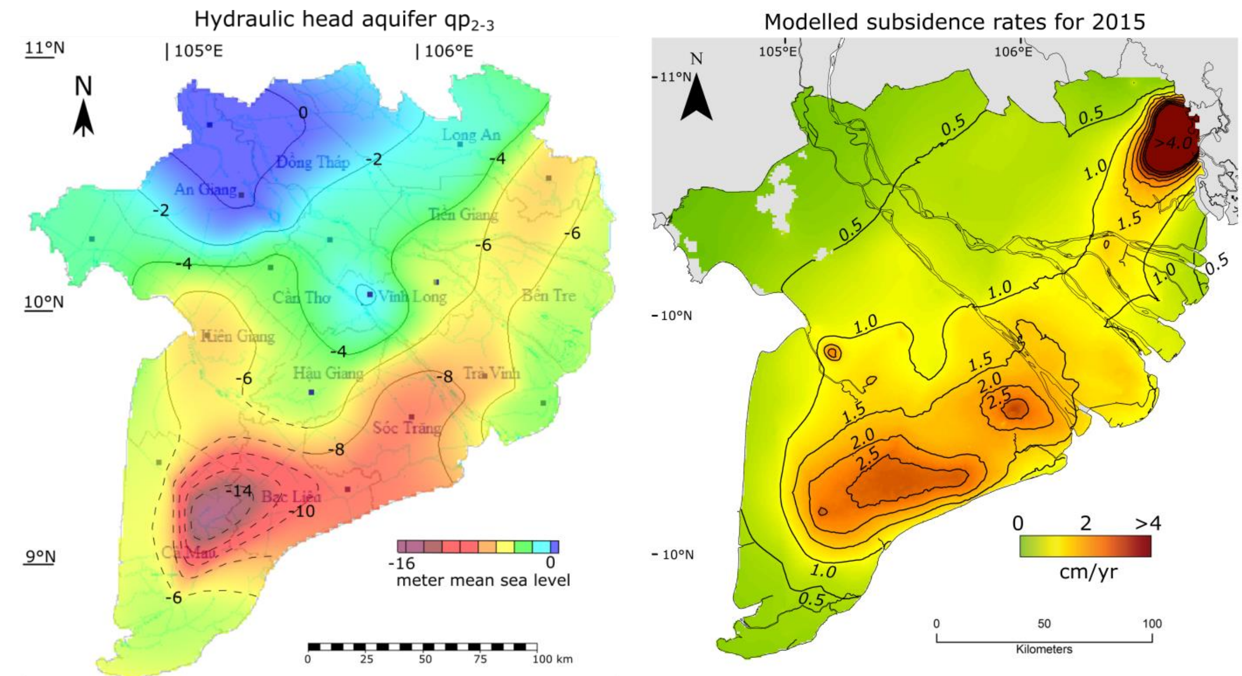

Figure 2: Groundwater contour map for aquifer qp$_{2-3}$ (left), interpolated from measurements in rainy season 2016 , and modelled groundwater extraction-induced subsidence rates (right) over the year 2015 computed by Minderhoud et al. (2017). The groundwater data was provided by NAWAPI, locations for groundwater head measurements are depicted by squares. Note that the depression cone around Ca Mau city, which has been measured and reported in older monitoring well data and studies (e.g., Erban et al., 2014; Nguyen, 2010) , was estimated (dashed contour lines), as no updated data for 2016 currently exists.

The modelled subsidence rates by Minderhoud et al. (2017) are currently the only available data that cover the complete Vietnamese Mekong Delta, as the InSAR analysis by Erban et al. (2014) covers the southern Mekong delta only partially. However, their modelling approach relies on average measures and estimates of geotechnical properties of the subsurface (compressibility constants and over-consolidation ratio) which are likely to vary spatially. The modelling results should therefore be regarded as estimates of groundwater extraction-induced subsidence, and true rates might fluctuate locally. Nevertheless, the spatial pattern of modelled subsidence rates for the Mekong delta matches the pattern of actual groundwater levels rather well (Figure 2). Accordingly, the modelling results suggest that groundwater extraction is one of the dominant drivers for land subsidence in the Mekong delta.

iii. Conclusions & recommendations

As the majority of the Mekong delta is elevated less than 2 m above mean sea level and already prone to flooding, the reported subsidence rates are alarmingly high. They largely exceed absolute sea level rise which is estimated locally at about 3-5 mm/year (Hak et al., 2016; Lovelock et al., 2015; Takagi et al., 2016). Consequently, immediate action is needed to keep the impact of accelerated land subsidence and associated risks of flooding, groundwater degradation, and damage to buildings and infrastructure to a minimum. In this regard, the following actions are recommended:

- Groundwater extraction from confined aquifers, which has been identified as a main driver for subsidence, should be reduced by the enforcement of restrictions on groundwater pumping. In order to replace groundwater as fresh water resource, alternative strategies for water supply and distribution need to be developed and promoted in the near future.
- Heavy, unfounded constructions in the coastal zone with highly compressible sediments near the surface should be avoided. Such structures are likely to experience high subsidence rates due to their own weight causing increased consolidation of the sediments below. This should also be taken into account when planning and constructing hard flood protection measures, such as dykes, as this process can seriously reduce the effective lifespan of flood protection structures.
- Further insight on the spatial extent and magnitude of subsidence and its drivers is needed. Thus, future challenges are to overcome the scarcity of reliable data on geotechnical soil properties and groundwater monitoring, as well as to verify subsidence in situ. This comprises exact in-situ measurements to validate the satellite (InSAR) and model based subsidence estimates, e.g. by the installation of GPS benchmarks, InSAR reflectors, and extensometers.
- Additionally, research on shallow subsidence and on effects of drainage and surface water regulation on the phreatic groundwater is recommended.
- Predictive modelling tools of delta subsidence should be developed and used to provide scenarios of subsidence under different (groundwater) management strategies to aid policymakers and delta planners.
- Last but not least, awareness raising for local people and for policy makers is considered very important in order to convey that land subsidence in the Mekong Delta is an urgent problem and solutions are needed to prevent the delta from drowning.

iv. References

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