CHAPTER 13

Groundwater resource challenges and abstraction-induced land subsidence in the Vietnamese Mekong Delta

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13.1 Introduction

River deltas are favorable areas for human habitation and economic developing due to their competitive natural conditions, diversity of ecosystems, availability of food, and natural resources. Coastal river deltas are the Earth's most densely populated areas (Syvitski et al., 2009; Fan et al., 2017; Tejedor et al., 2017; Loucks et al., 2019). The deltaic population has rapidly grown by 34% from 2000 to 2017 with about 339 million people living on river deltas in 2017 (Edmonds et al., 2020). However, many human activities such as change of land use, sand mining, agriculture, and industrial activities are threatening the sustainable development of river deltas (Syvitski and Saito, 2007; Best, 2019). Deltaic areas are also among the most vulnerable areas to climate change and relative sea-level rise, the combined effect of global sea-level rise, and land subsidence (Shirzaei et al., 2020). Those processes do not only reduced water quality by contamination and seawater intrusion but also triggered erosion, land subsidence, and result in losing land surface (Ericson et al., 2006; Syvitski et al., 2009; Giosan et al., 2014).

Groundwater has become an essential water resource for domestic, industrial, and agricultural sectors in many river deltas (Bierkens and Yada, 2019). Because surface water quality is degraded by contamination from anthropogenic sources (Thorslund et al., 2021) and salinization by drought and sea-level rise, groundwater has been also overexploited to meet the accelerated demands in river deltas around the world (Custodio, 2002; Konikow and Kendy, 2005; Famiglietti, 2014; Döll et al., 2014; Minderhoud et al., 2017). Groundwater overexploitation induces various environmental issues and poses a significant threat to the freshwater availability to the local population and ecosystems (e.g., Van der Kamp and Hayashi, 2009; MacDonald et al., 2016; Luijendijk et al., 2020). In fact, poor groundwater quality is directly associated with elevated human health risks (e.g., for salinity: He and MacGregor, 2009), reduced crop production (Maas and Hoffman, 1977), and deteriorated soil quality (Edmunds and Smedley, 1996). In addition, declining groundwater pressure heads drive compaction of the aquifer system (Galloway and Burbey, 2011; Shirzaei et al., 2020), which seriously accelerates land subsidence in already sinking coastal deltas (Syvitski et al., 2009; Herrera-García et al., 2021). In addition, climate change and relative sea-level rise extend the impacts on groundwater resources, for example, stimulating more groundwater abstraction due to drought, reduction of rainfall recharge, and inland movement of fresh-salt water wedge due to sea-level rise (Oude Essink et al., 2010; Green et al., 2011; Taylor et al., 2013; Befus et al., 2020).

Mekong Delta (MD) is one of three largest deltas in the world. The Vietnamese part of MD (VMD) is the home to 17 million people in 2020 and plays a key role in socio-economic development for Vietnam, providing 55% of all rice and other agricultural products for the entire country (GSO, 2021). Climate change impacts are already apparent in Vietnam (MONRE, 2016). Annual temperature has increased by an average of 0.62°C across the country, while annual rainfall has increased up to 19.8% in the VMD during the period 1958–2014. Sea level is increasing with a rate of ~3.3 mm/year. Due to climate change, more rain will occur during the rainy season but less rain during the dry season (MONRE, 2016). According to the RCP 8.5 scenario, temperature and precipitation in the VMD will increase up to 4.6°C and 32%, respectively, by the end of this century. Conversely, the VMD will also face more intense droughts and more frequently during the dry season (Park et al., 2021). The sea level is projected to rise by 106 cm by the end of this century (MONRE, 2016). In addition, anthropogenic causes (e.g., sand mining) and relative sea-level rise will lead to a more severe salt intrusion within the VMD region that leads to a reduced freshwater availability in the decennia to come (Eslami et al., 2021).

Groundwater is an important freshwater resource for people in the VMD (Michael, 1971; Vo et al., 2007; Danh and Khai, 2015; Bui et al., 2015). Especially during the dry season, as the quality of surface water is deteriorated in large parts of the delta (Giao et al., 2022; Eslami et al., 2019), groundwater has been exploited at a large scale in recent decades, causing groundwater pressure in the aquifer system to decline throughout the delta (Minderhoud et al., 2017; Ha et al., 2019a; Le et al., 2021). Several studies showed that the decreasing groundwater pressure drives aquifer-system compaction and causes land subsidence in many parts of the delta (Erban et al., 2014; Minderhoud et al., 2017, 2019), also in nearby Ho Chi Minh city (Thoang and Giao, 2015; Dinh et al., 2015). Subsidence in the VMD is also caused by other factors. Natural processes such as shallow compaction of Holocene sediments (Zoccarato et al., 2018) and deep-rooted tectonics and isostatic adjustment of the earth crust tend to cause subsidence of several mm/yr, with the exception of young coastal mangrove forests, where shallow compaction rates can reach several cm/yr (Lovelock et al., 2015; Zoccarato et al., 2018). On top of that, humans accelerate subsidence, in addition to groundwater overexploitation also by land-use change and associated drainage (Minderhoud et al., 2018) and loading by buildings and infrastructure (de Wit et al., 2021). However, the effect of these additional subsidence drivers tends to be localized, while the impact of abstraction-induced subsidence causes much larger areas of the delta plain to lose elevation, making groundwater overexploitation the main cause of delta-wide subsidence in the VMD (Minderhoud et al., 2017; Minderhoud et al., 2020). To maintain economic development and food security, groundwater may continue to be overexploited, which can cause substantial subsidence in the large part of the delta to sink below sea level in coming decades (Minderhoud et al., 2020). The combined effect of global sea-level rise and abstraction-induced subsidence result in further saltwater intrusion (Eslami et al., 2021) and threaten the large part of the delta with permanent inundation in the near future. Although fluvial sedimentation is often mentioned as a promising method to build elevation and counterbalance relative sea-level rise (Van Staveren et al., 2018), a recent study highlights there is simply not enough sediment available for it to be a feasible strategy at delta scale (Dunn and Minderhoud, 2022). The combined impacts of depleting fresh groundwater reserves and increased relative sea-level rise and salinization due to human activities on top of climate change impacts pose more challenges and make it much more difficult for the VMD to develop in a sustainable way in the long run. In this chapter, we will summarize previous studies focused on groundwater and abstract-induced subsidence to recommend solutions for regionally groundwater management to improve water quality, reduce the decline of fresh groundwater resources availability, and cope with land subsidence and water scarcity in the VMD.

13.2 Overview of the Vietnamese Mekong Delta

13.2.1 The geographical conditions: Elevation, climate, river system, and land use

The VMD is about 40,800 km^2 and has a flat land surface with a low elevation generally less than 2 m above mean sea level (MSL) with an average elevation of its delta plain of ~0.8 m (Fig. 13.1, Minderhoud et al., 2019). The climate has two distinct seasons; the rainy season starts from May to November, and the dry season lasts from December to April of the following year. Annual rainfall is around 2000 mm/year; however, 90% of total rainfall occurs in the rainy season. Average monthly temperature varies from 24 to 29°C.

When entering the VMD, the Mekong River divides itself into two main branches and discharge to the East Sea of Vietnam through eight

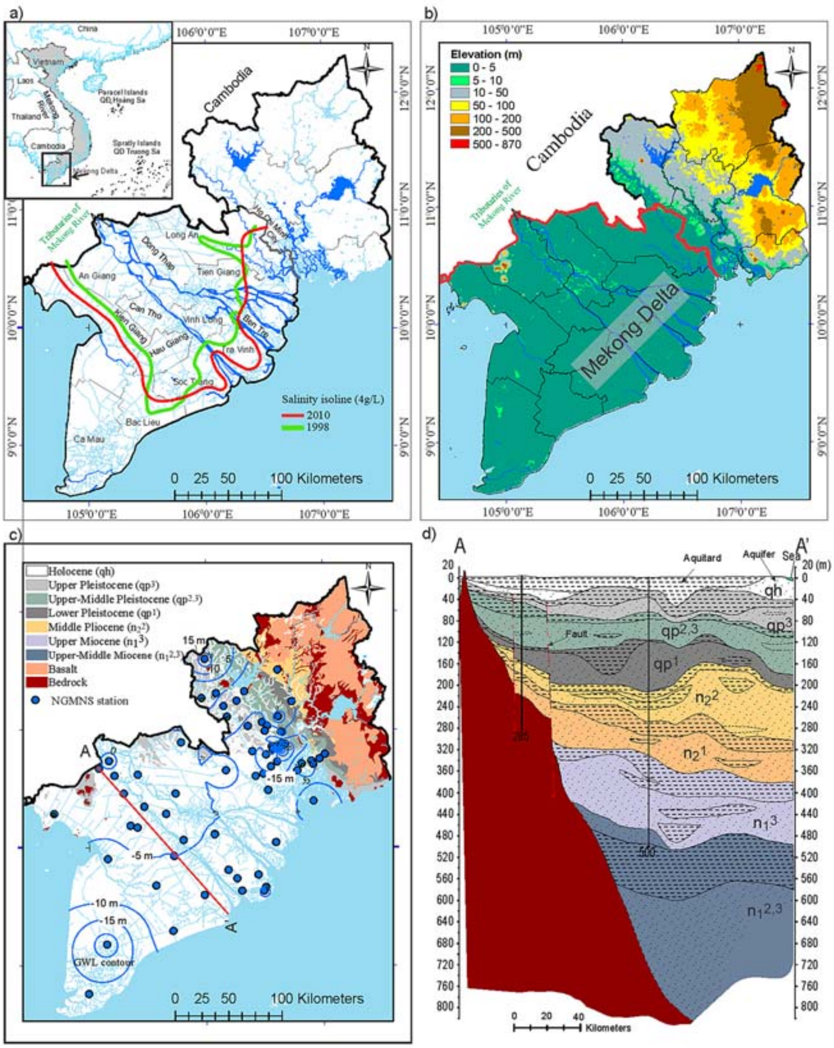

Figure 13.1 Location of provinces and salinity isolines of surface water in 1998 and 2010. (a), topographic map (b), geological map, location of National Groundwater Monitoring Network for the south of Vietnam (NGMNS) stations (blue points) and groundwater pressure head distribution in the upper−middle Pleistocene aquifer in 2015 (blue line) (c), and geological cross-section A-A in c (d) of the Vietnamese Mekong Delta. *(Data from Southern Institute of Water Resources Research. (a) and (b) Data from NGMNS; DWRPIS, 2015. Annual Report on the National Groundwater Monitoring Network for the Southern Vietnam. Division of Water Resources Planning and Investigation for the South of Vietnam (in Vietnamese). (c) Modified from NGE.)*

subbranches. About 15,000 km of main major canals, 27,000 km of secondary canals, and 50,000 km of farm canals have been excavated in the VMD over the last 200 years for irrigation and transportation purposes (Nguyen et al., 2016; Le et al., 2018). The hydrological conditions in the area are regulated by the discharge from the upstream, precipitation, land use, and the sea tides from the Gulf of Thailand and the East Sea (Smajgl et al., 2015). About 64 dams have been constructed in the upstream area of Mekong River, which influenced the hydrological conditions of the MD to a large extent (Xue et al., 2011; Pokhrel et al., 2018). In the VMD, a total of 15,000 km of dykes and 80 sluice gates have recently been built or are under construction to control floods from the river branches, canals, and saltwater intrusion from the sea (Le et al., 2018).

Due to droughts, low elevation, deepening of the riverbed by sand mining activities and sea-level rise, saltwater can intrude far into the land through river branches and thus reduces the freshwater availability (e.g., Eslami et al., 2019). Normally, saline surface water (salinity >4 g/L) can be detected up to 60 km upstream from estuaries of the Mekong River branches (Fig. 13.1a). However, during the severe droughts of the years 2016 and 2020, saline surface water has moved up to even 93 and 110 km in land, respectively (Park et al., 2021). During these severe salinization and drought events, people in the coastal areas faced severe freshwater shortages, driving an increase in groundwater abstraction.

Land use and land cover in the VMD has undergone tremendous changes due to population growth and economic development. By analyzing satellite images from 1979 to 2015, Liu et al. (2020) show that the proportion of planting land in the VMD decreased from 80% in 1979 to 72% in 2015, respectively. Meanwhile, the area of aquaculture practices has increased and covered about 19% of the VMD area in 2015. The residential land also increased more than 10 times from 1979 to 2015 (Liu et al., 2020).

13.2.2 Geology

According to a geological survey of Southern Geology and Mapping Division of Vietnam (SVGMD, 2004), the unconsolidated sediment of Neogene and Quaternary age is covered on top of the basement rock. The sediment layer thickness varies from 200 m in An Giang province to 300 m in Ca Mau province and about 500 m in Tien Giang province. In Tra Vinh province, the thickness of unconsolidated sediment is even up to 2200 m. The sediment layers include geological formation from Holocene to

Miocene age. The sediment generally consists of medium to fine sand, silt, and clay. Organic matter is also commonly observed in the sediments. The clay layer of Holocene sediment is characterized by soft and rich organic matters (Giao et al., 2014; Thoang and Giao, 2015). The average initial void ratio and unit weight of Holocene clay sediments are about 2.23 and 1.48 ton/m^3 (Thoang and Giao, 2015). In contrast, clay sediment of Upper Pleistocene and deeper parts generally classified into stiff and very hard level. The average of initial void ratio and unit weight of Pleistocene and Pliocene sediment are generally greater than 1.93 and less than 0.73, respectively (Thoang and Giao, 2015). The sand is from medium dense to dense condition. Therefore, high buildings are preferred to install foundations up to depths from 50 to 80 m (de Wit et al., 2021).

13.2.3 Hydrogeology

Basically, the multilayered aquifer system in the VMD has an alluvial basin structure (SVGMD, 2004). The groundwater system in the VMD is divided into eight hydrogeological units including Holocene, (upper, upper-middle, lower) Pleistocene, (middle and mower) Pliocene, and (upper, upper-middle) Miocene (Fig. 13.1c and d; Table 13.1). These aquifers are located below land surface around 0−49 m, 31−193 m, 153−381 m, and 275−550 m, for Holocene, Pleistocene, Pliocene, and Miocene formations, respectively. Each hydrogeological unit comprises two parts: a part that is composed of low permeability silt, clay or silty clay (aquitard); and a part, the underlying part that is more permeable and is composed of fine to coarse sand (aquifer). Holocene sediments (qh) outcrop almost the whole VMD (Fig. 13.1c and d). The Holocene aquifer mostly contains saline or brackish groundwater. Upper-middle Miocene (n_1^{2-3}) is the deepest confined aquifer in the Mekong River Basin, and it is directly overlying Mesozoic bed-rocks. Hydrogeological characteristics and groundwater potential of this unit are still under-discovered (this kind of information is limited due to not many drillings).

13.3 Dynamic of groundwater system in the Vietnamese Mekong Delta

13.3.1 Groundwater use

The groundwater abstraction in the VMD region increased significantly from 140,000 m^3/day in 2001 (Wagner et al., 2012) to approximately 1.92 million m^3/day in 2010 (Fig. 13.2; Bui et al., 2015). The groundwater is

Table 13.1 Hydrogeological characteristics of six out of eight major aquifers in the VMD (the aquifers qh and $n_1^{2,3}$ are not shown here).

Aquifer	Total area	Average of aquifer thickness (m)	Average specific yield, μ (–)	Average specific storage, μ^* (–)	Average horizontal hydraulic conductivity (m/day)	TDS (g/L)	Saline groundwater area (km^2)	Groundwater abstraction rate in 2010 (m^3/day)
qp^3	39,468	29.14	0.2	0.0047	20.6	0.04–20.4	28,974	**114,945**
$qp^{2,3}$	39,279	41.45	0.19	0.0032	21.2	0.05–33.7	24,338	**977,514**
qp^1	39,340	38.16	0.18	0.003	24.7	0.04–21.5	25,694	**130,077**
n_2^2	36,267	51.33	0.18	0.0003	19.7	0.04–31.0	22,253	**477,359**
n_2^1	34,546	53.78	0.17	0.00005	13.6	0.09–22.0	18,277	**87,652**
n_1^3	31,560	58.79	0.15	0.00005	9	No data	2117	**118,235**

Based on Bui, T.V., Dang, T.L., and Le, T.M.V., 2015. Groundwater issues and hydrogeological survey of the Mekong River basin in Vietnam. In: Ha, K., Nguyen, T.M.N., Lee, E., and Jayakumar, R. (Eds.), Current Status and Issues of Groundwater in the Mekong River Basin. KIGAM-CCOP-UNESCO Bangkok Office, pp. 93–121.

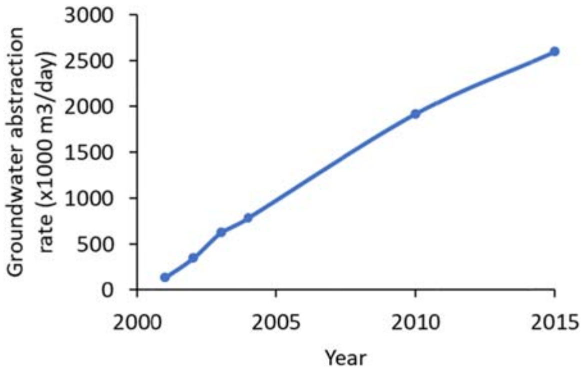

Figure 13.2 Groundwater abstraction in Mekong Delta. *(Data from 2001–04 and 2010 collected from Wagner, F., Tran, V.B. and Renaud, F.G., 2012. Groundwater resources in the Mekong Delta: availability, utilization and risks. In: The Mekong Delta System (pp. 201–220). Springer, Dordrecht and Bui, T.V., Dang, T.L., and Le, T.M.V., 2015. Groundwater issues and hydrogeological survey of the Mekong River basin in Vietnam. In: Ha, K., Nguyen, T.M.N., Lee, E., and Jayakumar, R. (Eds.), Current Status and Issues of Groundwater in the Mekong River Basin. KIGAM-CCOP-UNESCO Bangkok Office, pp. 93–121, respectively; data in 2015 is collected from Division for Water Resources Planning and Investigation for the South of Vietnam.)*

mainly abstracted out of the aquifers $qp^{2,3}$ and n_2^2 with rates of ~980,000 and 480,000 m^3/day, respectively (Table 13.1, last column; Bui et al., 2015). According to DWRPIS data, the groundwater abstraction rate still increases sharply in recent years in coastal area and dense cities. For instance, the withdrawal rates in Ca Mau and Tra Vinh provinces have increase 2.7 and 1.4 folds from 2010 to 2015; the annual groundwater abstraction rate in Can Tho City increased about 16% per year during 2010–17. Only An Giang province, the groundwater abstraction rate reduced from 94,000 m^3/day in 2010 to 30,000 m^3/day in 2015.

Due to a lack of freshwater in the dry season, groundwater is used for various purposes, including domestic, agricultural, aquaculture, and industrial activities (Fig. 13.3). According Bui et al. (2015), the proportion of groundwater used for agriculture is high in coastal area. Note that the amount of groundwater abstraction for aquaculture is not counted in the data.

In the early 2000s, most dug wells and tube wells with a depth of 80–120 m are UNICEF-made types. They are the most popular type of groundwater pumping for domestic uses in the VMD (Danh, 2008, Dinh et al., 2015). In the period 1998–2002, the number of wells used for domestic purposes almost doubled in some rapidly developing areas as Can

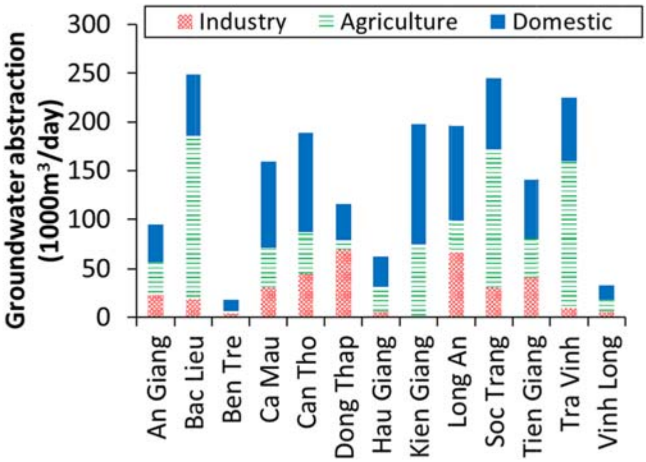

Figure 13.3 Groundwater use for difference purposes in the Mekong Delta. Note: Groundwater used for aquaculture is not present in these data. *(Based on Bui, T.V., Dang, T.L., and Le, T.M.V., 2015. Groundwater issues and hydrogeological survey of the Mekong River Basin in Vietnam. In: Ha, K., Nguyen, T.M.N., Lee, E., and Jayakumar, R. (Eds.), Current Status and Issues of Groundwater in the Mekong River Basin. KIGAM-CCOP-UNESCO Bangkok Office, pp. 93–121.)*

Tho city (Danh, 2008). Groundwater abstraction wells at freshwater supply plants that reaches depths of 200–450 m below MSL (corresponding Pliocene and Miocene aquifers) are mainly used for industrial areas or water supply stations as part of the Rural Clean Water Supply Program (Wagner et al., 2012; Dinh et al., 2015). According to the statistic from Bui et al. (2015), the VMD has around 553,135 groundwater wells in which only 932 wells were licensed for exploitation with capacity higher than 200 m^3/day. It is very difficult to record the exact number of small private wells because they are installed without any license or permission. However, the number of wells seems to increase. For examples, the number of wells in Tra Vinh province increased from 90,000 wells in 2010 to 150,000 wells in 2017 (DWRPIS, 2018). Nguyen et al. (2018) referred from data of the Center of Clean Water and Environmental Sanitation in Rural Areas of the VMD, total number of small wells in the VMD was 779,503 (in 2015).

Although regulations on groundwater management have been promulgated, strategies and approaches to groundwater development still have faced many barriers due to gaps in assessment of potential or sustainable groundwater exploitation (Boehmer, 2000). Since 2015, water resource planning in Vietnam has been focused more on groundwater resources but still relatively minor actions have been adopted to promote sustainable groundwater development. In Vietnam, large-scale groundwater wells of supply units and industrial zones need licenses for construction and operation based on the "Law on Water Resources", approved in 1998 and the recent version issued in 2012 by the Vietnamese government. However, local authorities usually meet many difficulties in implement these regulations due to low capacity and consistency (Danh, 2008; IUCN, 2010).

13.3.2 Groundwater pressure head decline

Groundwater pressure head in the Mekong Delta is in declining trends (DWRPIS, 2015, Table 13.2). During the 1960s, groundwater pressure heads were generally equal to the land surface (Anderson, 1978). According to the data of the National Groundwater Monitoring Network for the

Table 13.2 Groundwater pressure head in meter with repect to the land surface 1995 and in 2015 over the different aquifers in the Mekong Delta.

	1995			2014		
Aquifer	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**
Holocene (qh)	−1.4	−3.0	−0.3	−2.1	−7.7	−0.3
Upper Pleistocene (qp^3)	−2.7	−5.1	−0.8	−4.5	−9.0	−1.3
Upper-middle Pleistocene ($qp^{2,3}$)	−3.4	−11.3	−0.5	−8.5	−39.0	−2.3
Lower Pleistocene (qp^1)	−3.2	−8.6	−0.2	−7.4	−24.1	−1.9
Middle Pliocene (n_2^2)	−3.2	−11.4	0.0	−10.0	−29.7	−2.3
Lower Pliocene (n_2^1)	−2.5	−5.8	0.0	−8.8	−18.6	−4.6
Upper Miocene (n_1^3)	−1.3	−4.1	1.3*	−10.5	−23.0	−4.4

Based on NGMNS; DWRPIS, 2015. Annual Report on the National Groundwater Monitoring Network for the Southern Vietnam. Division of Water Resources Planning and Investigation for the South of Vietnam (in Vietnamese).

Southern Vietnam (NGMNS) in 1995, some abstraction wells were even artesian, with groundwater pressure heads higher than the land surface (Table 13.2). According to monitoring data, the overall variabilities of the declining trends of groundwater pressure heads confirm a decline rate of 0.09–0.78 m/year (Erban et al., 2014). The trend of groundwater pressure head varies per aquifer. The shallow Holocene aquifer shows a stable trend since the beginning of data collection in 1996, being the result of a close hydraulic connection with the surface water bodies (Mekong River network) and rainfall recharge as well as the compaction of the young sediments composing the aquifer (Wagner et al., 2012; Le et al., 2021). In general, groundwater pressure heads in the Holocene aquifer are smaller than 7.7 m below MSL in 2014 (Ha et al., 2019a).

In contrast, the rapidly decline trend of groundwater pressure heads is observed in both Pleistocene aquifers and up to 0.45 m/year at some groundwater supply stations of Tra Vinh province from 1996 to 2017 (Van and Koontanakulvong, 2019). The drawdown of groundwater pressure heads in Pliocene and Miocene aquifers shows an average of high rates (0.3–0.5 m/year) throughout the whole VMD region (Le et al., 2021). But the rates are even higher in urban areas with high population densities such as Can Tho and in coastal provinces such as Ca Mau, Bac Lieu, and Tra Vinh with less availability of fresh surface water resources (Van and Koontanakulvong, 2019; Le Duy et al., 2021).

A nonparametric time-series decomposition approach on the dataset of observed groundwater pressure heads in the VMD from 1996 to 2017 (22 years) also showed that groundwater exploitations highly exceeded groundwater replenishment by difference sources like rainfall recharge and river water influxes, resulting in a considerable decline of groundwater pressure heads and fresh groundwater volumes in the VMD over this period (Pham et al., 2019; Le et al., 2021) and consequently, to the widespread land subsidence in the VMD (Erban et al., 2014; Minderhoud et al., 2017, 2020). Similar trends can be seen in many other deltas and coastal areas around the world (Gambolati and Teatini, 2015).

13.3.3 Salinization of groundwater

The fresh, brackish, and saline groundwater distribution (in total dissolved solid [TDS], for example, for saline groundwater >1 g TDS/L) is widely observed in the VMD (Ha et al., 2019a, 2022a). The TDS levels of the groundwater samples in NGMNS range of 0.04–20.4, 0.05–33.7, 0.04–21.5, 0.04–31.0, and 0.09–22.0 g/L in the qp^3, $qp^{2,3}$, qp^1, n_2^2, and

n_2^1, respectively (Table 13.1). Ha et al. (2022a) show that about 66% of total (n = 191) groundwater samples collected in NGMNS in 2014 is saline (Ha et al., 2022a). The saline groundwater was also observed in many private wells in Long An, Dong Thap (Ha et al., 2019b), Soc Trang (Ha et al., 2021; Tran et al., 2021), and Ca Mau provinces (Ha et al., 2022b) and make them unsuitable for drinking purpose (Ha et al., 2022a, 2022b).

According to the data of Bui et al. (2015), the area of saline groundwater is the largest in the Upper Pleistocene aquifer (qp^3), while in other aquifers, saline groundwater also widely covers from 54% to 62% of the aquifer surface areas (Table 13.1). In the recent study of Gunnink et al. (2021), all existing salinity data from DWRPIS are geostatistically processed into a 3D groundwater salinity distribution in the entire VMD, see Fig. 13.4. Also, fresh groundwater volumes are given per province per aquifer, including uncertainties because the salinity and geological data are not always equal accurate. Results yield an estimated fresh groundwater volume for the VMD of 867 km^3 with an uncertainty range of 830–900 km^3. Though this is soundly huge in compared to the yearly groundwater abstractions, but at a local scale, severe upconing of saline groundwater can easily happen.

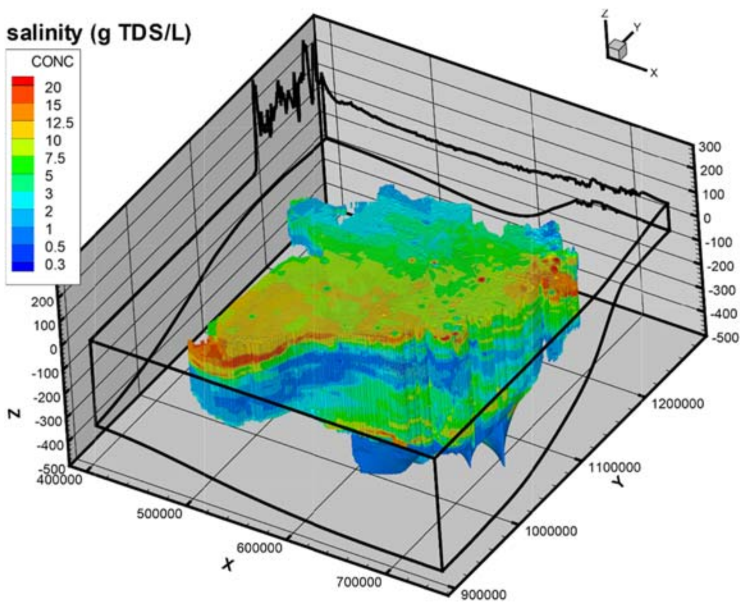

Figure 13.4 Fresh, brackish, and saline groundwater in the Mekong Delta. *(Drawn based on data of Gunnink et al. (2021).)*

Due to the dominant presence of saline groundwater in the VMD, fresh groundwater is susceptible to salinization (Ha et al., 2022a). In addition, the sea-level rise is a considerable threat of groundwater salinization. In a paleo-hydrogeological reconstruction of the VMD using a conceptual model over the past 60 ka (Pham et al., 2019), it is shown that when land is flooded by seawater, the saline seawater can rapidly infiltrate and salinize the aquifer. Other causes of groundwater salinization on a local scale are also possible, such as interaquifer flow, leakage from salt farming (e.g., at aquacultural areas), and return flow from agricultural activities (Ha et al., 2019b, 2022a). The reason of groundwater salinization is likely also related to the increase of groundwater abstractions in the last decades. The intensive groundwater abstraction in VMD has continuously declined groundwater pressure head and thus, increased the hydraulic gradient of areas with saline groundwater resources with respect to fresh groundwater areas, causing salinization due to advection and hydrodynamic dispersion (Tran et al., 2021). Recent climate change and sea-level rise consequences are expected to affect the degree of groundwater salinization, directly due to decreasing of rainfall recharge rates, and saltwater intrusion from the sea or indirectly by the increase of groundwater abstractions (Taylor et al., 2013; Ferguson and Gleeson, 2012; Mabrouk et al., 2018).

13.3.4 Other contaminations

In addition to the issue of salinization, groundwater quality is at an alarming rate of contamination with heavy metals such as As, Fe, Mn, Cd, Al, and NH_4^+ (Ha et al., 2019a; 2022a, Table 13.3). According to 379 samples collected within NGMNS, about 19.6% of the samples are As-rich groundwaters with an average value of 13.1 μg/L. The highest As concentration observed in the NGMNS database is 871 μg/L and even higher being at 1470 μg/L as reported by Erban et al. (2013). The extremely high As concentrations (>100 ug/L) are only observed in An Giang and Dong Thap provinces located adjacent to the Mekong River (Erban et al., 2013; Buschmann et al., 2008, Hoang et al., 2010; Nguyen and Itoi, 2009). Erban et al. (2014b) investigated groundwater samples from more than 40,000 wells and also found out that the highest As concentrations became significantly lower when the wells were located further from the river or closer to the coastal areas. As-rich groundwater is generally observed in shallow aquifers containing Holocene sediments near to the Mekong River, while groundwaters from deep and confined aquifers are usually safe with regard to As contamination. This observation suggests that As is likely to be

Table 13.3 Trace metals concentration in groundwater during 1990–2014.

Parameters	N	Average	Median	Range	Exceedance of WHO DWS (%)	WHO DWS
As (μg/L)	397	13.1	2.56	ND–871	19.6	10
Fe (mg/L)	4184	13.3	0.07	ND–1680	12.4	0.5
Mn (mg/L)	388	0.92	0.21	ND–25	36.9	0.4
Al (mg/L)	3715	0.05	0.001	ND–4.28	4.74	0.2
Cu (μg/L)	398	21.6	1.26	ND–5870	0.25	2000
Pb (μg/L)	398	3.87	0.01	ND–840	4.27	10
Zn (μg/L)	398	46.1	8.29	ND–4390	0.25	3000
Hg (μg/L)	398	0.17	0.01	ND–4.85	0	6
Cd (μg/L)	398	1.27	0.55	ND–11.8	13.6	3
Se (μg/L)	319	1.23	0	ND–41.7	0.31	40
Ni (μg/L)	265	5.43	2.13	ND–326	0.75	70
Cr (μg/L)	398	2.93	0.6	ND–91.9	0.5	50
NH_4^+ (mg/L)	4184	5.69	0.28	0––312	30.8	1.5
NO_3^- (mg/L)	4183	3.23	1.07	0–132	0.8	50

Based on NGMNS; DWRPIS, 2015. Annual Report on the National Groundwater Monitoring Network for the Southern Vietnam. Division of Water Resources Planning and Investigation for the South of Vietnam (in Vietnamese).

originated mainly from geologic origins, including soil and minerals containing a substantial amount of As. These sediments, in the reducing environments triggered by decomposition of organic matter, are able to be dissolved easily and release As into groundwaters as a result. This process is well supported by the geochemical characteristics of As-rich groundwaters, which show positive correlations between concentrations of As and other parameters including Fe, DOC, NH_4^+, or PO_4^{3-} as well as a negative correlation between As levels and Eh values (Buschmann et al., 2008; Nguyen and Itoi, 2009; Hoang et al., 2010). Reid et al. (2021) found that there is a relationship between As concentration in groundwater and grain inorganic As. They suggested that the surficial sediments with high concentrations of soluble and plant-available As may release arsenic to down-gradient shallow aquifers via rainfall recharge. In addition, As-bearing pyrite is another possible source of As, which can introduce As into groundwater through pyrite oxidation in the oxidizing condition (Nguyen and Itoi, 2009).

Iron, manganese, and many other trace metals are also observed in the NGMNS as well as previous studies carried out in the VMD (Buschmann et al., 2008; Nguyen and Itoi, 2009; Hoang et al., 2010; Ha et al., 2019a, 2019b). Iron and manganese have been widely observed in groundwater samples that are collected from the study area, with the highest concentrations of iron (1680 mg/L) and manganese (25 mg/L). According to the NGMNS dataset of DWRPIS, over 12.4% and 36% of the groundwater samples taken from monitoring wells in southern Vietnam contain Fe and Mn concentrations that exceed the WHO permissible levels for drinking water of 0.3 mg/L for Mn and of 0.3 mg/L for Fe. The 112 groundwater samples that Buschmann et al. (2008) collected from southern Vietnam show Fe-rich and Mn-rich groundwaters, with percentages of 33% and 80% of the total number of samples, respectively. These observations clearly show that Fe and Mn contaminations are serious in the VMD. It is apparent that Fe and Mn are two of the most abundant metals in Earth's crust; therefore, they occur naturally in soil, rocks, and minerals, even though Mn is, in fact, much less available in comparison to iron (Appelo and Postma, 2005). As a result, in the reducing environment which is typical for most aquifers, the reductive dissolution of Fe and Mn—contained oxides or minerals can easily release Fe, Mn, and other trace elements (especially Arsenic) into groundwater (Nguyen and Itoi, 2009; Hoang et al., 2010). In addition, pyrite oxidation occurring in the oxidizing condition may also contribute significantly to the elevated Fe levels (Nguyen and Itoi, 2009; Ha et al., 2019b).

Considering other trace metals including Al, Cu, Pb, Zn, Hg, Cd, Se, Ni, and Cr, which are commonly not well studied in the VMD, the NGMNS dataset from DWRPIS (2015) showed that 13.6% of the total groundwater samples show Cd concentration exceeding WHO guidelines for drinking waters, following by Al and Pb with about 5% of all the samples, while the WHO exceedance rates for other metals in the samples are less than 1%. However, it is also noticeable that many groundwaters with extremely high levels of these metals are observed, suggesting that the contamination of these heavy metals seems to be serious in specific areas and should not be overlooked. In addition, some exceptionally high concentrations of other metals including Cu with 5.87 mg/L and Zn with 4.39 mg/L are also observed. Ha et al. (2019a) suggested through executing leaching experiments and analyzing data that these elevated values could be the result of the acidification process, which causes acidic groundwater and enhances the solubility of metals as well as the dissolution of minerals.

As consuming drinking waters with high nitrate levels can exacerbate a risk to human's health, WHO set a guideline value of 50 mg/L for nitrate (NO_3^-). The NGMNS dataset from DWRPIS shows that nitrate contamination is not so serious in the VMD, with average values being at only 3.23 mg/L and the exceeding WHO guidance rate being very low (less than 1%). It is also interesting that most NO_3^--rich groundwaters with the highest level of 132 mg/L typically resides in Holocene aquifers with shallow depths, indicating that they are certainly influenced by anthropogenic sources such as agricultural activities. Unlike nitrate, ammonium (NH_4^+) does not cause health problems in a direct way, but it can affect the removal of manganese in water and cause odor problems when its concentration more than 1.5 mg/L (WHO, 2017). Among more than 4000 data from DWRPIS, about 30.8% of groundwater samples show NH_4^+ level exceeding this value with the average concentration of 5.69 mg/L, suggesting that this is also a concerning problem when this groundwater source is used for drinking purposes. Finally, it is surprising that an exceptionally high value of 312 mg/L is also recorded for NH_4^+ in the VMD. The main reasons for this elevated level of ammonium could be the natural process, especially the decomposition of organic matter (Buschmann and Beg, 2009) and/or anthropogenic activities (Nguyen et al., 2012).

13.3.5 Land subsidence

Site-specific land subsidence is a commonly observed phenomenon in the VMD, posing damages to the infrastructure such as roads, buildings, pavements, and bridges. However, regional land subsidence in the VMD was recognized for the first time by Erban et al. (2013), which deployed InSAR-derived estimates of subsidence. After that, other publications also found high rates of land subsidence in VMD. Erban et al. (2013, 2014) estimated land subsidence rates of 10–40 mm/year after analyzing satellite images over the period 2006–2010. Minderhoud et al. (2020b) estimated that, according to the ESMN-057 and ESMN-062 datasets using PS InSAR, land subsidence rates over the period 2014–19, subsidence in the VMD substantially increased over that 10-year period, with subsidence rates locally as high as 60 mm/year (ESMN-057, 2018; ESMN-062, 2019). The observation land subsidence rates are comparable to the direct in-situ measurements by Lovelock et al. (2015) in Ca Mau cape and Mekong River mouths and by Karlsurd et al. (2020) in Ca Mau and these measurements are similar to observations of the Vietnamese government (MONRE) during the period 2005–2017 by a survey of national benchmarks (reported in Minderhoud et al., 2020b).

The spatial analysis of Minderhoud et al. (2018) showed that land subsidence rates vary for different land-use types in the VMD. The rate is high in urban area with a high density of buildings and infrastructure; with highest rates observed in cities centers, for example, Ca Mau, Can Tho, Tra Vinh, and My Tho (Yan et al., 2020). However, in the rural areas and fruit forest areas, the land subsidence rates are considerably larger than the "background subsidence rates" of ~6 mm/year, which was observed in natural areas with limited human influence (Minderhoud et al., 2018). Another recent study by de Wit et al. (2021) revealed that urban differential subsidence rates are variable for different building types. Large buildings normally experience much less subsidence than their surroundings. This is because large buildings are usually foundation piles nested into deeper sandy layers, while the smaller buildings and roads and infrastructure have little to no foundation. Therefore, they experience also compaction happening in the shallow, soft Holocene sediments, which are well-known for their high compressibility (Zoccarato et al., 2018; Karlsrud et al., 2020), which is also recognized around the world (Tornqvist et al., 2008; Shirzaei et al., 2020). Lovelock et al. (2015) measured shallow compaction rates in the first 20 m in coastal mangrove forests the most southern point of the VMD as high as ~40 mm/yr. Zoccarato et al. (2018) showed that these high rates could be a result of natural compaction as the highly compressible and recently deposits sediments are still experiencing high rates of "autocompaction" as a result of overlying sediments. However, the mangrove forests observed by Lovelock et al. (2015) are not losing elevation as annual deposition rates go up to ~60 mm/yr, allowing the mangroves at the monitoring locations to build elevation with respect to sea level by trapping new sediments. However these observations may be biased, as the monitoring stations are only located in pristine mangrove forests, and other, unobserved, mangroves along the coast have been reported to disappear, presumably by the combination of coastal erosion (Anthony et al., 2015) and land subsidence. As such the exceptional situation of extremely high shallow compaction and sedimentation rates is likely only representable for a small portion of the VMD's coastline and it is for sure not representable for the interior of the delta as natural (auto)compaction rates rapidly decrease several kilometers in-land (Zoccarato et al., 2018; Minderhoud, 2019; Dunn and Minderhoud, 2022).

Also other natural and human-induced processes may contribute to subsidence in the VMD. For example, deep-rooted natural subsidence drivers are tectonics, natural compaction of Quaternary units, and isostatic adjustment (Minderhoud et al., 2015; Shirzaei et al., 2020). In the VMD, their contribution to subsidence have been quantified in the order of a few mm/yr over the late-Holocene (Nguyen et al., 2000). A study by the SVDGM suggested extremely fast neo-tectonic movements up to several cm/yr (Do et al., 2015) is incorrect as it suffers from erroneous measurement interpretation. In their interpretation of the vertical motion of unfounded surface benchmarks compaction of unconsolidated material as a result of other processes, for example natural compaction, or extraction-induced compaction was neglected, thereby ascribing all subsidence wrongly to neotectonics. A spatial residual analysis on InSAR also did not reveal any correlation between subsidence rate or pattern and known locations of tectonics faults (Chapter 7 in Minderhoud, 2019). Additionally, oil and gas exploitation can also drive subsidence and areas offshore of the VMD are undergoing seismic exploration and initial drilling (Allison et al., 2017). If exploitation starts close to the VMD, future hydrocarbon explorations may contribute as well to the deltas' subsidence. However, at present, deep-rooted subsidence plays only a minor role in the present-day subsidence rates in the VMD.

The effects of drainage-driven shallow compaction and aeration-triggered oxidation of organic matter on subsidence in the VMD have not been studied in detail yet but have been suggested to play a role given different subsidence rates occurring for different land-use types (Minderhoud et al., 2018). Examples of these processes driving shallow compaction are found in the Rhine-Meuse (The Netherlands) (van Asselen et al., 2009;

Koster et al., 2018) and Po (Italy) (Zanello et al., 2011) river deltas and may create rates >10 mm/yr when water tables are lowered in organic-rich peatlands.

At delta scale, many studies have identified groundwater abstraction to be the underlying cause of the present-day high land subsidence rates in the VMD (Erban et al., 2013, 2014; Minderhoud et al., 2017, 2020; Minderhoud, 2019; Karlsrud et al., 2020), as the steady decline of groundwater pressure head increasingly causes the thick aquifer-system of the VMD to compact. A recent study used residual water-level data from 11 tide- and water-level monitoring stations ato create independent observations of VLM (Nguyen et al., 2023). These finding independently validated the previous modelled magnitude and acceleration of extraction-induced subsidence (Minderhoud et al., 2017, 2020a), underscoring groundwater depletion as main delta-wide driver of subsidence. Together with natural shallow compaction, predominantly at the coast, and potentially the effect of surface water drainage, groundwater extraction is what currently drives the majority of the relative sea-level rise in the VMD and threatens the future of the VMD.

13.4 Recommendations for groundwater management to minimize land subsidence

According to Poland (1984), methods to control land subsidence include among others reduction of groundwater exploitation, artificial recharge of aquifers, or combination of this technique. Several techniques can be applied for minimizing groundwater exploitation. For examples, in Thailand, the Chao Phraya River basin has similar geological conditions to the VMD with thick sediment layer (>500 m) and clay-rich organic matter on the top of the geological strata (Lorphensri et al., 2011). Since 1977, the basin has dealt with serious land subsidence by groundwater abstraction. The land subsidence rate has been up to 100 mm/year during the period 1978–1981 with a maximum recorded settlement of 100 cm during the period 1978–1999. According to Lorphensri et al. (2011), the Thailand government set a series of management actions such as not allowing new pumping wells, creating groundwater critical zones, and providing a groundwater tariff and conservation task. As a result, since 2000, groundwater abstraction is controlled at a sustainable rate of 1.2 million m^3/day, while the land subsidence rate has been reduced from 10 to <1.3 cm/year since 2000. Other examples of successfully reducing land subsidence can be found in USA, where surface water has been transferred from other areas to minimizing groundwater abstractions at the area of interest (Poland, 1984). According to Sato et al. (2006), in Tokyo, Japan, groundwater abstractions have not only been restricted, but also infiltration rates of surface water have been increased. As a result, in Tokyo, the land subsidence rate has been reduced from 20 cm/year during the 1970s to almost zero in recent years (Sato et al., 2006). In Shanghai, water injection through wells techniques has been applied to compensate land subsidence and groundwater (Shi et al., 2016).

In the VMD, several studies also suggest to reduce groundwater abstraction to minimize land subsidence and groundwater salinization (Erban et al., 2014a; Karslrud et al., 2018/2020; Minderhoud et al., 2017, 2020a; Minderhoud, 2019;Kondolf et al., 2022). In cities centers at the upstream provinces such as An Giang, Dong Thap, and Can Tho, the reduction of groundwater pumping could be easily executed as a fresh surface water supply system is available. However, in the rural and especially coastal provinces such as Ca Mau, Soc Trang, and Bac Lieu, this approach is difficult due to the lack of fresh surface water supply system as well as due to the contamination of surface water. For instance, 100% of the freshwater supply in the Ca Mau province comes from the groundwater resource. Moreover, the groundwater demand is expected to increase due to economic development, climate change, and sea-level rise. Therefore, to reduce groundwater pumping, the coastal areas may need to save groundwater from unimportant uses. A lot of groundwater is used for agriculture such as irrigation and aquaculture production in coastal areas. Water savings by smarter irrigation techniques are another solution to reduce groundwater abstraction. Furthermore, the reuse of wastewater as a reclamation water regulation strategy may also provide possible options for water stressed areas.

In the coastal zone, the reduction of groundwater abstraction could also be achieved by conjunctive use of groundwater, surface water, and rainwater. This may be the effective approach to increase the efficiency of freshwater management. The VMD has intensive rainfall and a large amount of fresh surface water in the rainy season. Annual precipitation is high (~2000 mm), of which 90% of precipitation occurs in the rainy season. Meanwhile, the Mekong River brings an abundant flow of 4.5 km^3/year to the VMD. However, in the past, local people have collected rainwater from house roofs and stored in water tanks for later use. But this technique has increased mosquito numbers in their houses leading to dengue (Tran et al., 2010). In order to promote rainwater harvesting as an option means, the collection technique has to be improved while it remains difficult to convince local people (Bui et al., 2019). Other attempts in the VMD aim to store fresh water in surface water reservoirs, such as dug ponts. However they have been reported to suffer from contamination by salt and polutants, or create undesired side-effects, such as actively draining and evaporating nearby shallow groundwater reserves (Oude Essink et al., 2022). As the VMD has one of the flattest delta plains in the world (Minderhoud et al., 2019), there is little vertical relief to capture and store excess fresh water.

Fresh surface water can also be stored below ground in natural, sand-rich geological layers (high porespace) like buried beach ridge systems and the underlying aquifer system, even when saline, during rainy season for later use (Fig. 13.5). There are many techniques to apply this concept called "managed aquifer recharge" (Dillon et al., 2019; Zheng et al., 2021). When applied sucessfully it can close the gap between water supply and demand in space and time and prevent land subsidence and salinization by using brackish groundwater for freshwater production. A well-known technique is called "aquifer storage and recovery." This technique is a cost-effective method for storing water because no big reservoir and storage sites are available. Nguyen et al. (2011) have conducted a rainwater injection test in the fresh groundwater aquifers in the Ho Chi Minh City area. They found that this technique is suitable and could be a feasible solution to reduce the freshwater stress and for a sustainable water management.

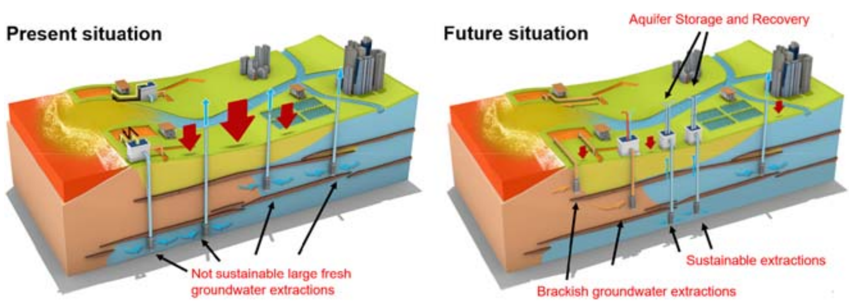

Figure 13.5 The concept of some managed aquifer recharge techniques: Aquifer Storage and Recovery in the Vietnamese Mekong Delta. *(Adapted from Oude Essink, G.H.P., Faneca Sànchez, M., Hùng, P.V., Quân, N.H., Minderhoud, P.S.J., Mahya, M., Jansen, S., Zimmel, G., Galvis Rodriguez, S., Van Halsema, G.E., Kruijt, A., Shakel, J., Bregman, S., Verduijn, H., Dinh, T., Jansen, S., Shankel, J., 2022. Freshwater Availability in the Mekong Delta (FAME). Deltares Rapport 11203362-001-BGS-0001 147.)*

However, Ha et al. (2018) also conducted a rainwater injection test in saline groundwater zone in Ho Chi Minh City area and observed the mobilization of trace metals (i.e., As, Fe, Mn). Other studies over the world also indicate that rainwater or surface water injection to the aquifer system can cause adverse impact on environments such as biological growth, clogging, reduction of permeability, and trace metal mobilization (e.g., Hartog and Stuyfzand, 2017). Nevertheless, these hydrogeochemical problems can often be solved. The high potential of managed aquifer recharge (MAR) is clear from the large increase in MAR projects that have successfully been implemented over the last 60 years in many areas of the world (Sprenger et al., 2017; Dillon et al., 2019; Zheng et al., 2021). However, it should be noted that with the current high rates of groundwater abstraction, MAR will not be feasible as a solution as such quantities cannot be reached.

13.5 Conclusions

This study summarizes previous studies on groundwater and land subsidence in the VMD. It shows that this economically important but very low-lying river delta faces many challenges by anthropogenic activities as well as natural changes. Over-exploitation of groundwater induces groundwater pressure head decline in many provinces driving salinization, trace metals contamination, and aquifer-system compaction. On top, climate change and sea-level rise puts additional stress on the groundwater system. Contaminations will affect human health as the groundwater in the VMD is also used for drinking water. Land subsidence in the VMD is caused by both natural causes and anthropogenic activities. Therefore, different strategies are required to deal with the different causes of land subsidence. Natural compaction cannot be stopped and is a process the VMD can only adopt to, for example, by compensating elevation loss by re-instating sedimentation (Dunn and Minderhoud, 2022). However, anthropogenic-induced land subsidence is dominantly driven by groundwater overexploitation. Therefore, the reduction of groundwater abstraction is a straightforward strategy to mitigate abstraction-induced subsidence. However, from a practical viewpoint, this is a challenge as alternative freshwater sources, such as surface water, are rather limited. For instance, in the coastal area, fresh surface water is not available during the dry season, and the availability of freshwater resources is further exacerbated in the context of climate change, relative sea-level rise, and increased salinity intrusion in the estuaries. Hence, we suggest that to abate groundwater abstraction by identifying alternative freshwater resources combined also with efforts to seriously reduce water demand, for example, by strict water management regulations and licensing. In addition, MAR techniques can be implemented in which the excess of water in the rainy season is stored in the aquifer system and later used during the dry season. The main message of this chapter is that fresh groundwater, a precious resource in the VMD, is rapidly becoming a scarce commodity under the threat of a spectrum of serious stresses, and therefore, it must be preserved and managed very carefully. A smart combination of reducing groundwater use by providing alternative water sources and water saving techniques, and subsurface solution such as MAR application in targeting areas where abstraction-induced land subsidence is most severe (e.g., Ca Mau city) could provide a feasible way forward for sustainable groundwater management in the VMD.

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