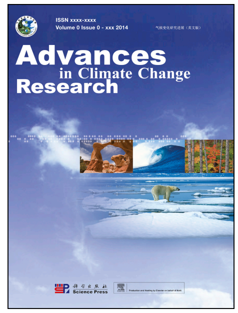

Saltwater intrusion into groundwater systems in the Mekong Delta and links to global change

Han Xiao, Yin Tang, Hai-Ming Li, Lu Zhang, Thanh Ngo-Duc, De-Liang Chen, Qiu-Hong Tang

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Review Article

Saltwater intrusion into groundwater systems in the Mekong Delta and links to global change

Han Xiao[1], Yin Tang[2], Haiming Li[1], Lu Zhang[3], Thanh Ngo-Duc[4], Deliang Chen[5], Qiuhong Tang[2,6*]

1. College of Marine and Environmental Sciences, Tianjin University of Science & Technology, Tianjin, China
2. Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
3. CSIRO Land and Water, Canberra, ACT 2601, Australia
4. Department of Space and Aeronautics, University of Science and Technology of Hanoi, Vietnam Academy of Science and Technology, Hanoi, Vietnam
5. Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden
6. University of Chinese Academy of Sciences, Beijing, China

*Corresponds to tangqh@igsnrr.ac.cn

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Saltwater intrusion into groundwater systems in the Mekong Delta and links to global change

XIAO Han[1], TANG Yin[2], LI Hai-Ming[1], ZHANG Lu[3], NGO-DUC Thanh[4], CHEN De-Liang[5], TANG Qiu-Hong[2,6*]

1. College of Marine and Environmental Sciences, Tianjin University of Science & Technology, Tianjin, 300457, China
2. Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
3. CSIRO Land and Water, Canberra, 2601, Australia
4. Department of Space and Aeronautics, University of Science and Technology of Hanoi, Vietnam Academy of Science and Technology, Hanoi, 10000, Vietnam
5. Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, 41296, Sweden
6. University of Chinese Academy of Sciences, Beijing, 100049, China

*Corresponding author: Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China. tangqh@igsnrr.ac.cn (Tang Q.-H)

Abstract

In recent decades, changes in temperature, wind, and rainfall patterns of Southeast Asia induced by climate warming in the Tibetan Plateau result in many environmental changes that have serious impacts on the lower reach of the Mekong River basin, a region already battling severe water-related environmental problems such as pollution, saltwater intrusion, and intensified flooding. In the densely populated Mekong Delta located at the mouth of the Mekong River basin in southern Vietnam, the hydrogeological systems have been transformed from an almost undisturbed to a human-impacted state and saltwater intrusion into surface water and groundwater systems has grown to be a detrimental issue recently, seriously threatening freshwater supply and degrading the eco-environment. In this article, the impacts of human activities and climate change (e.g., groundwater over-exploitation, relative sea-level rise, storm surge, changing precipitation and temperature regimes, uncontrolled drainage canals, operation of hydropower dams, and rapid development of aquaculture) on saltwater intrusion into groundwater systems in the Mekong Delta are briefly reviewed. Based on current status of research findings regarding saltwater intrusion and the subsequent groundwater quality degradation under the impacts of human activities and climate change, major knowledge gaps and challenges are identified and discussed, including thickness and permeability of the silt and clay aquitard, present-day highly heterogeneous 3D distribution of saline groundwater zones, dynamic variation of saltwater/freshwater transition zone, and the most effective and economical control measure. To bridge these gaps, future work should: 1) apply environmental isotope techniques in combination with borehole tests to gain detailed hydrogeological information regarding spatial variation of permeability and thickness of the silt and clay aquitard; 2) intensify regular groundwater monitoring and collect as much groundwater samples from multiple hydro-stratigraphic units at different depths as possible to visualize the present-day highly heterogeneous 3D distribution of saline groundwater; 3) develop a series of variable-density coupled groundwater flow and salt transport models representing various scenarios of human activities and climate change for predicting future extent of saltwater intrusion; and 4) identify the dominant factor causing saltwater intrusion and determine the most effective and economical engineering technique to address saltwater intrusion problems in the Mekong Delta.

Keywords**：** Human activity; Climate change; Saltwater intrusion; Groundwater system; Mekong Delta (southern Vietnam)

1. Introduction

The Mekong River stretches nearly 5000 km flowing from its source located at the Three Rivers Source National Nature Reserve high in the Tibetan Plateau in China along the borders of Myanmar, Laos and Thailand, through Cambodia and ending in Vietnam, forming the Mekong Delta (MKD) located at the mouth of the complex Mekong River basin in the southern part of Vietnam. The Tibetan Plateau, also often called the Third Pole, is considered the water tower of Asia because it is the source of many major Asian rivers. According to the Mekong River Commission for Sustainable Development[1], the upper reaches of the Mekong River are in the Tibetan Plateau and much of the upper Mekong River basin is snow-covered in winter while melting snow feeds the streamflow in the middle and lower reaches. Based on meteorological station data and remote sensing, the Tibetan Plateau is experiencing rapid warming and is currently in its warmest period in the past two thousand years and will continue to warm in future, which facilitates intense and broad glacier melting accompanied by lake expansion and water cycle intensification over the region (Liu and Chen, 2000; Chen et al., 2019; Yao et al., 2019). Due to significant

[1] https://www.mrcmekong.org/about/mekong-basin/climate/

warming and aridity change, severe environmental problems such as glacier retreat (Yao et al., 2004), desertification (Gao et al., 2015), precipitation increasing (Zhang et al., 2019), and intensified geo-hazards such as landslides and active debris flows (Wei et al., 2018) have been observed in the Tibetan Plateau in recent decades. Climate warming in the Tibetan Plateau affects the temperature, wind, and rainfall patterns of South Asia, resulting in many environmental changes greatly aggravating ecological problems in the lower reach of the Mekong River basin, a region already battling water pollution, saltwater intrusion, loss of aquatic biodiversity, and rising susceptibility to flooding (Kang et al., 2010; Yao et al., 2012; Chen et al., 2015). The changes in glacier and river streamflow on the Tibetan Plateau will lead to cascading impacts in downstream areas including the MKD (Tang et al., 2019a, 2019b).

According to the statistical data from General Statistics Office of Vietnam[2], the MKD is home to about 18 million people and produces about 56% of national rice yields which contributes substantial portion of national GDP (Vu et al., 2014). The surface water systems comprised of natural rivers (the Hau River, the Tien River, the Vam Co River, etc.) and artificial canals encounter serious problems of saltwater intrusion (SWI) especially during the dry season from November to April. Surface water salinity measurements at different locations in the dry season showed an annual increase of 0.2‰ over the last two decades (Eslami et al., 2019), and the situation is even worse in coastal region, since samples taken from coastal region showed higher salinity level (chloride concentration ranging from 8−9 kg m^{-3}) in comparison to those taken from inland region (chloride concentration ranging from 1−6 kg m^{-3}) (Pearse-Smith, 2012; An et al., 2014). For this reason, consumptive use of surface water becomes greatly limited, while groundwater serves as the primary freshwater supply source, meeting over 80% freshwater demand for agricultural, aquacultural, industrial, and domestic utilizations (Brennan, 2000; Bui et al., 2017). However, the occurrence of SWI into the groundwater systems in the MKD has been observed recently under the impacts of human activities and climate change, and has been recognized as a significant challenge to sustain the ever-increasing freshwater demand in this region, posing a great threat to freshwater supply and eco-environment safety (Smajgl et al., 2015; Nguyen et al., 2019; Tran et al., 2020).

In the Anthropocene, the terrestrial water cycle is undergoing rapid changes under the influence of multiple global change factors including climate change, land use/cover change, and human water use (Tang, 2020). As anthropogenic disturbance has reached unprecedented levels, global change can cause cryosphere melt on the Tibetan Plateau, hydrologic change in the river source regions, accelerated water resources development, groundwater pumping, and seawater intrusion. Globally, SWI into groundwater systems has been widely recognized as a critical issue of public concern, and many researchers worldwide have provided thorough reviews regarding its mechanism, pathway, and scope in Africa (Steyl and Dennis, 2010), Australia

[2] http://www.gso.gov.vn

(Werner, 2010), China (Shi and Jiao, 2014), Europe (Custodio et al., 2010), North America (Barlow and Reichard, 2010), Pacific Islands (White and Falkland, 2010), and South America (Bocanegra et al., 2010). The worldwide occurrence of SWI into groundwater systems are mainly induced by human activities (e.g., groundwater over-exploitation) and climate change (e.g., sea-level rise, storm surge, precipitation/recharge change, etc.) (Michael et al., 2013), and the main pathways of SWI include: 1) lateral intrusion from the sea and/or the surrounding saline waterbodies; 2) downward intrusion from overlying saltwater due to storm- and/or tidal-driven seawater flooding in coastal low-lying areas; and 3) upward intrusion from deep saline groundwater zones due to upconing beneath pumping wells (Bear et al., 1999; Yu et al., 2016, 2019).

Groundwater plays a key role in sustaining the communities and economies in most coastal areas in the MKD since groundwater is of great importance for water supply in populated cities and rural areas devoid of other reliable freshwater sources. Groundwater utilization has exponentially increased since the 1990s, resulting in groundwater depletion and water quality deterioration (e.g., SWI). Monitoring, control, and management work regarding SWI into groundwater systems have been initialized in the MKD, including theoretical studies, analytical analyses, laboratory tests, field experiments, as well as engineering measures. Although SWI problems have been of great interest for many researchers, there is a lack of an overview of this issue in the MKD. The objective of this study is to review recent research progresses upon SWI into groundwater systems in the MKD (southern Vietnam) in Southeast Asia in the context of human activities and climate change impacts, aiming at gaining a comprehensive and interdisciplinary understanding of their contributions. This review specifically focuses on: 1) hydro-climatic and hydrogeological characteristics of the MKD; 2) impacts of groundwater over-exploitation, relative sea-level rise, storm surge, changing precipitation and temperature regimes, uncontrolled drainage canals, operation of hydropower dams, and rapid development of aquaculture on SWI into groundwater systems in the MKD as well as their relative significance; and 3) current status of knowledge gaps and challenges in urgent need to be addressed regarding SWI studies in the MKD.

2. Hydro-climatic and hydrogeological characteristics

The MKD covering a total land area about 40,816.4 km^2 of fertile alluvial plain is located at the mouth of the complex Mekong River basin in southern Vietnam (see Fig.1), bounded by the South China Sea to the east and south, the Gulf of Thailand to the west, and the Cambodian border to the north (Tanabe et al., 2003; Carling, 2009). The MKD has very low land surface elevation ranging from 0.3−2.0 m above mean sea-level with very small topographic variation except for a few hilly areas and high coastal dunes existing in Kien Giang province, and is classified as a wave-influenced and tide-dominated delta (Ta et al., 2005; Eslami et al., 2019).

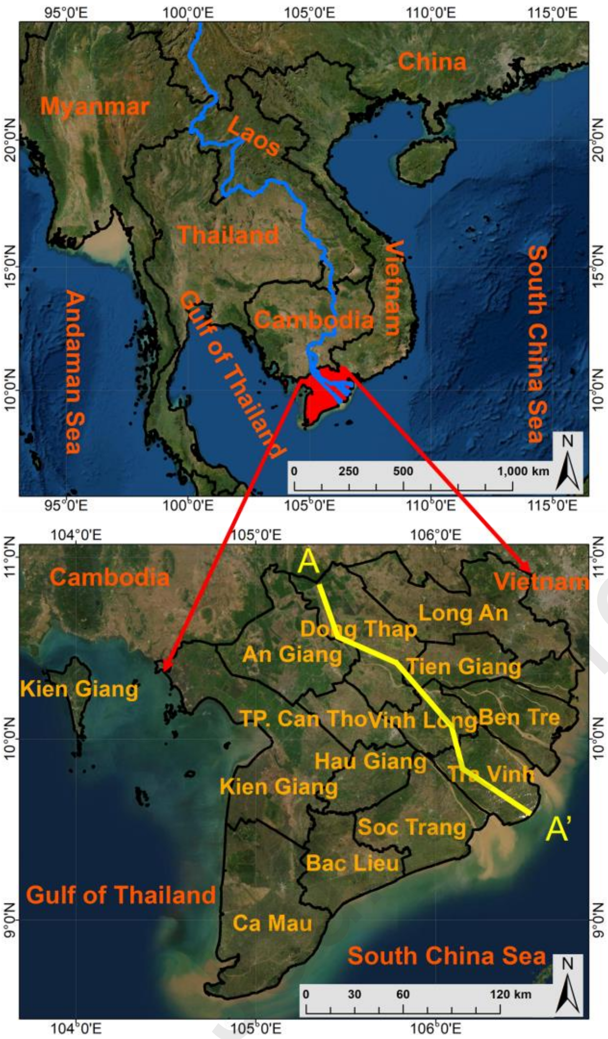


Fig. 1. Location of the Mekong Delta (MKD) in southern Vietnam (Line A–A' shows the location of the hydrogeological cross-section in Fig. 2).

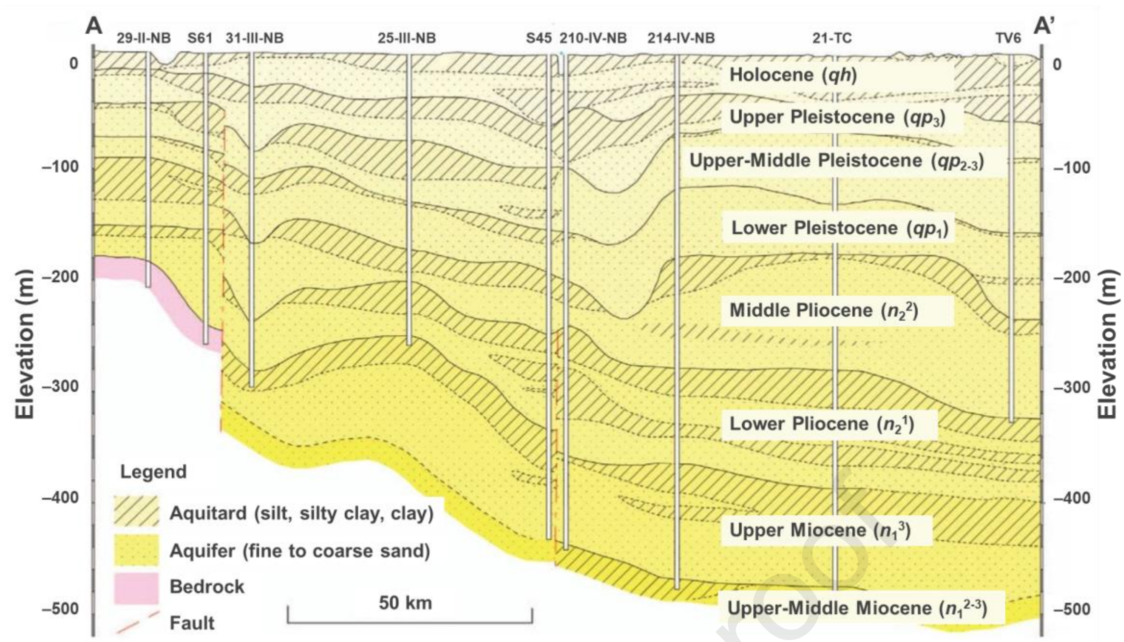


Fig. 2. Hydrogeological formations of the MKD with the interpretation of the main hydro-stratigraphic units (modified after Minderhoud et al., 2017).

The climate of the region is classified as tropical monsoon with two different monsoonal seasons influenced by: 1) the Southwest monsoon in the wet season from May to October, which brings more than 90% amount of annual rainfall (1300−2500 mm); and 2) the Northeast monsoon in the dry season from November to April. Relatively high temperature occurs during March−September with the highest average monthly temperature of around 28−29 °C in April−May. Relatively low temperature occurs during October−February with the lowest average monthly temperature of around 24−26 ºC in December−January (Nguyen and Nguyen, 2004; Phan et al., 2009; Ngo-Duc et al., 2014).

The hydrogeological framework and the characteristics of each hydro-stratigraphic unit in the MKD were described in detail in Wagner et al. (2012). In general, the hydrogeological settings are very complex and the highly heterogeneous subsurface structures of intersecting aquifers and aquitards are presented due to active faulting and repetitive transgression and regression of sea-level as well as the regression/transgression phases of sea-level changes and the subsequent sedimentation/erosion processes over the past several millennia. The sedimentary deposits of various geological/hydrogeological formations in the MKD can be classified into eight groups as shown in Fig. 2. In addition to the *qh* group, each group can be further divided into two parts. The upper part is low permeable which is primarily composed of silt, clay or silty clay, and the lower part is permeable which is primarily composed of fine to coarse sand, gravel, and pebble with medium to high water yield.

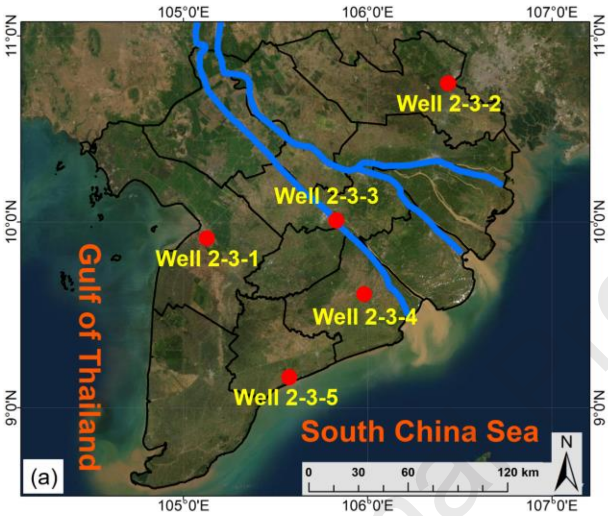
In the following text, shallow groundwater systems within the *qh* aquifer are abbreviated as SGW, and deep groundwater systems within the qp_3, qp_{2-3}, qp_1, n_2^2, n_2^1, n_1^3, and n_1^{2-3} aquifers are abbreviated as DGW. Isotopic studies indicated that: 1) SGW are closely connected with surface water systems and are replenished by infiltrated rainwater; 2) DGW are isolated with SGW and were mostly recharged 60–12 ka before present when mean sea-level reached its lowest stage and the overlying silt and clay aquitard was relatively permeable; 3) interactions between SGW and DGW at present are very limited and DGW receive little groundwater recharge since the sedimentation process during the Holocene reduces the permeability of the silt and clay aquitard gradually; 4) SGW is mostly classified as Na-Cl type (brackish or saline); and 5) DGW is mostly classified as Ca-HCO_3 type (fresh). Since the 1990s, deep groundwater extracted from some parts of the qp_3 aquifer and most parts of the qp_{2-3} and qp_1 aquifers has become to serve as preferable freshwater source to meet households, agricultural, and industrial demands especially in coastal areas where surface water is serious salinized and cannot be utilized directly.

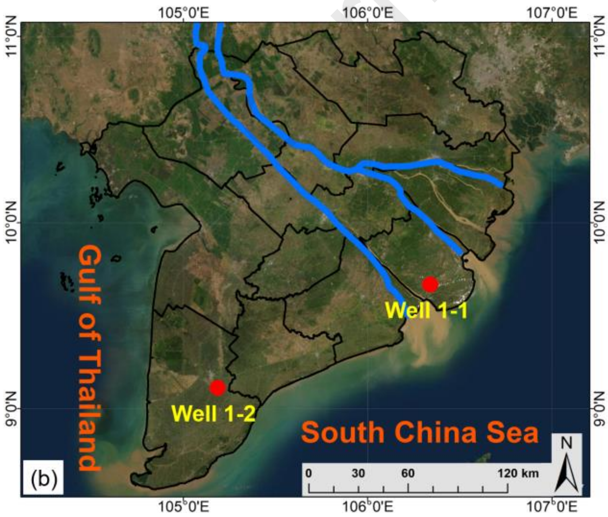
3. Human activities and climate change impacts on SWI into groundwater systems

3.1 Groundwater over-exploitation

Prior to the 1990s, groundwater withdrawal in the MKD was very limited as the freshwater demand was relatively low, and water tables of SGW varied from 0−2 m above mean sea-level and potentiometric levels of DGW were even several meters above mean sea-level (Bui et al., 2017). Due to the rapid development of agriculture, aquaculture, and manufacture since the 1990s, an ever-increasing freshwater demand for domestic use, upland crops irrigation, aquacultural use, and industrial purposes has led to extensive deep groundwater extraction (Wagner et al., 2012). The total quantity of groundwater withdrawal from large consumptive-use wells as well as small household wells reached approximately 2.5×10^6 m^3d^{-1} in 2015, which is 25 times greater than the amount of groundwater withdrawal in 1990 (Minderhoud et al., 2017). Consequently, a continuous lowering of potentiometric levels of the qp_3, qp_{2-3}, and qp_1 aquifers (especially the qp_{2-3} aquifer) with an annual-average decline rate of 0.26 m (ranging from 0.09 to 0.78 m) was observed based on time-series data from 79 nested monitoring wells at 18 locations in the MKD (Bui et al., 2017; Erban et al., 2014). Observed data from monitoring wells indicated significant decline of potentiometric levels throughout much of the MKD since the 1990s (see Fig. 3), resulting in formation of depression cones located around major cities and industrial regions with extensive pumping well density and groundwater extraction (e.g., Bac

Lieu, Ca Mau, Soc Trang, etc.) (Fig. 4). Note that the decline of potentiometric levels is almost irreversible and natural recharge from infiltrated rainwater and other recharge sources cannot reverse the decline trend in that: 1) DGW cannot obtain downward groundwater flow because of the presence of the delta-wide silt and clay aquitard; and 2) DGW obtain limited lateral groundwater flow within relatively short period of time since the recharge areas are located outside the national border in Cambodia (Hoang and Baumle, 2019). Continuous lowering of potentiometric levels due to extensive pumping reduces freshwater hydraulic pressure in coastal aquifers and interrupts the dynamic balance between saline and fresh groundwater, resulting in the occurrence of SWI into DGW laterally from the sea.





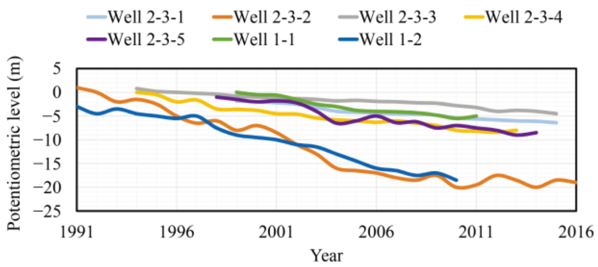


Fig. 3. Dynamic variation of potentiometric levels (Wells 2-3-1, 2-3-2, 2-3-3, 2-3-4, and 2-3-5 monitoring potentiometric levels of the $qp_{2–3}$ aquifer and Wells 1-1 and 1-2 monitoring potentiometric levels of the qp_1 aquifer) (modified after Minderhoud et al., 2017).

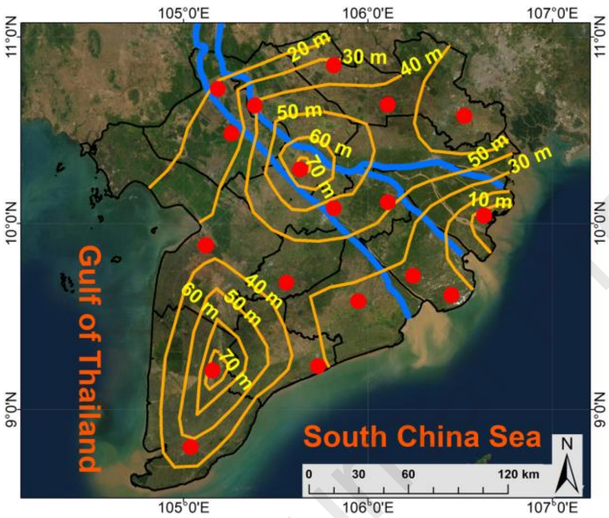


Fig. 4. Decline of potentiometric levels (drawdown) among the qp_3, qp_{2-3}, and qp_1 aquifers (interpolated from monitoring wells (marked as red dots) data) since 1990s and locations of the depression cones (modified after Erban et al., 2014).

3.2 Relative sea-level rise

The concepts of ‘relative sea-level rise’ (sea-level rise compared with land surface) and ‘absolute sea-level rise’ (sea-level rise compared with level surface) were applied. Relative sea-level rise is referred to a combination of absolute sea-level rise (resulting from thermal expansion of seawater as well as melting of ice sheets and glaciers driving by global warming), pumping-induced land subsidence (resulting from reduction of porewater pressure and compaction of sedimentary layers), natural settling of land surface, and reducing sediment accretion so that relative sea-level rise rate is usually greater than absolute sea-level rise rate (Sun et al., 2012). Based on satellite altimetry which monitors changes in sea surface height globally, annual-average rate of absolute sea-level rise was estimated to be 0.32 [0.28−0.36] cm per year (IPCC, 2013). The sea-level in the coast of southern Vietnam is projected to rise by 22 [13−32] cm and 25 [17−35] cm by 2050 under the RCP4.5 and RCP8.5, respectively (Katzfey et al., 2014; MONRE, 2016). Based on time-series data from 79 nested groundwater level monitoring wells at 18 locations in the MKD, annual-average pumping-induced land subsidence rate was estimated to be 1.6 [1−4] cm (Bui et al., 2017). By analyzing 78 ALOS PALSAR interferograms from InSAR, Erban et al. (2014) further estimated the annual-average subsidence rate between the years of 2006 and 2010 and found that: 1) much of the MKD was experiencing a widespread land subsidence of 1−4 cm per year; 2) a huge subsidence bowl was formed centered on Ho Chi Minh city located at the northeast corner of the MKD with a subsidence rate over 4; 3) 0.88 [0.35−1.4] m land subsidence and 1.0 [0.4−1.6] m additional inundation hazard were expected by the year of 2050 if groundwater withdrawal continues at present rates; and 4) pumping-induced land subsidence posed a severe flood inundation hazard compounded by the threat of absolute sea-level rise because most places in the MKD was less than 2 m above mean sea-level. Minderhoud et al. (2017) simulated groundwater drawdown and land subsidence in the MKD and simulation results (Fig. 5) indicated that pumping-induced subsidence rates in the MKD continuously increased over the past 25 years from 1991 to 2015 with present rate (delta-wide average of 1.1 cm per year, with areas surpassing 2.5 cm) exceeding local rate of absolute sea-level rise by an order of magnitude (0.3 cm). Minderhoud et al. (2017) also pointed out that the alarming subsidence rate may increase further and pumping-induced land subsidence contributed much more to coastal lowland inundation than absolute sea-level rise given that much of the MKD land surface is less than 2 m above mean sea-level. Minderhoud et al. (2018) quantified the subsidence rates under various land use and land cover patterns in the MKD and pointed out that the amplifying land subsidence processes over the past several decades were not merely induced by groundwater over-exploitation, but large-scale urbanization-induced land-use changes which increase surface loading contributed as well. Relative sea-level rise increases seawater hydraulic pressure and shifts the dynamic balance between saline and fresh groundwater, resulting in the occurrence of SWI into SGW and DGW laterally from the sea. Moreover, elevation loss resulting from relative sea-level rise can: 1) increase flood and storm surge vulnerability causing the MKD being likely to experience more frequent and prolonged saltwater inundation periods; and 2) increase SWI into the estuaries and the dense network of surface waterways, resulting in the occurrence of SWI into SGW and DGW vertically from saline surface water.

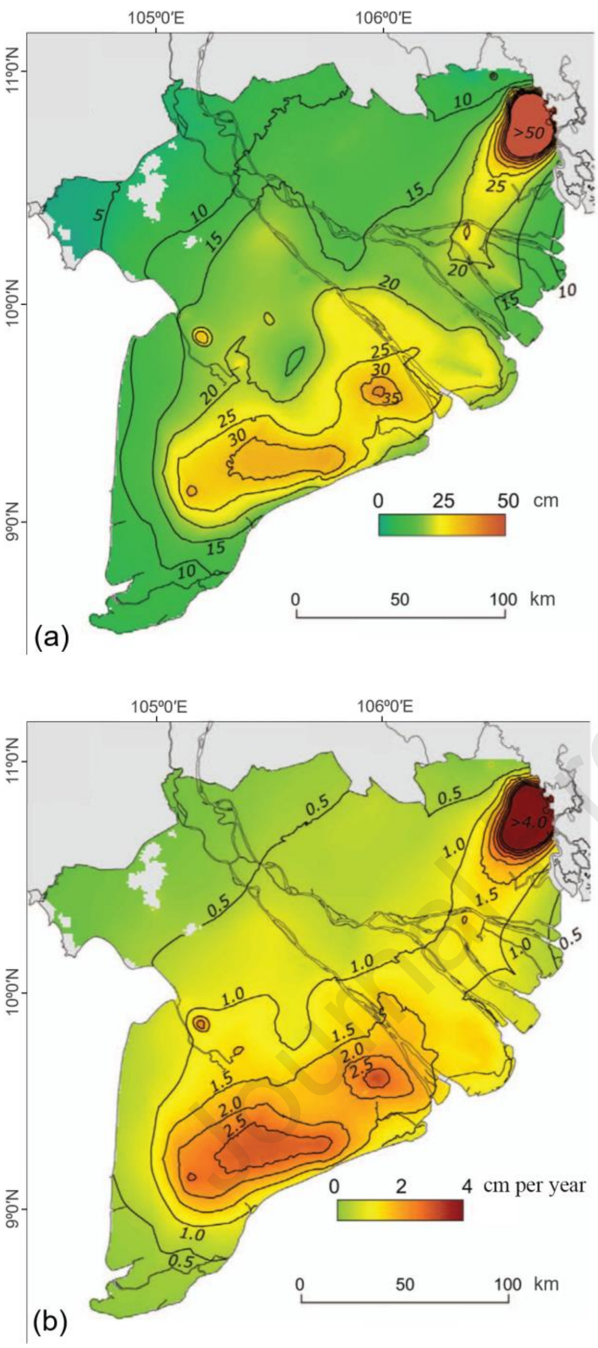


Fig. 5. Simulated cumulative pumping-induced land subsidence from 1991 to 2016 (a); (b) simulated pumping-induced land subsidence rate in the year of 2015 (modified after Minderhoud et al. (2017)).

3.3 Storm surge

The number of tropical cyclones that made landfall in southern Vietnam was about one-fourth of those which approached the northern and central parts, and the disasters brought by tropical cyclones were perceived to be less in southern Vietnam than in northern and central Vietnam (ADPC, 2003). However, it does not necessarily mean that the coastal areas in southern Vietnam are less vulnerable against tropical cyclones. For estimating the changing seawater elevation due to storm surge, Takagi et al. (2012) performed a series of numerical simulations for five selected tropical cyclones approaching southern Vietnam during 1951−2010, and found that storm surge heights at the Mekong River mouth were calculated to be 0.05 m (Typhoon Tilda, Nov. 1954), 0.30 m (Typhoon Lucy, Nov. 1962), 0.09 m (Tropical Storm Thelma, Nov. 1973), 0.70 m (Severe Tropical Storm Linda, Oct. 1997), and 0.39 m (Typhoon Muifa, Nov. 2004), respectively. For estimating the highest surge heights caused by the most severe tropical cyclone during the period from 1951 to 2010 (Tropical Storm Linda occurred in Oct. 1997), Tung et al. (2019) developed a storm surge model along the coast of MKD using nested two-dimensional depth-averaged models of Delft3D-Flow and MIKE21 considering various hydro-meteorological factors including typhoon characteristics (wind speed, landfall location and orientation, forward-movement speed), tide, sea-level rise and waves, and simulation results showed the highest surge height that occurred when the tropical cyclone landed was in the order of 1.5 m.

Due to the low-lying nature and flat topography, storm surge brought by typhoons and tropical cyclones can substantially increase the vulnerability of coastal areas being frequently inundated, even if surge heights might be relatively small and dikes have been built along many parts of the MKD. However, the risk of storm surge brought by tropical cyclones has not received significant attention yet and the risk of a combination of flooding (frequently-occurred) and storm surge are often neglected currently in the MKD.

The frequency of tropical cyclones in the South China Sea experienced a decreasing trend from 1961 to 2010 (Lee et al., 2012), and the annual number of their landfalls over Vietnam during 1949−2014 also decreases (Huang et al., 2017). Over the Western Pacific, the number of tropical cyclones has decreased and is projected to decrease in future (Herrmann et al., 2020), whereas the number of major typhoons has significantly increased (Emanuel, 2005; Holland and Bruyère, 2014). Due to the characteristics of low altitude and flat topography as well as land subsidence and sea-level rise in the MKD, an increase in both the frequency and magnitude of typhoons over the western Pacific would bring more frequent and intense storm surges sweeping over coastal MKD, resulting in coastal MKD being at high risk of being temporary or permanent inundated by seawater where coastal defense infrastructure are lacking or improperly maintained. In fact, the subsiding MKD is experiencing more frequent and prolonged periods of coastal lowland inundation and this trend has grown apparently in Can Tho city and Ho Chi Minh city (Huong and Pathirana, 2013; Takagi et al., 2016).

Storm-surge-driven saltwater flooding in coastal low-lying areas not only causes salinization problems for surface water and soil, but also substantially causes SWI into SGW, since stagnant saltwater trapped in the topographic depressions can infiltrate into the root zone forming saltwater plumes moving downwards and reaching water table eventually (Xiao et al., 2018). Storm-surge-driven saltwater flooding in coastal low-lying areas may not cause SWI into DGW in short- to mid-term in that the interactions between shallow and deep groundwater are greatly limited primarily due to the presence of the silt and clay aquitard. However, it is worth noting that abandoned deep wells breaching the aquitard suffered from physical damages of well casing are in high risk of being inundated when storm surge sweeps over and can act as point sources of downward SWI into DGW by transmitting overtopping saltwater directly from land surface to aquifers so that engineering measures such as backfilling of the damaged and abandoned production wells are necessary.

3.4 Changing temperature and precipitation regimes

In general, the temperature in the MKD increased by 0.36 ± 0.13 ºC per decade during the period 1971−2010 (Nguyen et al., 2014). The temperature in Vung Tau and Ca Mau located at coastal MKD increased by 0.24 ºC and 0.28 ºC per decade during the period 1960−2011 (Ngo-Duc, 2014a). Based on the Special Report on Emission Scenarios (SRES) which considered the impacts from emission of greenhouse gas and aerosol (IPCC, 2000; IPCC, 2007), the temperature in the MKD was projected to increase by greater than 1.2 ºC by the year of 2050 under IPCC A1B scenario (Ngo-Duc et al., 2014) and by 1.4 ºC and 2.6 ºC by the year of 2100 under the B1 and A2 scenarios, respectively (MONRE, 2009). Based on the Representative Concentration Pathways (RCP) scenarios provided by the IPCC 5th Assessment Report which considered the impacts from emission of greenhouse gas and aerosol as well as the impacts from changes in land use and land cover (IPCC, 2013), the annual-average temperature in the MKD was projected to increase by 1.5−1.6 ºC and 2.9−4.9 ºC by the year of 2100 under RCP4.5 and RCP8.5 scenarios, respectively (Shrestha et al., 2016; MONRE, 2016). Higher irrigation demand resulting from higher crop water requirements due to warmer temperatures may increase deep groundwater withdrawal for agricultural use, causing SWI into DGW in the MKD.

There is a slight increasing trend but insignificant for precipitation in the MKD during the recent past decades (Endo et al., 2009; Ngo-Duc et al., 2014a; Nguyen et al., 2014). Changes in future precipitation regimes in the MKD have been projected in several studies (MONRE, 2009, 2012, 2016; Ngo-Duc, 2014; Ngo-Duc et al., 2014; Shrestha et al., 2016; Tangang et al., 2018, Trinh-Tuan et al., 2019; Supari et al., 2020; Tangang et al., 2020). However, there are high uncertainties within the different rainfall projections, since some studies projected an increase in annual rainfall (MONRE, 2009, 2012, 2016; Shrestha et al., 2016) while others projected a decrease (Trinh-Tuan et al., 2019; Supari et al., 2020; Tangang et al., 2020). Seasonal changes in rainfall were projected to be different for the wet and dry seasons, and the wet season was projected to become even wetter while the dry season become even drier

(Shrestha et al., 2016; Trinh-Tuan et al., 2019). In the wet season, mean infiltrated rainwater (28 mm per year) was projected to remain unchanged throughout the 21st century although an increase of rainfall was projected (increase by 1.9% and 6.4% under RCP4.5 and RCP8.5 scenarios) mainly because rainfall would come in fewer but more intense events so that higher proportion of rainwater would be lost in the form of runoff rather than being absorbed (Shrestha et al., 2016). In the dry season, mean infiltrated rainwater (9 mm per year) was projected to decrease 2 and 4 mm per year under the RCP4.5 and RCP8.5 scenarios, respectively, since a decrease of rainfall (decrease by 0.75% and 2.1% under RCP4.5 and RCP8.5 scenarios) was projected (Shrestha et al., 2016). Infiltrated rainwater is very useful to replenish and renew shallow groundwater and prevent the occurrence of SWI into SGW by diluting/flushing saltwater and generating an effective freshwater hydraulic barrier. The projected decrease in infiltrated rainwater resulting from changes in precipitation regimes would exacerbate the extent of SWI into SGW, especially in the dry season.

3.5 Uncontrolled drainage canals

With the main purpose of developing agriculture and transportation, an extensive drainage canal network was developed in the MKD on a basis of numerous canals/channels constructed after 1975 (Shrestha et al., 2016). Dense drainage canals lacked of gated control structures to maintain canal stages greatly contribute to: 1) draining shallow groundwater and lowering water table; 2) inducing seawater propagating even 40−60 km inland especially during the dry season; and 3) causing SWI into SGW laterally from salinized drainage canals especially during the dry season (Tuan et al., 2007).

3.6 Operation of hydropower dams

The Mekong River basin has cascades of dams in place or planned. To date there are 364 dams in the Mekong basin of which 241 existing, 29 under construction, 91 planned, and 3 been cancelled (WLE, 2020). The impacts of dams on MKD hydrodynamics were marginal until 2010, and increased noticeably due to addition of new dams (Shin et al., 2020). It was indicated that new dam constructions could explain about 62% of the changes in the annual streamflow during 2010−2014, whereas climate change used to contribute over 80% of the changes during 1992−2009 (Li et al., 2017). Operations of upstream dams can help increase streamflow in the dry season and reduce streamflow in the wet season (Li et al., 2017; Pokhrel et al., 2018). From hydrological perspective, increasing streamflow in dry season could help prevent seawater propagating upstream, reduce downstream salinity level, maintain water table, and limit the extent of SWI into SGW (Smajgl et al., 2015). However, operations of upstream dams, as well as extensive sand-mining activities (e.g., extraction volume reaching 7.75×10^6 m^3 in 2011 (Bravard et al., 2013)) and the shift in tropical cyclone activities (Darby et al., 2016), would reduce sedimentation drastically in the MKD (ICEM, 2010; Kondolf et al., 2014; Manh et al., 2015). Decreasing sedimentation has led to an increase of shoreline erosion (Anthony et al., 2015) and amplification of land subsidence, causing SWI into SGW laterally from the sea.

3.7 Rapid development of aquaculture

Rice farming systems used to be dominant in the MKD but large amounts of cultivated lands were converted from paddy rice to marine aquaculture over the last twenty years due to the rapid development of shrimp aquaculture (Hagenvoort and Tri, 2013). The MKD is one of the primary shrimp-producing areas in Vietnam and Vietnam ranked 5th and 3rd among those shrimp-producing countries in the world in the years of 1999 and 2004[3] with a shrimp production of more than 290,000 t. High profitability and generation of foreign exchange are to blame for the major driving forces of rapid expansion of shrimp farming (Hens et al., 2009). Rapid development of aquaculture requires large amounts of freshwater to be extracted from DGW for mixing with seawater for shrimp cultivation, further aggravating the problems of groundwater over-exploitation and the extent of SWI into DGW laterally from the sea. Moreover, seepage of saltwater from shrimp culture ponds can cause SWI into soil and SGW (Rahman et al., 2019).

4. Major knowledge gaps and challenges

Groundwater plays a more and more important role in providing freshwater supply for agricultural, aquacultural, industrial, and domestic utilizations in the MKD (Ha et al., 2018). However, SWI and the subsequent groundwater quality degradation have been widely recognized as the most serious and compelling problems. So far, investigations and evaluations of the extent of SWI are limited, and little research has been conducted regarding the contributions from human activities and climate change impacts. Based on current research findings, major knowledge gaps and challenges are identified and described herein.

Firstly, it is the top priority to: 1) realize whether the silt and clay aquitard located between the *qh* and the qp_3 aquifer throughout the entire MKD can prevent downward SWI from salinized surface water and shallow groundwater into DGW; and 2) determine the locations and dimensions of existing hydraulic windows breaching the silt and clay aquitard that can provide pathways for transmitting salinized surface

[3] http://www.fao.org/fishery/topic/18042/en

water and shallow groundwater to DGW directly. Hoang and Bäumle (2019) have conducted environmental isotopic studies and demonstrated that the presence of the silt and clay aquitard in Soc Trang Province (one of the 13 provinces within the MKD) is potent enough to prevent downward SWI into DGW. However, the characteristics of the silt and clay aquitard in the other 12 provinces within the MKD remain unknown. To bridge current knowledge gap, future work should apply environmental isotope techniques in combination with borehole tests to gain detailed hydrogeological information regarding spatial variation of permeability and thickness of the silt and clay aquitard in other places in the MKD.

Secondly, it is of great importance to delineate the present-day highly heterogeneous 3D distribution of saline groundwater zones in the MKD. The national groundwater monitoring network comprised of over 200 monitoring wells maintained by the Division for Water Resources Planning and Investigation in the South of Vietnam (DWRPIS) and its subdivisions since the 1990s can serve as an important information source. However, observed data collected periodically from these monitoring wells are inadequate. To bridge current knowledge gap, future work should make great efforts to intensify regular groundwater monitoring and collect as much groundwater samples from multiple hydro-stratigraphic units at different depths as possible to visualize the present-day highly heterogeneous 3D distribution of saline groundwater in the MKD.

Thirdly, it is essential to predict future 3D distribution of saline groundwater by depicting the dimension and tracking the migration of freshwater/saltwater transition zone for recognizing the dominant factor causing future SWI into coastal MKD groundwater systems. To achieve optimum predictive results, numerical models capable of simulating 3D coastal groundwater flow and salt transport under variable-density conditions should be developed. Shrestha et al. (2016) used to develop a groundwater flow model to predict the changes in groundwater level and groundwater storage under future climate change in the MKD, indicating that meters to tens of meters decline of groundwater levels in various aquifers as well as a total of 120−160 million m^3 decline of groundwater storage can be expected by the end of the 21st century. Besides, Pham et al. (2019) developed a long-term 2D (NW-SE transect) groundwater flow and salt transport model to reproduce the characteristics of the historical and present-day fresh and saline groundwater dynamics in the MKD for better understanding of groundwater evolution and aquifer salinization processes from the late Pleistocene. To bridge current knowledge gap, future work should develop a series of variable-density coupled groundwater flow and salt transport models representing various scenarios of human activities and climate change for predicting future extent of saltwater intrusion in the MKD, since numerical method has become the most frequently used approach to solve SWI problems worldwide (Barlow and Reichard, 2010; Bocanegra et al., 2010; Custodio et al., 2010; Shi and Jiao, 2014; Steyl and Dennis, 2010; Werner, 2010; White and Falkland, 2010).

Fourthly, it is indispensable to determine the most effective and economical control measure to mitigate SWI and secure fresh groundwater resources in the MKD. In recent years, various traditional and innovative engineering techniques have been applied worldwide for solving the problems of SWI into coastal aquifers. For those cases of pumping- and sea-level-rise-induced SWI, reducing groundwater withdrawal rate and closure or landward relocation of coastal extraction wells, as well as installation of recharge wells parallel to the shoreline, are usually adopted for maintaining groundwater levels and generating submarine groundwater discharge to build up effective hydraulic barriers to prevent saltwater encroachment. For those cases of land-subsidence- and storm-surge-induced SWI, construction and maintenance of coastal defense structures such as sea-dykes are usually adopted for stabilizing beach and shoreline to prevent storm tides from reaching and passing over the crest causing coastal lowlands inundation and saltwater encroachment. In addition to these traditional approaches, innovative approaches such as developing an aquifer storage and recovery system storing freshwater in aquifers when supply exceeds demand during the wet season while extracting freshwater from aquifers when demand exceeds supply during the dry season have been applied as well. To bridge current knowledge gap, future work should first identify the dominant factor causing future SWI, then determine the most effective and economical engineering technique to address SWI problems in the MKD.

5. Conclusion

In recent years, groundwater quality degradation caused by SWI has been recognized as an important issue and great progress has been made in understanding the pathways of SWI and the impacts of human activities and climate change on affecting the extent of SWI into the SGW and DGW in the MKD. However, existing knowledge gaps and challenges greatly limit the development of SWI research in the MKD, including locations and dimensions of existing hydraulic windows breaching the silt and clay aquitard, present-day highly heterogeneous 3D distribution of saline groundwater zones, future 3D distribution of saline groundwater, and most effective and economical control measure to mitigate SWI. In future, observed data from monitoring wells supplemented with borehole geophysical data are required to characterize the highly heterogeneous hydrogeological conditions and 3D distribution of saline groundwater, and variable-density coastal groundwater flow and salt transport models incorporating the details of hydro-climatic and hydrogeological conditions are required to be developed to predict future extent of SWI into coastal MKD groundwater systems for determination of optimized strategies of pumping schemes for sustainable utilizations of groundwater resources in the MKD while mitigating the extent of SWI in the meanwhile.

The fragile ecosystems of the Tibetan Plateau where the upper reaches of the Mekong River locate are sensitive to climate change, and the critical link between the source of the Mekong River at the Tibetan Plateau and the mouth of the Mekong River at the MKD is threatened to be weakened resulting from climate change. With the awareness of climate change and its consequences to the Tibetan Plateau region and beyond, scientific communities must be empowered with a pro-active role in designing resilience for addressing challenges caused by climate change and supporting sustainable development.

Declarations of competing interest

The authors declare no conflict of interest.

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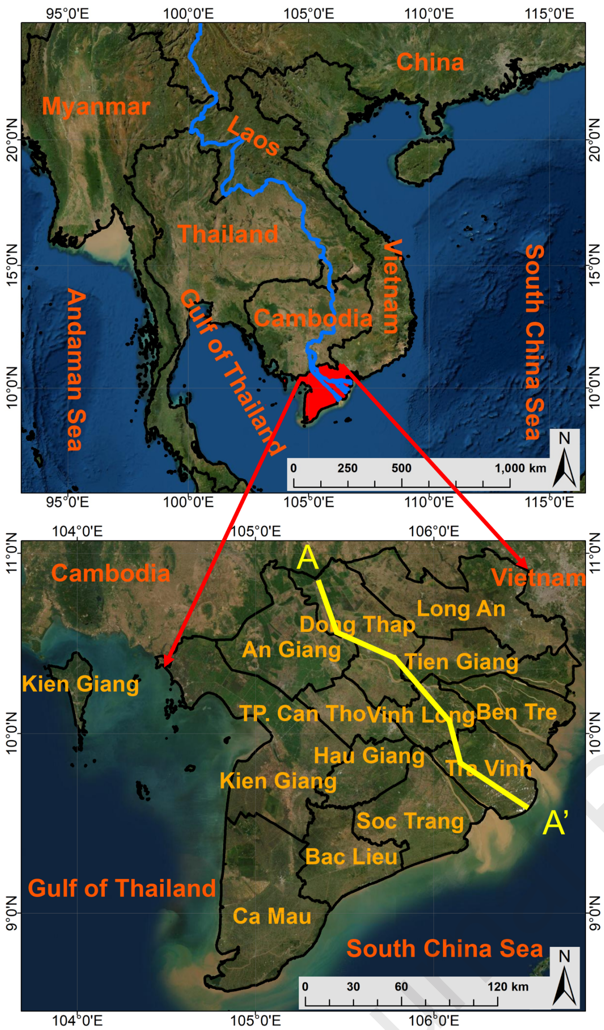
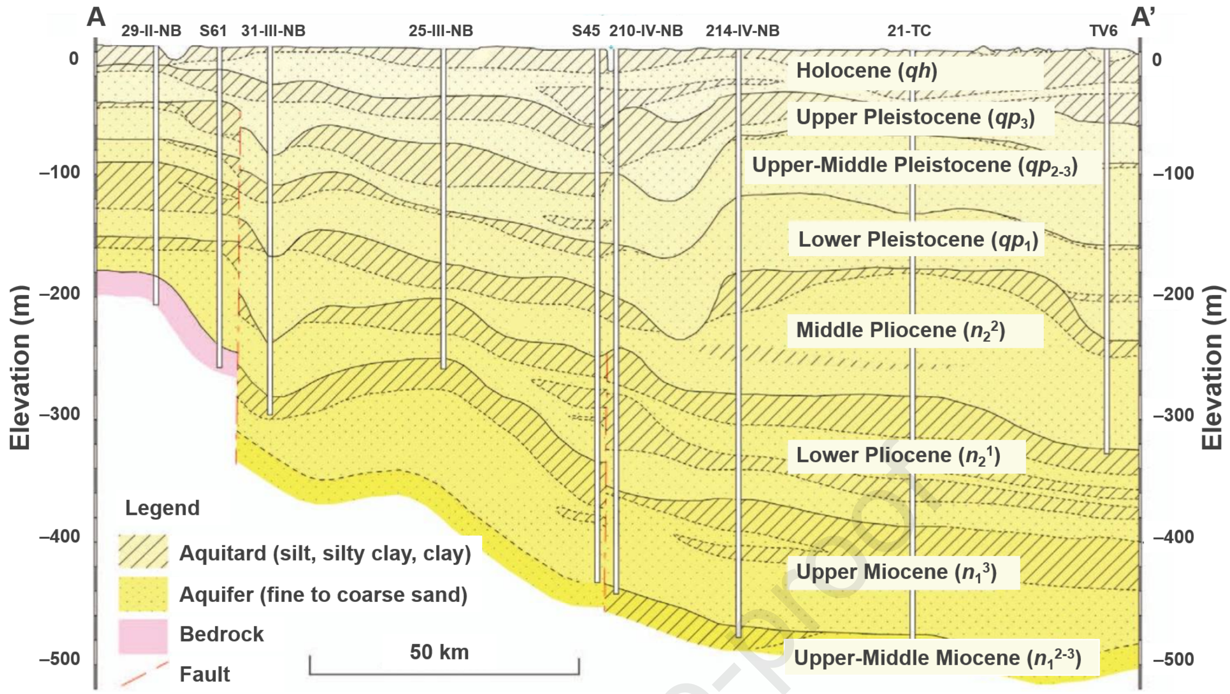
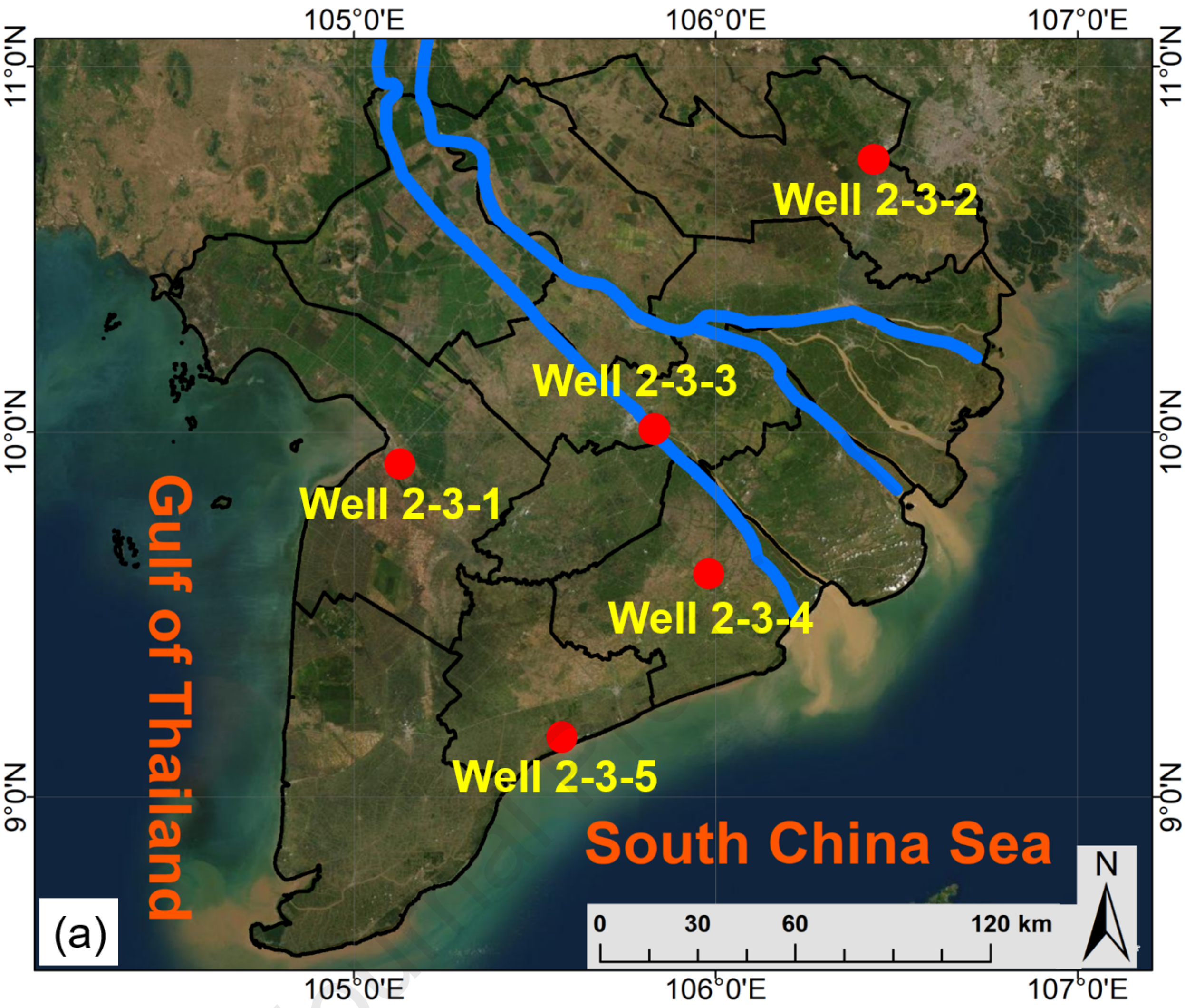
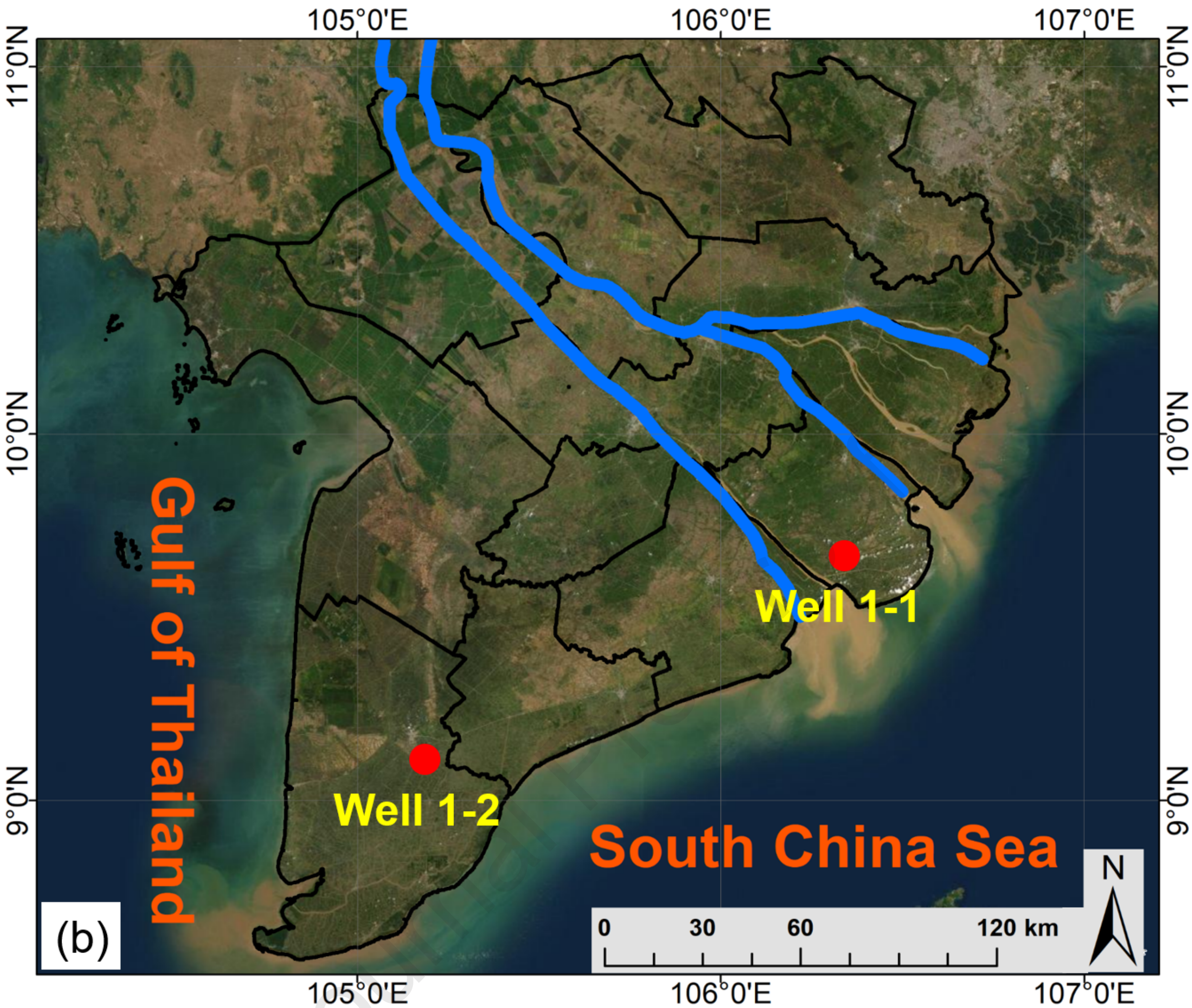
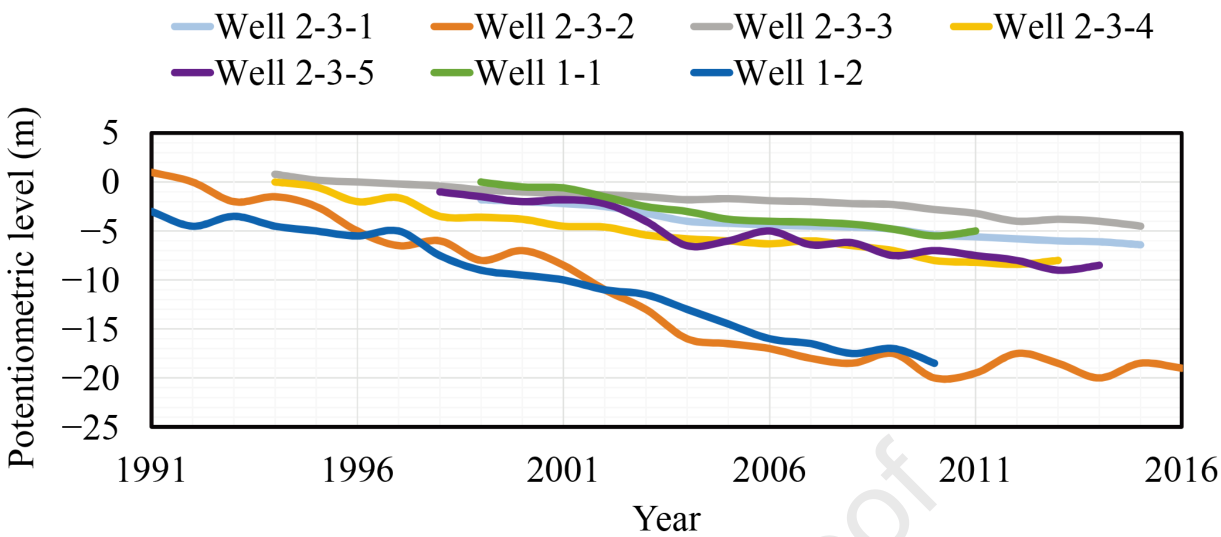

China
Myanmar
Laos
Thailand
Vietnam
South China Sea
Andaman Sea
Gulf of Thailand
Cambodia
0 250 500 1,000 km
N
Cambodia
Vietnam
A
Long An
Dong Thap
An Giang
Tien Giang
Kien Giang
TP. Can Tho
Vinh Long
Ben Tre
Hau Giang
Tra Vinh
Kien Giang
Soc Trang
A'
Bac Lieu
Gulf of Thailand
Ca Mau
South China Sea
0 30 60 120 km
N

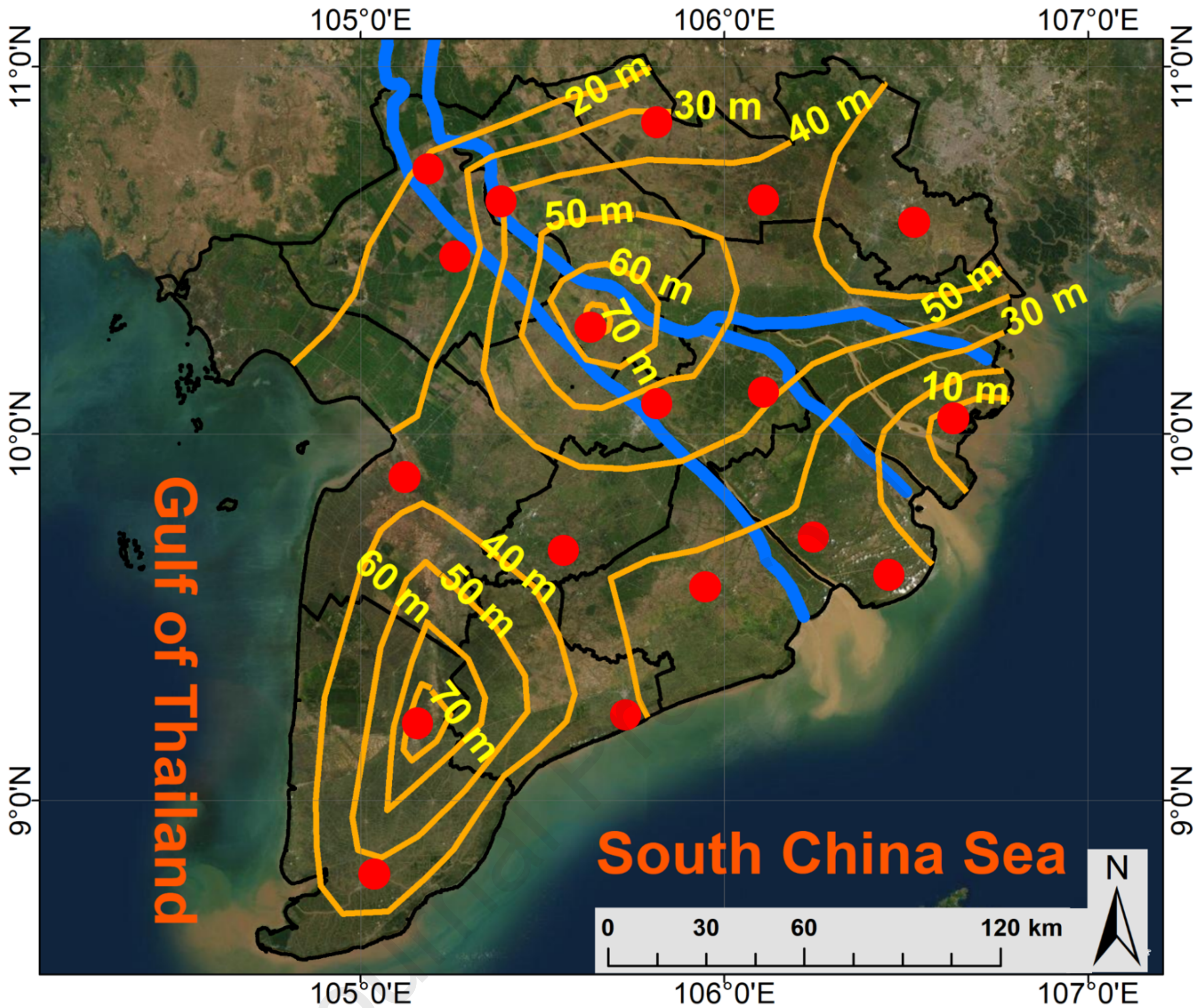


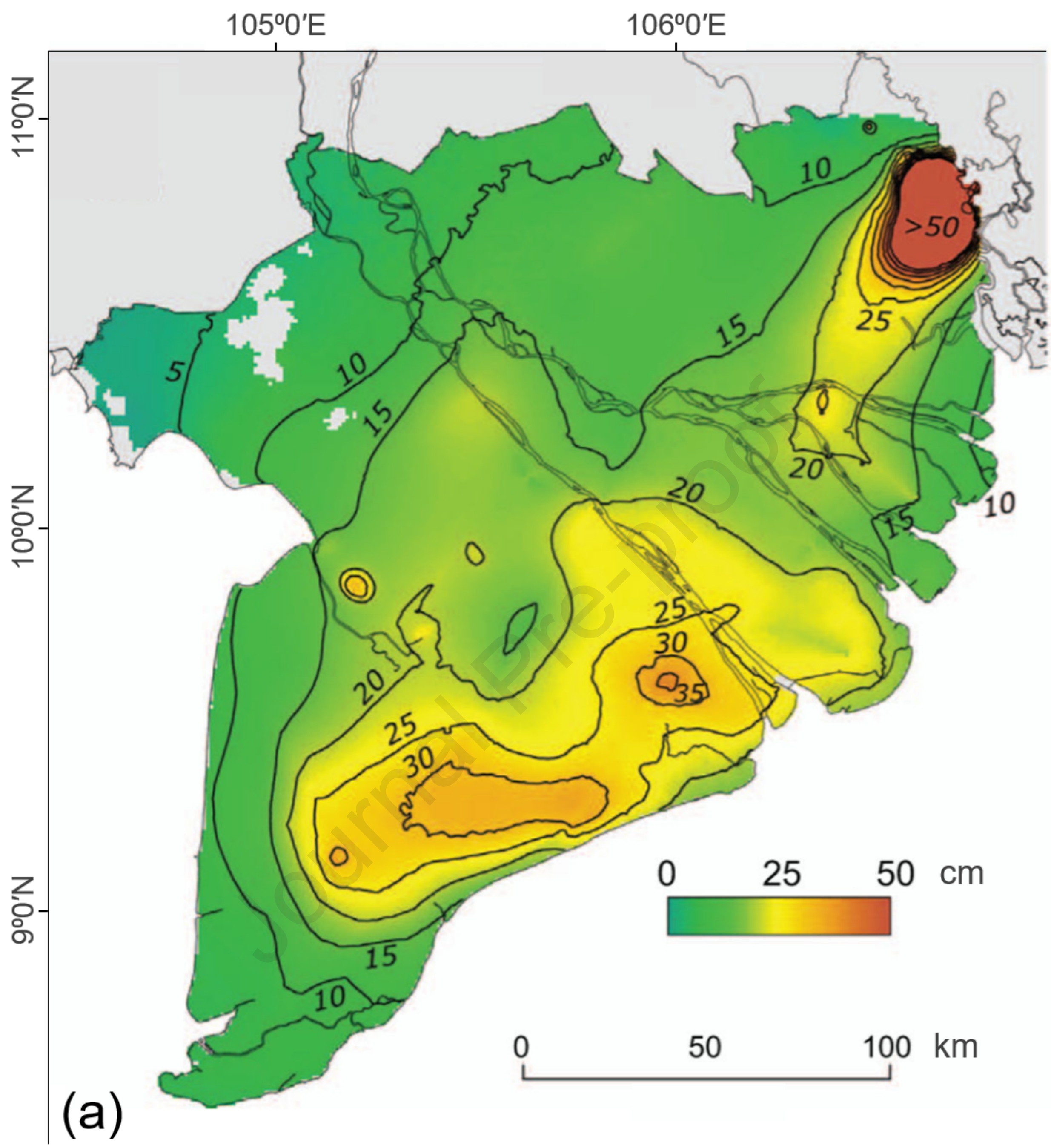
A
A'
29-II-NB
S61
31-III-NB
25-III-NB
S45
210-IV-NB
214-IV-NB
21-TC
TV6
Elevation (m)
0
–100
–200
–300
–400
–500
Holocene (qh)
Upper Pleistocene (qp3)
Upper-Middle Pleistocene (qp2-3)
Lower Pleistocene (qp1)
Middle Pliocene (n22)
Lower Pliocene (n21)
Upper Miocene (n13)
Upper-Middle Miocene (n12-3)
Legend
Aquitard (silt, silty clay, clay)
Aquifer (fine to coarse sand)
Bedrock
Fault
50 km

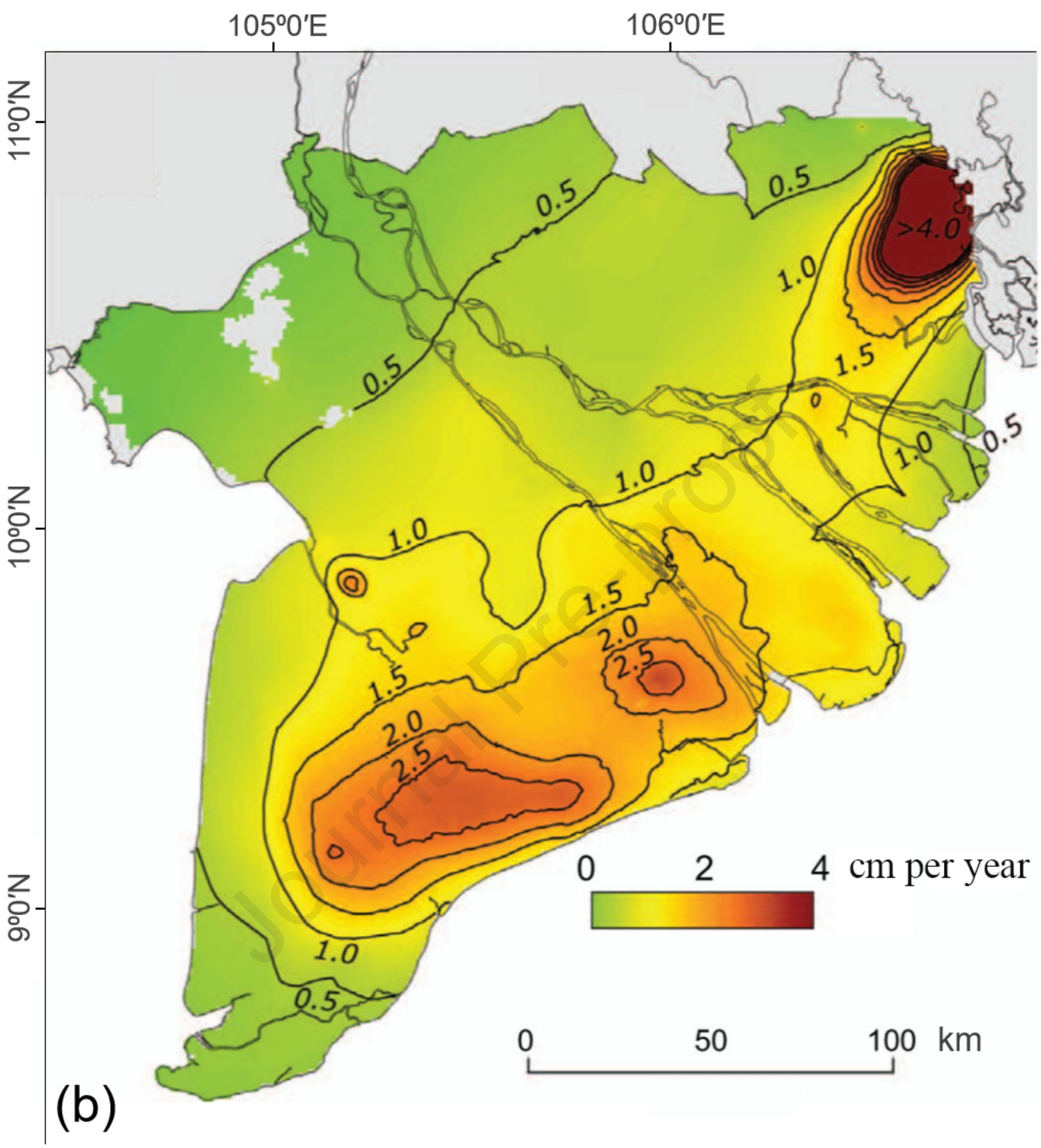

105°0'E
106°0'E
107°0'E
11°0'N
10°0'N
9°0'N
Well 2-3-1
Well 2-3-2
Well 2-3-3
Well 2-3-4
Well 2-3-5
Gulf of Thailand
South China Sea
(a)
0
30
60
120 km
N


105°0'E
106°0'E
107°0'E
11°0'N
10°0'N
9°0'N
Gulf of Thailand
South China Sea
Well 1-1
Well 1-2
(b)
0
30
60
120 km
N


Well 2-3-1
Well 2-3-2
Well 2-3-3
Well 2-3-4
Well 2-3-5
Well 1-1
Well 1-2
Potentiometric level (m)
5
0
−5
−10
−15
−20
−25
1991
1996
2001
2006
2011
2016
Year


105°0'E
106°0'E
107°0'E
11°0'N
10°0'N
9°0'N
20 m
30 m
40 m
50 m
60 m
70 m
10 m
Gulf of Thailand
South China Sea
0
30
60
120 km
N


105º0′E
106º0′E
11º0′N
10º0′N
9º0′N
>50
25
20
15
10
5
30
35
0 25 50 cm
0 50 100 km
(a)



105º0′E
106º0′E
11º0′N
10º0′N
9º0′N
0.5
0.5
0.5
0.5
0.5
0.5
1.0
1.0
1.0
1.0
1.0
1.0
1.5
1.5
1.5
2.0
2.0
2.5
2.5
>4.0
0
2
4
cm per year
0
50
100
km
(b)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: