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Establishing 3D hydrogeological solid model and database for sustainable groundwater management in the Vietnam Mekong delta

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Abstract:

The Vietnam Mekong delta (VMD) is a tide-dominated delta formed by the Mekong river system. The sediments are dominantly fine grained and were deposited in the receiving basin with slight inclination of pre-existing deposits in the East sea and gulf of Thailand. The VMD is homeland to about 18 million people that exploit about 4-6 million m^3/day of groundwater mainly for domestic use. In recent years, significant groundwater depletion has been occurring in many parts of the VMD due to excessive pumping. Consequently, the VMD has become increasingly faced with serious land subsidence, salt groundwater intrusion, and contamination. Establishing a 3D hydrogeological solid model and database are sorely needed to achieve sustainable groundwater management, and to serve as a basis for further in-depth analyses to quantify contributions from the above-mentioned hazards to current hydrogeological conditions. Therefore, a 3D hydrogeological solid model and database were built based on more than 1000 well logs available from the VMD. An areal distribution of the Holocene, Pleistocene, Pliocene, and Late Miocene subsurfaces from this 3D hydrogeological solid model and database showed zones of tectonic depression and uplift from Early Miocene - Quaternary. Also, the resulting areal distribution aquitards and aquifers thicknesses gave hints of ground saltwater intrusion and contamination.

Keywords: **groundwater extraction, subsurface modelling, Vietnam Mekong delta.**

Classification number: **5.3**

Introduction

The delta plain of the Mekong river is about 62,520 km^2 of which 52,100 km^2 is located in Vietnam, which is referred to as the VMD, and the remainder is located in Cambodia's territory. In Vietnam, the VMD spans 13 provinces with a population of 17.6 million [1]. The region represents a national rice bowl providing agricultural products not only for Vietnam but also other countries. In the VMD, the Bassac river known as the Hau river, runs along the development direction of the largest regional fault, which is 2,000 km long and vertically dipping down to 35 km deep. This fault line is internationally named the Mae Ping fault and also locally known as the Hau river fault for its part in Mekong delta [2, 3]. The VMD is known to be continuously sinking below sea level due to rising seawater levels and land subsidence. In many places within the delta, the land subsidence rate has been reported to be up to 10 cm/yr (Fig. 1A) [4], which is often linked to excessive groundwater pumping [5, 6]. The groundwater has been reported as being salty in many aquifers, especially in the coastal provinces of Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, and Ben Tre [7, 8]. An example of the salt groundwater distribution is given in Fig. 1B. Therefore, this region is selected for 3D hydrogeological modelling that aims to: (i) Better understand the spatial distribution of hydrogeological units existing in the region, especially the appearance of the bedrocks on the surface ground in the provinces of Kien Giang, Binh Duong, and their dipping towards the Hau river and towards the coastal provinces of Ca Mau, Bac Lieu, Soc Trang, and Ben Tre. Insight into this spatial hydrogeological distribution can provide certain explanations of the groundwater salt intrusion and land subsidence appearances in the delta; and (ii) to achieve the first necessary step toward building a groundwater flow and transport model for the entire VMD.

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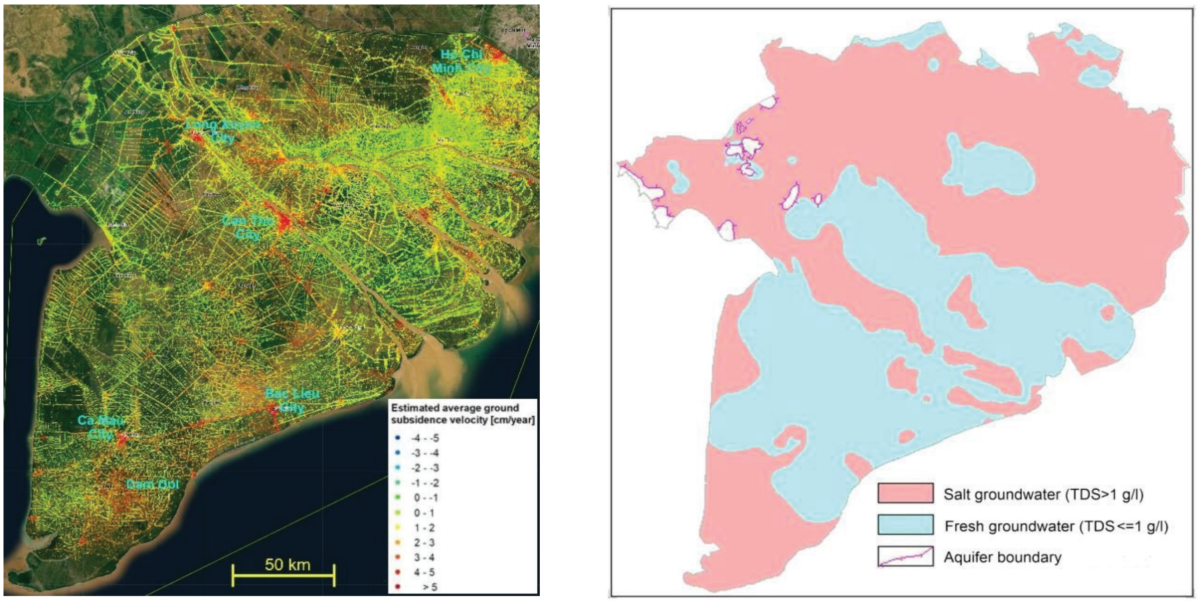


(A) (B)

Fig.1. (A) Land subsidence maps by Indra (2019) portraying Sentinel-1 imageries in the period 2014-2019 and (B) distribution of fresh and salt groundwater in aquifer 23 after DWRPIS [7].

Several 3D hydrogeological solid and groundwater flow models have been developed for the entire VMD. The first and most relatively complete one (in terms of modelling area and number of data used) is the groundwater model developed by the Division for Water Resources Planning and Investigation for the South (DWRPIS) [7]. The main objective of this model was to predict responses of the groundwater resources to several scenarios including future climate change and social-economic change in the VMD. This model was built on the basis of 903 well logs collected at that time in combination with Aquaveo GMS MODFLOW software with a 139(rows)x131(columns)x14(layers) cell grid with a cell resolution of 2x2 km^2. The modelling used the inversed distance weighting (IDW) interpolation method combined with am averaging and minimum thickness adjustment technique was applied to generate the top and bottom of all aquifers and aquitards. In this technique, when the interpolated bottom is higher than the interpolated top of an aquifer or aquitard, the top is adjusted by moving up half of a user-specified minimum thickness to above the interpolated value and moving down the bottom by the same interval to below the interpolated value. The minimum layer thickness (i.e., every layer must have a non-zero thickness everywhere in the modeling domain) is an essential requirement for a finite difference solution of the MODFLOW code. One major disadvantage of this modelling technique is the inability to delineate zones of "vertical hydrological window", i.e., zones where there is a direct connection between the aquifers, which occur in reality as they appear in well log G17-CM in Ca Mau city (Fig. 2).

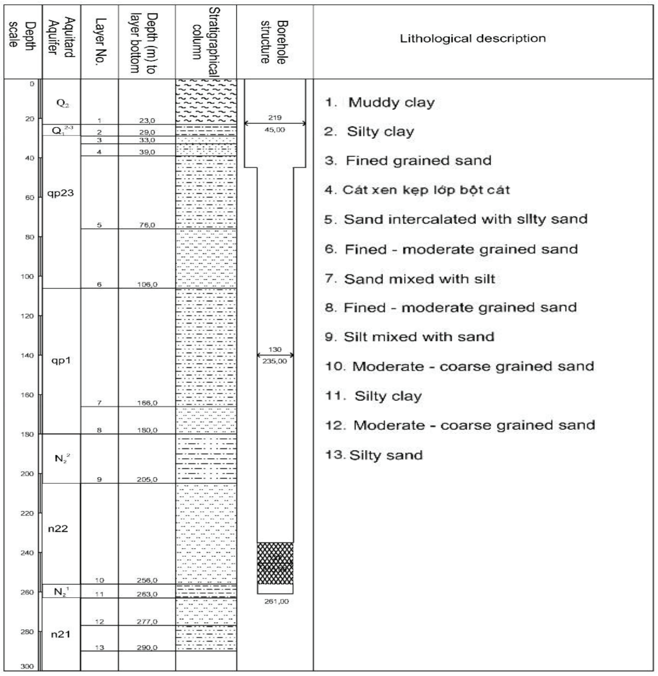


Fig. 2. The well log of borehole G17-CM in Ca Mau city shows the appearance of vertical hydrogeological windows at depth -23 m (no existence of aquifers qh or qp3, or aquitard Q13, and aquitard Q2 directly connecting with Q12-3), or at a depth -106 m (no aquitard Q11 separating aquifers qp23 with qp1).

At the same time as the above-mentioned modeling work was completed, a quasi-3D steady-state groundwater model of 410(rows)x308(columns)x8(layers) and cell resolution of 1x1 km^2 was developed by Vermeulen, et al. (2013) [9], which aimed to assess the groundwater resources in the VMD. This model was developed based on iMOD MODFLOW software and used only 95 boreholes collected from DWRPIS. Later, Minderhoud, et al. (2017) [6] built another 3D groundwater flow model to assess the impacts of the last 25 years of groundwater abstraction due to land subsidence in the VMD. This model is similar to Vermeulen's work in terms of modeling area, cell resolution, and data used, however, it is coupled with a 1D geotechnical subsidence module called SUB-CR. The simulated land subsidence rate was compared with the measured remotely using satellite-based synthetic aperture radar (SAR) imagery processed by interferometry (InSAR) for validation of the modelling. The results of this work implied that excessive pumping was the prevailing cause of land subsidence and groundwater level decline in the VMD, while neglecting other possible causes like tectonic displacement, surface loading, soil lithological properties, soil auto-compaction, and natural compaction. Indeed, it was later shown in a publication by Zoccarato, et al. (2018) [10] that the estimated average subsidence rate resulting from natural compaction of young Holocene sediments in the VMD can be as much as 2 mm/yr at the present shoreline and decreases gradually inland to 0.8 mm/yr towards the upper delta plain.

Very recently, Gunnink, et al. (2021) [11] produced a 3D groundwater salinity distribution and fresh groundwater volume model in the Mekong delta using a geostatistical analysis approach. One of the components of this research is the construction and update of the hydrogeological layer model (aquifers and aquitards discretized into voxels) from the existing model of Minderhoud, et al. (2017) [6]. Unlike other numerical groundwater flow and transport models, this research mainly used a point-based interpolation technique, namely, the ordinary kriging interpolation method, to generate a 3D groundwater salinity distribution per aquifer and aquitard, and to estimate the fresh groundwater volume per aquifer and per province for the entire VMD. Therefore, the saltwater transport pathway was not fully studied or clarified in this research work and questions such as how and where saltwater moves vertically (i.e., leaching through low permeable aquitard or flowing through vertical hydrogeological windows) remain unanswered.

Thus, a 3D hydrogeological solid model is an essential tool for various studies of groundwater resource and groundwater-related catastrophe management. However, in previous modelling works, the number of well logs was relatively sparse for such a large modelling area and, additionally, about two third of the boreholes do not reach the deepest aquifer. Therefore, existing 3D models do not give accurate local variations of thickness and subsurface of hydrogeological units as well as the possible existence of "vertical hydrogeological windows" in the groundwater system of the VMD. Since 2014, more water resource investigation projects with new, deep boreholes have been implemented by the National Center for Water Resources Planning and Investigation (NAWAPI). Indeed, well logs from these new boreholes were collected in this research. Besides, a sophisticated combination of the point IDW interpolation technique (for creating the tops and bottoms of hydrogeological units using measured data from the collected well logs) and the subsurface truncation method (the bottom elevation is lowered to the top elevation where the interpolated value of bottom is higher than the interpolated value of the bottom) are applied to this 3D solid modelling work to reveal zones of "vertical hydrogeological windows". Therefore, the 3D solid model and the associated database resulting from this research work is more detailed and accurate than the available ones as it overcomes the previously mentioned constraints. The 3D solid model is later applied to assess the contribution of tectonic vertical displacement to the current land subsidence status and to estimate possible pathways of salt and pollutant transport in the groundwater system in the VMD.

Study area

The VMD is a subaerial plain that has prograded ~220 km southeastward within the past 6,000-7,500 years [12, 13] and is tectonically controlled by three regional deep faulting systems: the NW-SE trending faults, the N-S trending fault, and SW-NE trending faults (Fig. 3). The Hau river runs along the development direction of the biggest regional fault and is about 2,000 km long and almost vertically dips down 35-70 km deep. It is internationally named Mae Ping fault and locally known as the Hau river fault for its part in the Mekong delta. The VMD is a tide-dominated delta formed by the Mekong river system. The study region is a flat lowland of 0.5-2.5 m elevation except for some hills and mountains of exposed bedrock in the northern parts of the Kien Giang and An Giang provinces. In the lowland area, the sediments are dominantly fine grained and were deposited in the receiving basin with slight inclination of pre-existing deposits in the South China sea and gulf of Thailand.

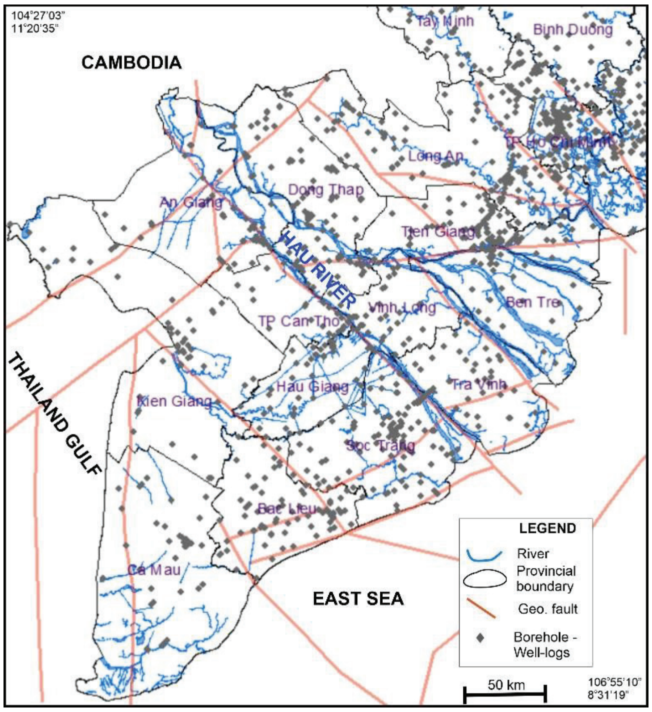


Fig. 3. Location of study region and selected boreholes for 3D hydrogeological model and geological faults adapted to Hoa (1996) [14] **and Trang (2019)** [13].

So far, through different hydrogeological mapping works at scales 1:50,000-1:200,000, the Vietnamese hydrogeologist association has conceptualized the whole unconsolidated sediments from the Late Miocene to the Quaternary in the VMD as being composed of 14 hydrogeological units, namely, the 7 aquitards (from top to bottom) Q_2, Q_1^3, Q_1^{2-3}, Q_1^1, N_2^2, N_2^1, and N_1^3, and the 7 aquifers qh, qp3, qp23, qp1, n22, n21, and n13. Deeper unconsolidated sediments of Middle Miocene N_1^{2-3} have been observed in few geological-hydrogeological wells and/or petroleum exploration wells near the Hau river in the provinces of Hau Giang and Ben Tre. For example, clayish silt aged N_1^{2-3} below a depth of -495 m in borehole 17-III-NB (Hau Giang province); or a set of intercalated layers of clay, silt, and sand aged Neogene (?) at depths of -508 to -798 m found in the 1190-m deep petroleum exploration well HG1 in Hau Giang province. However, because of the very small number of such deep wells that enable the characterization of deeper water-bearing porous formations, the porous groundwater system of 14 hydrogeological units is conceptualized to overlie much less permeable Paleozoic - Cenozoic bedrocks as appearing in a number of well logs from the provinces of An Giang, Kien Giang, Ca Mau, and Bac Lieu.

In the VMD, groundwater is a very important source of water for domestic use as well as for aquaculture-agricultural production demands. The total number of licensed production wells (i.e., wells of pumping discharge ≥10 m^3/day) in the region is 9,287 with an abstracted volume of 1.97x10^6 m^3/day [15]. A recent detailed investigation in Ca Mau province shows the actual abstracted volume (i.e., including also unlicensed production wells of pumping rate <10 m^3/day) is 426.4x10^3 m^3/day while the licensed abstraction volume is only 143.9x10^3 m^3/day [16]. Therefore, it is roughly estimated that the actual abstracted volume is 2-3 times higher than the licensed volume. This huge abstraction volume has been causing deep cones of groundwater depletion in aquifers qp23, qp1, and n22 where most of the production wells are being pumped.

Data overview and remarks

The baseline of this work is the well log dataset of the NAWAPI. This dataset consists of 1,545 well logs of geological-hydrogeological investigative boreholes drilled across 19 provinces of the Southern Plain of Vietnam, and most of them were collected during the implementation of the project "Assessment of impact of global climate change to the groundwater resources in the Vietnam Mekong delta, proposal of resilient measures" [7] and the project "Groundwater resources compilation - mapping scaled 1:200,000 for provinces of Vietnam" [8]. The abovementioned dataset does not include all available well logs since only the deepest well logs for each national groundwater monitoring station are input into the dataset (each is often composed of 3-6 boreholes monitoring different aquifers, which are located few meters distant from each other).

For 3D hydrogeological modelling, 1,214 boreholes located in the study region were selected from the abovementioned well log dataset, and each well log contains a downhole hydrogeological stratification and lithological description of every drilling interval of a borehole. An example of a well log is shown in Fig. 1A, and a quick check of these well logs shows that many of them do not seem to be very reliable as they exhibit very similar lithological sequences and the hydrogeological units found in the lithological description of these well logs were not distinguished. This check also demonstrates that a small number of well logs do not have geographic coordinates, or the specified coordinates do not match the specified locality name. Hence, 331 well logs with questionable information were discarded. Fig. 3 shows the location of the 1,214 well logs selected for the modelling.

It should be noted that only 436 out of 1,214 boreholes were drilled through the 14 hydrogeological units. In the study region, the deepest well (drilling depth -558.79 m), which does not reach the bottom of aquifer n13, is Q618070 in the Soc Trang province. So, the uncertainty of the modeling increases with depth.

It is observed that the selected boreholes are not equally distributed spatially in the study region as most production wells are found near cities or townships. In addition, high lithological heterogeneity and sudden change in thickness of lithological layers are observed in some places. Therefore, bumpy interpolation of the top and bottom surfaces of the hydrogeological units in some places are expected due to these aforementioned factors.

From an individual well log sheet of the selected dataset, the following information are extracted and input into an MS Excel file, which is later imported to ArcGIS software for building the 3D hydrogeological solid model and GIS database: (i) Name, x-y coordinate, and z-value (ground elevation) of the borehole and (ii) name of hydrogeological unit (for instance aquitard Q2, aquifer qh, etc.), bottom elevation, thickness, and lithological description in top-down order until the bottom of the borehole.

Building the 3D hydrogeological solid model and database

As mentioned earlier, the Vietnam Hydrogeological Society has so far been conceptualizing the entirety of the unconsolidated sediments aged from Neogene to Quaternary in the VMD as a system of 7 aquifers and 7 aquitards. This system of stratification has appeared in most groundwater resource investigation projects or research publications for the study area, for example, in [7, 8, 17]. This stratification is based on a vertical distribution of lithological composition and the geological age of the soil layers appearing in the well logs. As a rule-of-thumb often exerted in practice, a layer or consecutive layers of fine grains (i.e., clay, silt, loam-silt) with a total thickness ≥5 m is stratified as an aquitard, and vice versa for an aquifer. In reality, that rule has been loosely applied to individual well logs based on personal expertise, and often without a reference to surrounding boreholes. This can result in a sudden change in thickness of a hydrogeological unit when a 3D stratification solid model is built. In this work, we still follow the abovementioned rule, but with careful verification and reference to nearby well logs as described in more detail in the following paragraphs. The building process of the 3D hydrogeological solid model and GIS database is shown in Fig. 4.

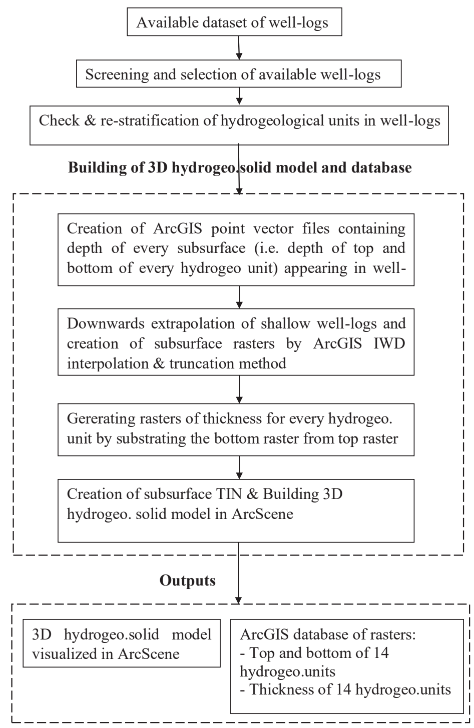


Fig. 4. Flowchart for building the 3D hydrogeological solid model and GIS database.

The modelling was carried out with ArcGIS software and underwent the following steps:

(i) Check and re-stratification (if necessary) of the hydrogeological units defined in the well logs:

In this research work, hydrogeological units are defined on the basis of the following criteria where each hydrogeological unit is composed of one or several consecutive lithological layers falling within one geological age. The unit is considered as an aquifer if (i) the total thickness of coarse-grained layers is ≥60% of the total thickness of that unit and (ii) the minimum thickness of the unit is ≥5 m. Vice versa, an aquitard is assigned if the total thickness of fine-grained layers is ≥60% of the total thickness of that unit and the minimum thickness of the unit is ≥5 m. The unit is given a name in accordance with geological age, i.e., aquitard Q2 and aquifer qh are Holocene age, etc. It is also conceptualized that for each geological age, the aquitard is overlying the aquifer. For instance, aquitard Q_1^3 is located above the aquifer qp3 (Table 1).

Table 1. Averaged thickness and distribution depth of geological and hydrogeological units.

Geological age	Overlying aquitard, average thickness and distribution depth (m)	Underlying aquifer, average thickness and distribution depth (m)
Holocene	$Q_{2;}$ 20.8; +0.1 ÷ -72.9	qh; 5.1; +1.8 ÷ -72.9
Upper Pleistocene	$Q_{1;}^{3}$ 2.9; -0.9 ÷ -104.3	qp3; 19.5; -2.1 ÷ -134.2
Middle-upper Pleistocene	Q_1^{2-3}; 16.4; -6.1 ÷ -161.5	qp23; 33.1; -13.2 ÷ -180.7
Lower Pleistocene	Q_1^1; 17.1; -28.3 ÷ -219.9	qp1; 32.3; -31.2 ÷ -248.4
Middle Pliocene	N_2^2; 15.8; -55.3 ÷ -316.3	n22; 37.9; -61.3 ÷ -413.4
Lower Pliocene	N_2^1; 23.4; -81.1 ÷ -430.3	n21; 22.1; -102.8 ÷ -458.3
Upper Miocene	N_1^3; 21.6; -142.4 ÷ -492.7	n13; 22.3; -161.1 ÷ -558.6

With the definition and criteria described above, a careful check and restratification (if necessary) was carried out for each well log to better define each hydrogeological unit appearance in the selected well logs. If a short drilling interval composed of one or several very thin lithological layers (i.e., the total thickness is less than 5 m) appears in the well logs, which is supposed to be defined as a hydrogeological unit, a cross-check was carried out to see if such unit exists in the nearby well logs. If it does exist there, the thin drilling interval is defined as a hydrogeological unit regardless of the 5-m minimum thickness criteria. This criteria-break is necessary as it mitigates the abrupt disappearance of a hydrogeological unit in some places, and thus allows a modelling of a smooth edged thinning of a unit as it appears in reality.

(ii) Extrapolation for shallow boreholes and creation of unit surfaces:

As mentioned in the above section, not all the selected boreholes were drilled through the 14 hydrogeological units (Table 2). The well logs of shallow boreholes must be extrapolated downwards to capture the elevation of the top and bottom of subsequent lower aquitards/aquifers for 3D modelling. An interpolation was initially used for NAWAPI's well log dataset by applying averaging (or inverse distance weighting - IDW) of the elevation of the top (or bottom) from the known elevation from the surrounding well logs. A detailed check for well logs in Ca Mau province revealed that elevation averaging method does not work well in some situations, especially those where the average bottom elevation for a hydrogeological unit is higher than the known bottom elevation of an overlying hydrogeological unit at the interpolation point. Therefore, a surface truncation method in combination with ArcGIS IDW interpolation was applied to create the top and bottom surfaces of each hydrological unit using known elevations. An in depth discussion on 3D structural geologic modelling can be found in F. Wellmann, et al. (2018) [18], while comparison of the three most common numerical interpretation methods, namely, IDW, triangulation, and kriging, are discussed in Russell, et al. (2015) [19] and MacCormack, et al. (2012) [20]. A pictorial explanation of the surface truncation method is presented in Fig. 7 in Wellmann, et al. (2018) [18], and insight into the ArcGIS IDW interpretation method is given in the following website: https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/how-invers e-distance-weighted-interpolation-works.htm.

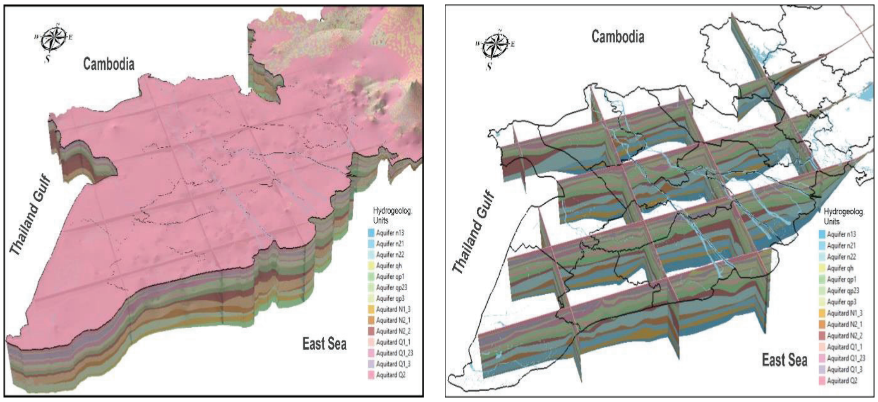
Table 2. Number of boreholes reaching into each aquifer.

Total number of selected boreholes	Aquifer qh	Aquifer qp3	Aquifer qp2-3	Aquifer qp1	Aquifer n22	Aquifer n21	Aquifer n13	Bedrock
1,214	1,214	1,158	946	816	773	615	472	436

To apply the abovementioned methods for the 3D modelling of the VMD, the surface was created from the top down, i.e., the Q_2 top surface was created first, followed by the Q_2 bottom using ArcGIS IDW, etc. The ArcGIS IDW interpolation was carried out in two steps. The first step was using boreholes that reach the bottommost unit to generate a "tentative" surface, and to assign a surface elevation to a borehole that does not reach the bottom if the drilling depth is shallower than the "tentative" surface elevation (i.e., downwards extrapolation for shallow boreholes). The second step is done with all boreholes, including the extrapolated boreholes, to generate the unit bottom. The thickness of Q_2 was then formed by subtracting the bottom from the top. The cells with negative thickness were considered to be areas where the unit does not exist, i.e., creating a "vertical hydrogeological window", and therefore were assigned zero thickness values. The bottom was then recalculated by subtracting the new thickness from the top, which also became the top of the underlying aquifer (i.e., truncating the bottom where it is higher than the top). This calculation sequence was carried out for every hydrogeological unit from the uppermost to the bottommost to create a set of 200 m resolution raster files representing the top, thickness, and bottom of each aquifer and aquitard.

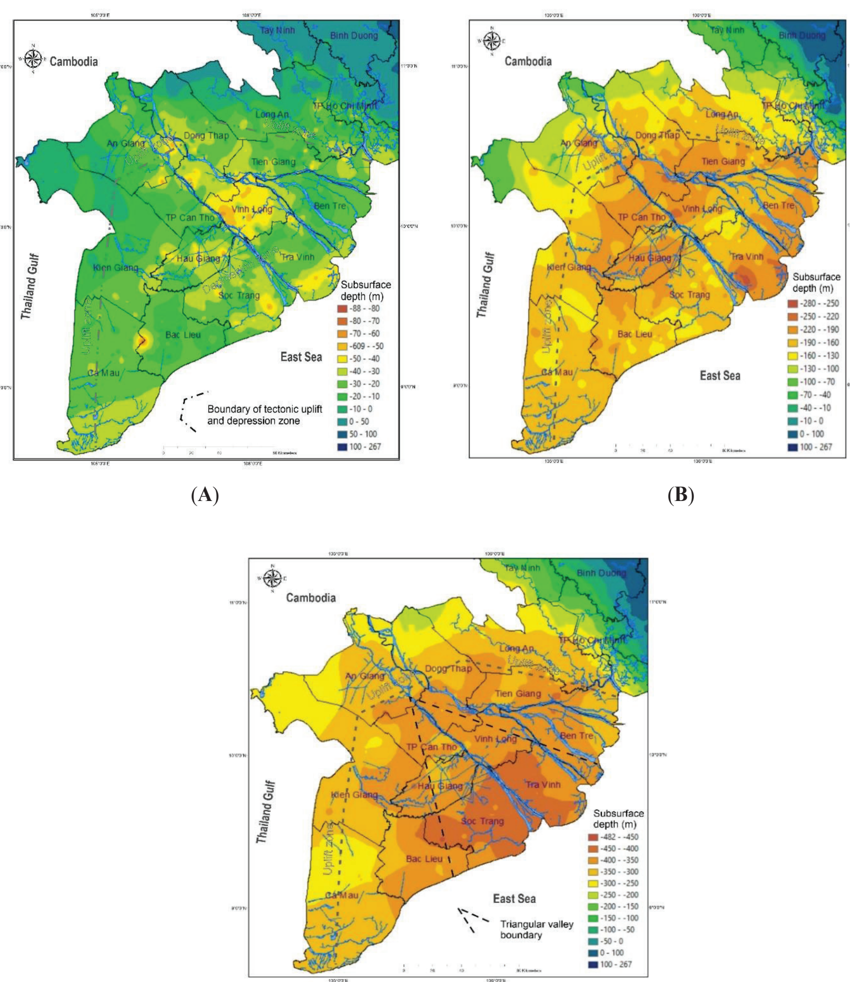
Results

The resulting 3D hydrogeological solid model and GIS database, i.e., the set of rasters for the top, bottom, and thickness of the 14 hydrogeological units, can be visualized in 3D view with AcrScene or 2D view with ArcMap as shown in Figs. 5 and 6 below. Although the 3D model and GIS database are built for ArcGIS software, they can be viewed with any geological-water resource professional software like Rockworks or GMS without any complicated import/export procedure.



(A) (B)

Fig. 5. A 3D view of (A) the 3D hydrogeological model and (B) cross-sections in the VMD.



(A) (B)

(C)

Fig. 6. Subsurface depth of the VMD at the beginning of (A) Holocene (8.2-11.7 Ka), (B) Pleistocene (1.8-2.58 Ma), (C) Late Miocene (7.3-11.63 Ma), and boundary of tectonic uplifted zones outlined by Bao, et al. (2001) [21] **and Trang, et al. (2019)** [13].

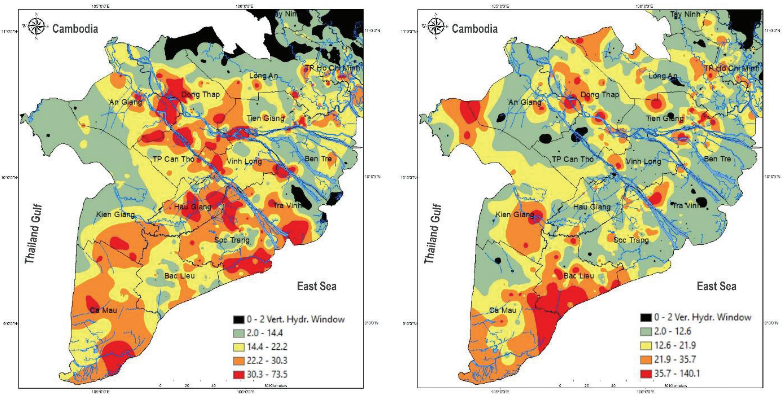
Discussion

The 3D hydrogeological solid model and GIS database constructed in this work can be exploited in various ways for different types of groundwater management. In this research work, we present only two examples of using the 3D model and GIS database for two specific topics related to groundwater use and management in the VMD: land subsidence and vertical intrusion of contaminants and salt water.

Role of tectonic vertical displacement in current land subsidence

Land subsidence in the VMD is often linked to excessive groundwater exploitation, but it can be also caused by other factors like tectonic vertical displacement. In this research work, we verify this assumption as described below.

A recent publication by Schmidt, et al. (2017) [22] describes the structural features and deformation history of the Cuu Long basin (offshore of the Mekong delta) in significant detail. In this work, the authors connected the onshore North - Northwest oriented mafic veins with similar offshore faulting systems in the Cuu Long basin. These veins are considered weak zones in the basement prior to rifting and were later reactivated in early Eocene rifting. Besides, this paper describes a major faulting system in the Mekong delta and defines a linkage between the Mae Ping fault in Thailand and Cambodia oriented on the western side of the Kampot Folding system. The change from left-lateral displacement to right-lateral displacement during the transpression period from mid-early Oligocene to mid-late Oligocene (31-25 Ma) (Morley, et al., 2007 [3]; Schmidt, et al., 2017 [22]) and the reactivation since Early Eocene (20-25 Ma) of this fault has been considered to result in vertical neo-tectonic movement in some locations in the Mekong delta (Bao, et al., 2001 [21]). The present delta was formed and shaped in the Holocene (Lap, et al., 2000 [12]; Oanh, et al., 2002 [23], Trang, et al., 2019 [13]). In this study, a verification and delineation of uplift and depression zones from the abovementioned publications are made using the 3D solid model and 3D hydrogeological database. As shown in Fig. 6C, in the Late Miocene, the VMD was shaped as a triangular valley of alluvium and a depression zone at depths of -400 to -480 m were observed in the provinces of Soc Trang and Tra Vinh along the Hau river. Surrounding this valley is an uplift zone. The transgression from Late Miocene to Early Pleistocene filled up this valley with marine sediments, but it remained a depression zone at depths ranging between -160 and -280 m in the central provinces of Hau Giang, Can Tho, Vinh Long, and Dong Thap, and the coastal provinces of Tra Vinh and Ben Tre (Fig. 6B). In the Early Holocene, depression zones were much less prevalent in both area and magnitude, although the uplifting continued (Fig. 6A). Therefore, the contribution of tectonic vertical displacement to the current land subsidence at a rate of 1-4 cm/year [4, 5] is not meaningful.



(A) (B)

Fig. 7. Thickness distribution maps of (A) aquitard Q_2 and (B) aquitard Q_1^{2-3} showing "vertical hydrogeological windows" (where aquitard thickness <2 m) and possible seeping zones (where aquitard thickness 2-14 m) between aquifer qh - ground surface and qp23 - qp3.

Vertical intrusion of contaminant and salt water

Salt water is reported to appear in many areas distributed along the coastal provinces of Ca Mau, Bac Lieu, Soc Trang, and Tra Vinh. Especially in the Ben Tre province, the groundwater is almost salty and therefore the surface water is the main source of water supply for domestic use and agricultural production [8]. In addition, other contaminations in the VMD have been reported in a publication by Buschmann, et al. (2008) [24]. From this report, the arsenic concentration ranged from 0.1-1,340 µg/l with 37% of the studied wells exceeding WHO guidelines of 10 µg/l arsenic. Meanwhile, 50% of the studied wells exceeded the manganese WHO guideline of 0.4 mg/l. In this research work, we attempt to obtain a prediction of the pathway of these contaminations with the 3D solid model and the 3D hydrogeological database.

Contaminant transport likely occurs in either direct hydraulic interaction zones through "vertical hydrogeological windows" or in seeping zones of less permeable aquitards. Maps of seven aquitards were created with the 3D hydrogeological database, which show aquitards are 20-140 m thick and are quite well confined from the aquifers around each other. A few zones of direct hydraulic interaction (i.e., thickness ≤2 m) and zones of possible seeping (i.e., thickness 2-14 m) are an exception, and these occur in the topmost aquitard Q_2 and in the aquitard Q_1^{2-3} intercalated between aquifers qp3 and qp23 (Fig. 7). Distributions of these zones in the topmost aquitard show arsenic and manganese contamination in groundwater are not likely exogenetic in origin, at least for the central part of the VMD and the Ca Mau peninsular (Figs. 7A, 7B). Vertical intrusion of contaminants from aquifers qp3 to qp23 is possible through an extensive distribution of seeping zones where aquitard thicknesses range between 2-12.6 m. Contamination seepage from other aquifers likely does not occur because of the thick aquitards confining them. The above facts imply an endogenous origin of these contaminants related to sediment deposition.

Conclusions

A 3D hydrogeological solid model and GIS database of the VMD were constructed in this research work. The database and solid model were based on 1,214 carefully selected boreholes scattered across the study region. Because of the high heterogeneity of lithology, and only a small number of well logs reaching the deepest aquifer, inverse distance weighting (IDW) was used to interpolate the elevations of the top and bottom from the known elevations from the surrounding well logs as well as a surface truncation method being applied when the bottom is higher than the top.

The constructed 3D hydrogeological database and 3D stratification solid model are applied to analyze the role of tectonic vertical displacement in current land subsidence and the possible vertical intrusion of contaminants and salt water in the VMD. The result shows that tectonic vertical displacement is negligible in comparison to the current land subsidence rate of 1-4 cm/year, and the contamination is of endogenous origin and likely does not transfer across aquifers.

Apart from the abovementioned application, the 3D hydrogeological solid model and GIS database can also be applied to different types of groundwater management, for instance, groundwater vulnerability mapping, site selection and design of artificial recharge, underground construction to mitigate saltwater intrusion, rough estimation of transboundary groundwater flow, or site selection of a production well field, etc.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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