

Supplementary Information for

**Simulating Extraction-induced Subsidence in the
Mekong Delta: Investigating the Effects of
Discretization and Conductivity Uncertainty**

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Contents

S1 Geomechanical Model Parameters	3
S2 Analysis of Horizontal Hydraulic Conductivity Point Data	4
S3 Characteristics of Horizontal Hydraulic Conductivity Fields	7
S4 Monte Carlo Simulation of Vertical Aquifer Anisotropy	8
S5 Correlation Between Hydraulic Head and Compaction Rate Differences	10
S6 Hydraulic-Head Evolution from the HHC Monte Carlo Ensemble	11
S7 Hydraulic Head Distribution in Particular Aquitards	12

S1 Geomechanical Model Parameters

All simulations are built on the Mekong delta (MKD) base model of Minderhoud et al. [1, 2] and use the same SUB-CR geomechanical parameterisation [3, 4]. The a , b , c constants, namely elastic recompression, plastic compression, and secondary (creep) compression, and the overconsolidation ratio (OCR) are identical to the original set-up and are listed in Table S1. No re-calibration was performed, as the present analysis targets uncertainty from HHC and aquitard discretisation.

Model layer	Description	OCR	a	b	c
2	Aquitard 1	1.63	1.6E-02	8.0E-02	3.1E-03
3	Aquifer 1	1.63	1.0E-03	3.0E-03	0.0E+00
4	Aquitard 2	1.63	1.0E-02	5.1E-02	2.0E-03
5	Aquifer 2	1.63	7.7E-04	2.3E-03	0.0E+00
6	Aquitard 3	1.63	8.1E-03	4.0E-02	1.6E-03
7	Aquifer 3	1.63	1.1E-03	1.8E-03	0.0E+00
8	Aquitard 4	1.63	6.6E-03	3.3E-02	1.3E-03
9	Aquifer 4	1.63	4.9E-04	1.5E-03	0.0E+00
10	Aquitard 5	1.63	5.3E-03	2.6E-02	3.1E-03
11	Aquifer 5	1.63	4.0E-04	1.2E-03	0.0E+00
12	Aquitard 6	1.63	4.4E-03	2.2E-02	8.7E-04
13	Aquifer 6	1.63	3.3E-04	9.9E-04	0.0E+00
14	Aquitard 7	1.63	3.6E-03	1.8E-02	7.2E-04

Table S1: The OCR and a , b , c parameters of the model layers used for subsidence modelling in the MKD model [1, 2].

S2 Analysis of Horizontal Hydraulic Conductivity Point Data

The spatial distribution of HHC measurements across MKD aquifers is uneven. Counts per aquifer are listed in Table S2. For example, in aquifer 3 most measurements lie within the Saigon catchment and fewer within the Mekong catchment (Figure S1). The datasets contain both clusters and isolated points, yielding variable point density across the domain; this motivated testing declustering prior to spatial analysis.

Aquifer	MKD	Mekong catchment	Saigon catchment	Mean HHC (m d ⁻¹)
1 (QH)	25	5	20	8
2 (QP3)	131	50	81	20
3 (QP23)	207	66	141	19
4 (QP1)	191	59	132	23
5 (N22)	258	90	168	21
6 (N21)	143	72	71	17
7 (N13)	40	22	18	17

Table S2: HHC data points per aquifer, MKD and catchment, and mean HHC.

We tested spatial declustering using Voronoi polygons constructed per aquifer in ArcGIS Pro. The relative area of each polygon (with respect to the model domain) was used as a weight for the associated data point. However, this procedure did not improve normality, and the Voronoi weights were therefore not used in subsequent analyses.

Because kriging assumes approximately Gaussian residuals, we assessed normality for all aquifers and found it insufficient for kriging realisations. Several transformations were evaluated; the fourth-root transform,

$$\text{trHHC} = \text{HHC}^{1/4},$$

provided the closest approximation to a Gaussian distribution (here, trHHC denotes the transformed HHC).

We then examined linear trends, as ordinary kriging requires a trend-free mean. Quadratic trends were also tested for aquifers 4 and 6 (the least and most pronounced E–W linear trends), but were not significant. We therefore restricted detrending to linear terms, consistent with parsimony. The significance of linear trends for the transformed HHC by dataset and aquifer is summarised in Table S3.

Finally, we assessed spatial correlation by fitting spherical semivariogram models. Where a linear trend was present, models were fitted to residuals of trHHC; otherwise, they were fitted directly to trHHC.

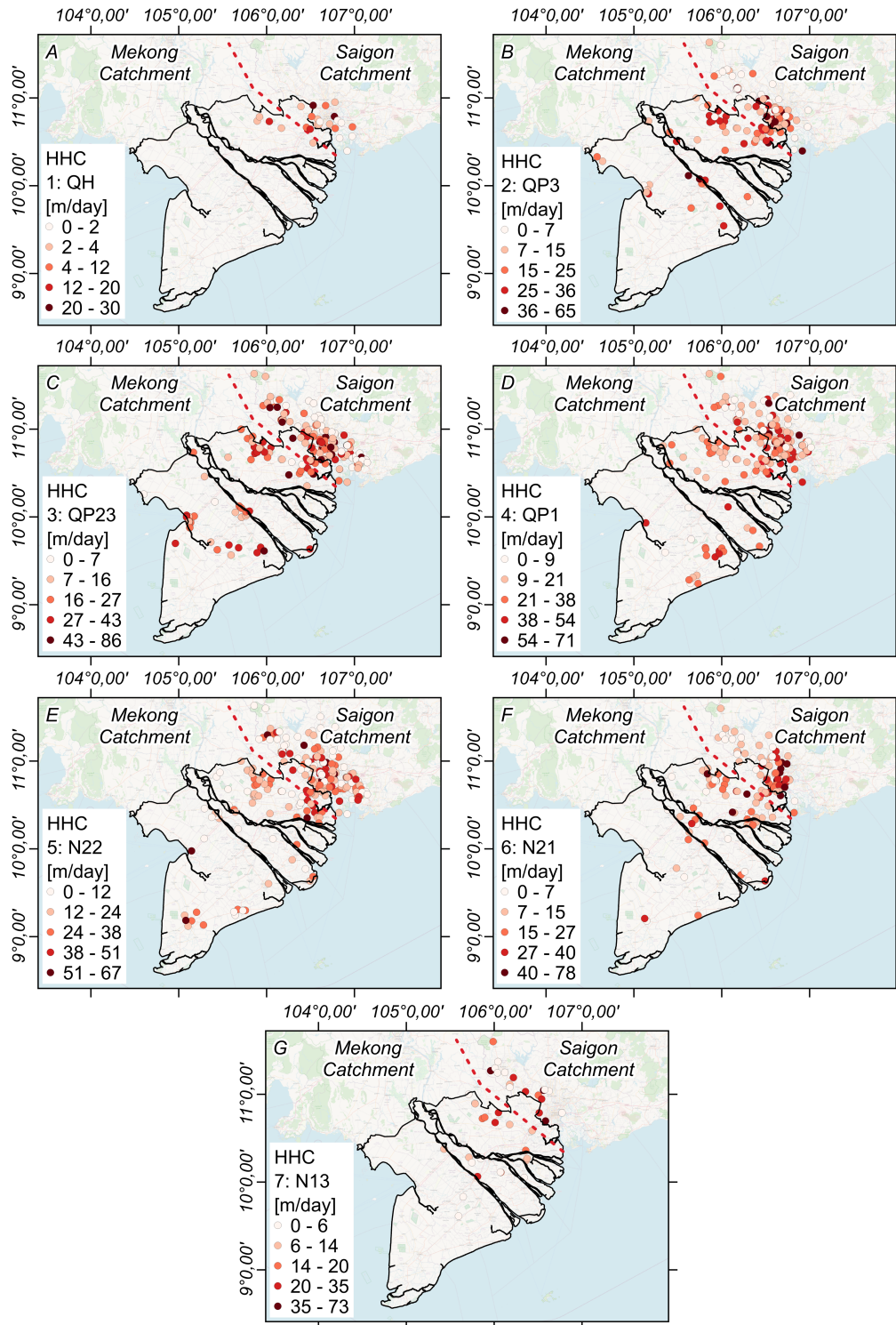


Figure S1: Spatial distribution of HHC measurement points in aquifers 1 (A) to 7 (G) of the MKD. Data source: Division for Water Resources Planning and Investigation for the South (DWRPIS)[5].

Aquifer	MKD	Mekong catchment	Saigon catchment
1	No significant linear trends	—	—
2	Trend N-S** Significant semivariogram	No significant linear trends	Trend N-S** Significant semivariogram
3	Trend E-W**	No significant linear trends Significant semivariogram	Trends E-W*** and N-S***
4	No significant linear trends	No significant linear trends Significant semivariogram	No significant linear trends
5	Trend E-W** Significant semivariogram	No significant linear trends Significant semivariogram	No significant linear trends
6	Trend E-W*** Significant semivariogram	No significant linear trends	No significant linear trends Significant semivariogram
7	No significant linear trends	—	—

Table S3: Spatial properties of the transformed HHC by dataset (MKD, Mekong catchment, Saigon catchment) and aquifer. Asterisks denote significance levels.

S3 Characteristics of Horizontal Hydraulic Conductivity Fields

For each of the seven aquifers, we generated 50 white-noise fields using the R package `RandomFields` (simulation B). Each field was combined with the aquifer-specific spatial trend and fitted semivariogram to produce an HHC realisation, yielding 7×50 realisations in total. For reproducibility, the random seeds used to generate the white-noise fields are listed in Table S4.

Realisations				
A1 seed = 1234	B1 seed = 1224	C2 seed = 1314	D1 seed = 1054	E1 seed = 0954
A2 seed = 1244	B2 seed = 1214	C3 seed = 1324	D2 seed = 1044	E2 seed = 0944
A3 seed = 1254	B3 seed = 1204	C4 seed = 1134	D3 seed = 1034	E3 seed = 0934
A4 seed = 1264	B4 seed = 1194	C5 seed = 1124	D4 seed = 1024	E4 seed = 0924
A5 seed = 1274	B5 seed = 1184	C6 seed = 1114	D5 seed = 1014	E5 seed = 0914
A6 seed = 1284	B6 seed = 1174	C7 seed = 1104	D6 seed = 1004	E6 seed = 0904
A7 seed = 1294	B7 seed = 1164	C8 seed = 1094	D7 seed = 0994	E7 seed = 0894
A8 seed = 1334	B8 seed = 1154	C9 seed = 1084	D8 seed = 0984	E8 seed = 0884
A9 seed = 1344	B9 seed = 1144	C10 seed = 1074	D9 seed = 0974	E9 seed = 0874
A10 seed = 1354	C1 seed = 1304	C11 seed = 1064	D10 seed = 0964	E10 seed = 0864

Table S4: Random seeds used to generate white-noise fields with `RandomFields` (R) for the 50 HHC realisations (simulation B).

S4 Monte Carlo Simulation of Vertical Aquifer Anisotropy

To study the uncertainty due to vertical aquifer anisotropy (VAA), a second Monte Carlo (MC) simulation was performed (Table S5, simulation B2). In the original model (Table S5, simulation A), a constant anisotropy ratio of 3 was used, based on literature estimates in the absence of local data [6]. To test the sensitivity of the model to this assumption, 50 random realisations were created using white noise centred around a mean value of 3 with a standard deviation of 2.9. This follows estimates of aquifer anisotropy ratios from western Louisiana, which typically range from 1 to 3, with some outliers up to 8 [6].

The realisations lacked spatial correlation and were applied uniformly across aquifers in randomised order. As with the HHC Monte Carlo simulation, each realisation was used as input to a full simulation of hydraulic head and subsidence for the period from 1991 to 2020.

The results of the VAA simulation are not shown in the main manuscript because vertical flow within aquifers is minimal in this setting. However, VAA influences vertical connectivity between aquifers and aquitards, which could in principle impact delayed compaction processes. Therefore, it was included in the uncertainty analysis to ensure completeness.

The results show that, in contrast to the HHC ensemble (see Section Uncertainty Due to Aquifer Hydraulic Conductivity (HHC) in the main text), varying VAA has no impact on subsidence at the delta scale, both in terms of mean and standard deviation (Figure S2). This negligible influence is attributed to the fact that most compaction occurs in the aquitards, where VAA is not applied, and the limited role of vertical flow within the aquifers under the imposed boundary conditions. As such, the effect of VAA on interlayer pressure propagation is too small to significantly alter compaction dynamics.

Simulation	Layers per aquitards	Aquitard VAA specification
A	1	Constant anisotropy ratio
B1 (Simulation B in the main text)	1	Constant anisotropy ratio
B2	1	MC realisations (unconditional; mean constrained to the deterministic model)

Table S5: Model simulations used in this study. Simulations B are adaptations of the original MKD hydrogeological model (simulation A) [2].

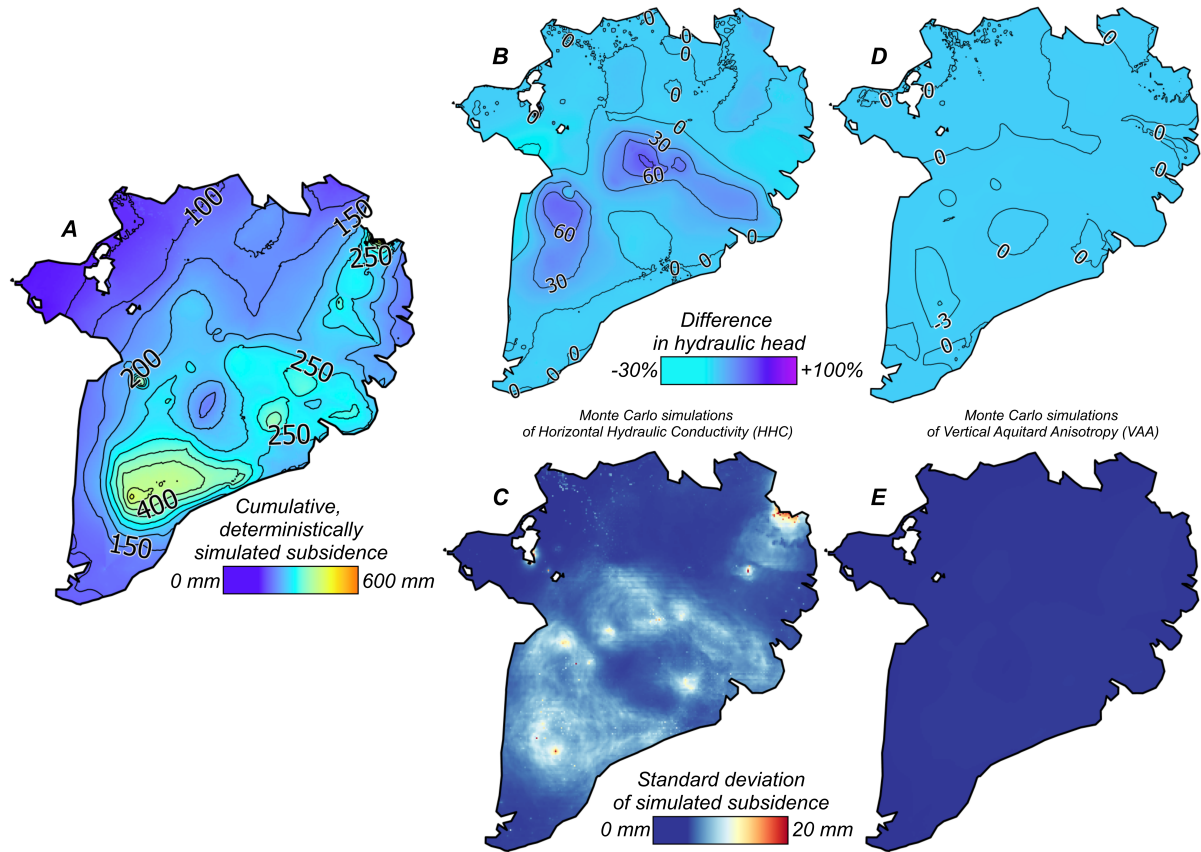


Figure S2: (A) Deterministic cumulative land subsidence (CLS) in the MKD, 1991-2020 (simulation A) [2]. (B) Difference in CLS between the HHC Monte Carlo (MC) ensemble mean (simulation B1) and the deterministic simulation (simulation A). (C) Standard deviation of CLS across HHC MC realisations (simulation B1). (D) Difference in CLS between the VAA MC ensemble mean (simulation B2) and the deterministic simulation (simulation A). (E) Standard deviation of CLS across VAA MC realisations (simulation B2).

S5 Correlation Between Hydraulic Head and Compaction Rate Differences

Aquitard	Correlation of difference in simulated hydraulic head and subsidence	Correlation of standard deviation in simulated hydraulic head and subsidence
2	SR: 0.76	SR: 0.90; PC: 0.85
3	SR: 0.77	SR: 0.92; PC: 0.88
4	SR: 0.83	SR: 0.86; PC: 0.86
5	SR: 0.86	SR: 0.79; PC: 0.87
6	SR: 0.86	SR: 0.77; PC: 0.81
7	SR: 0.84	SR: 0.64; PC: 0.76

Table S6: Spearman’s rank (SR) and Pearson (PC) correlation coefficients between simulated hydraulic heads and land subsidence per aquitard. Left: correlation of differences. Right: correlation of standard deviation. Subsidence simulations are based on the mitigation M1 groundwater extraction scenario (simulation A) [2].

S6 Hydraulic-Head Evolution from the HHC Monte Carlo Ensemble

To assess the influence of horizontal hydraulic conductivity (HHC) uncertainty on simulated groundwater dynamics, we analysed hydraulic-head time series from the Monte Carlo (MC) ensemble of 50 HHC realisations (simulation B). Two representative locations were selected within the MKD to illustrate the variability in simulated head behaviour.

The simulations reveal different responses in head evolution depending on the local hydrogeological setting and the stochastic input field. At one site, the ensemble shows a systematically faster decline than the deterministic (simulation A) reference case, while at the other, the spread includes both slower and faster drawdown trajectories. This illustrates how uncertainty in HHC translates into differences in the rate and timing of drawdown under similar forcing conditions (Figure S3).

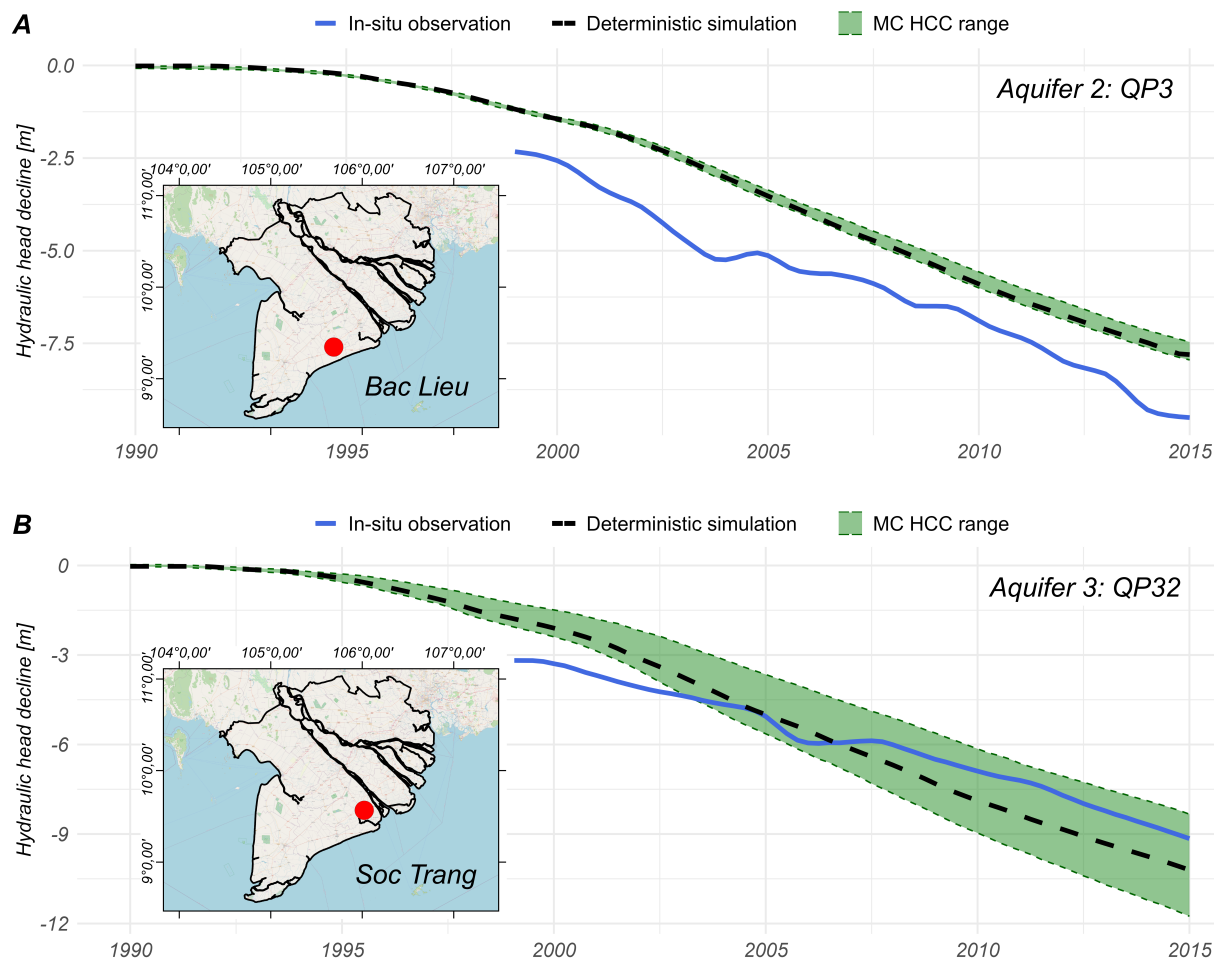


Figure S3: Hydraulic head levels over time at Bac Lieu (A) and Soc Trang (B), as computed from the 50 HHC Monte Carlo simulations (simulation B, coloured lines), compared to the deterministic reference simulation A (dashed line) and the field observations (dotted line).

S7 Hydraulic Head Distribution in Particular Aquitards

This section presents the distribution of hydraulic head in all aquitards, based on results from both the single (simulation A) and five-layer model (simulation C3) of the MKD for the period 1991–2020. The data are shown for selected locations representing four categories of groundwater head decline:

- low decline (Figure S4),
- medium decline (Figure S5),
- high decline (Figure S6),
- and extremely high decline (Figure S7).

These points are situated in different regions of the MKD. Their locations are indicated in Figure 5 of the main text. Note that the horizontal axes in Figures S4, S5, S6, S7 differ according to the year and location shown.

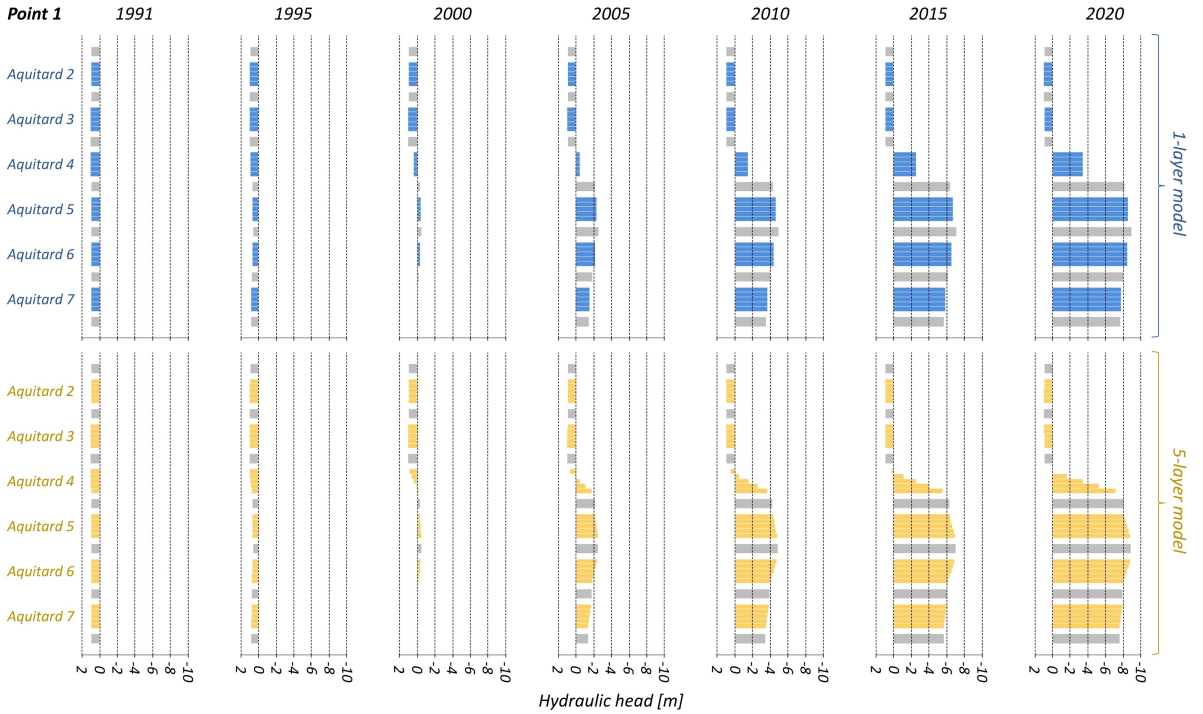


Figure S4: Hydraulic head distribution in particular aquitards as retrieved from the single (simulation A) and five-layer model (simulation C3) of the MKD between 1991 and 2020 in Point 1 (low groundwater head decline). See Figure 5 in the main text for Point 1 location.

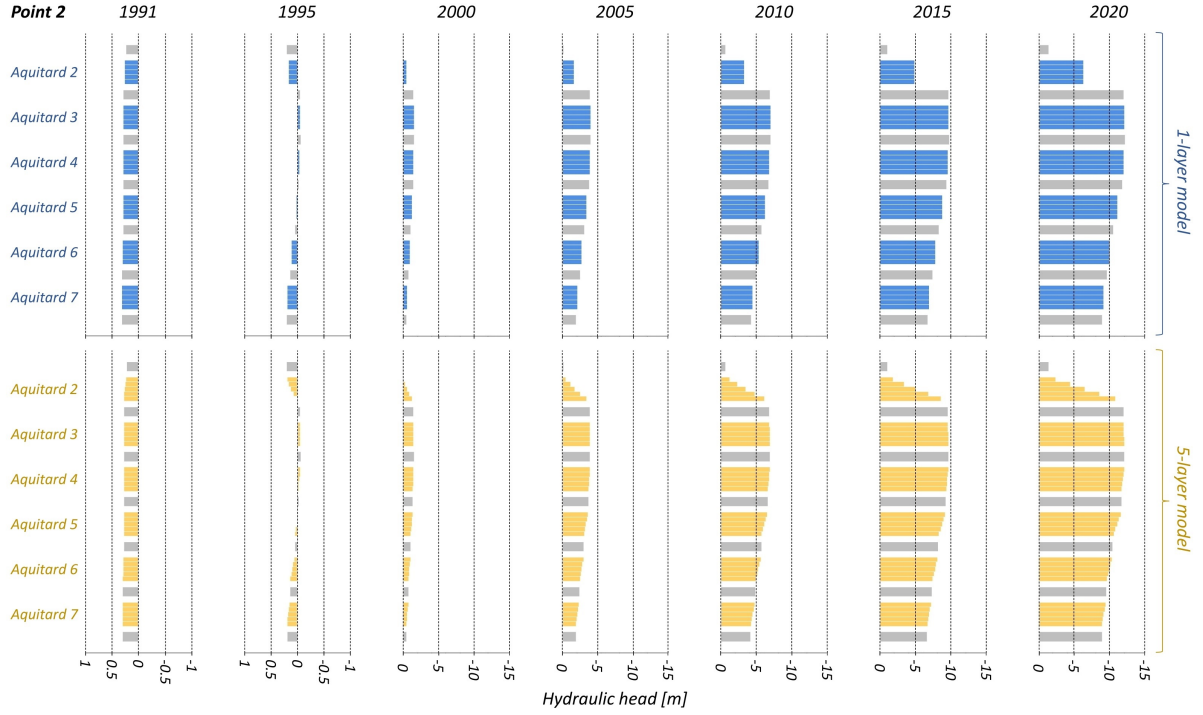


Figure S5: Hydraulic head distribution in particular aquitards as retrieved from the single (simulation A) and five-layer model (simulation C3) of the MKD between 1991 and 2020 in Point 2 (medium groundwater head decline). See Figure 5 in the main text for Point 2 location.

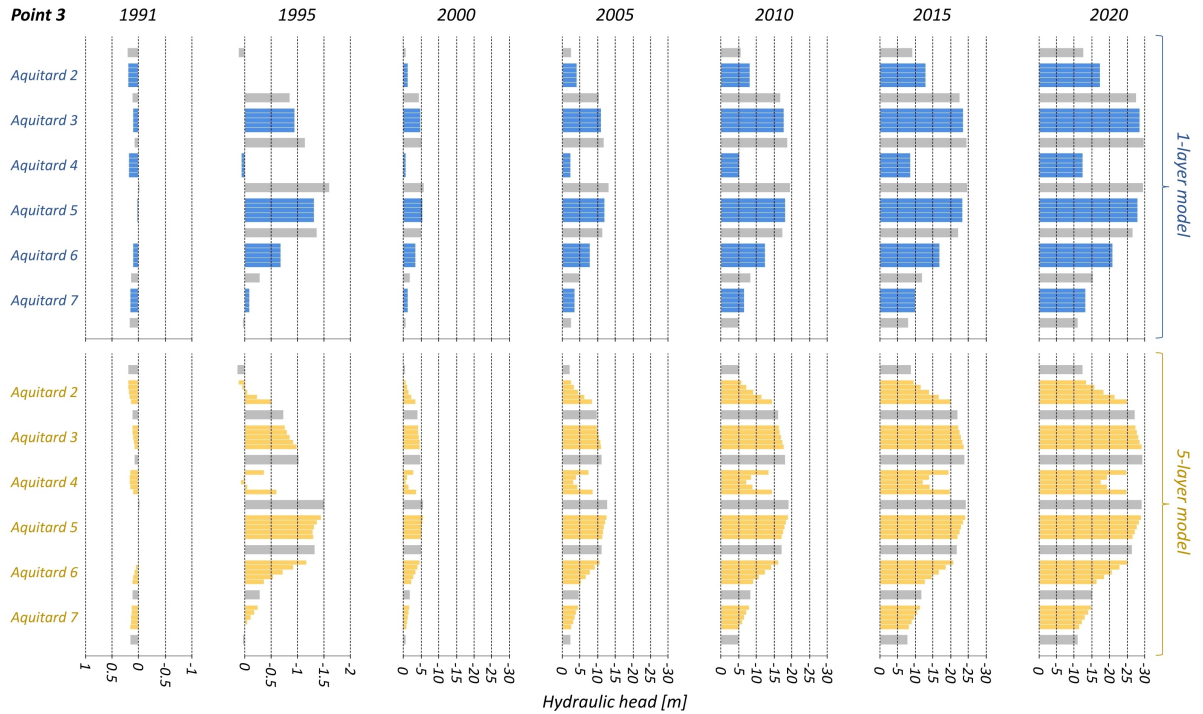


Figure S6: Hydraulic head distribution in particular aquitards as retrieved from the single (simulation A) and five-layer model (simulation C3) of the MKD between 1991 and 2020 in Point 3 (high groundwater head decline). See Figure 5 in the main text for Point 3 location.

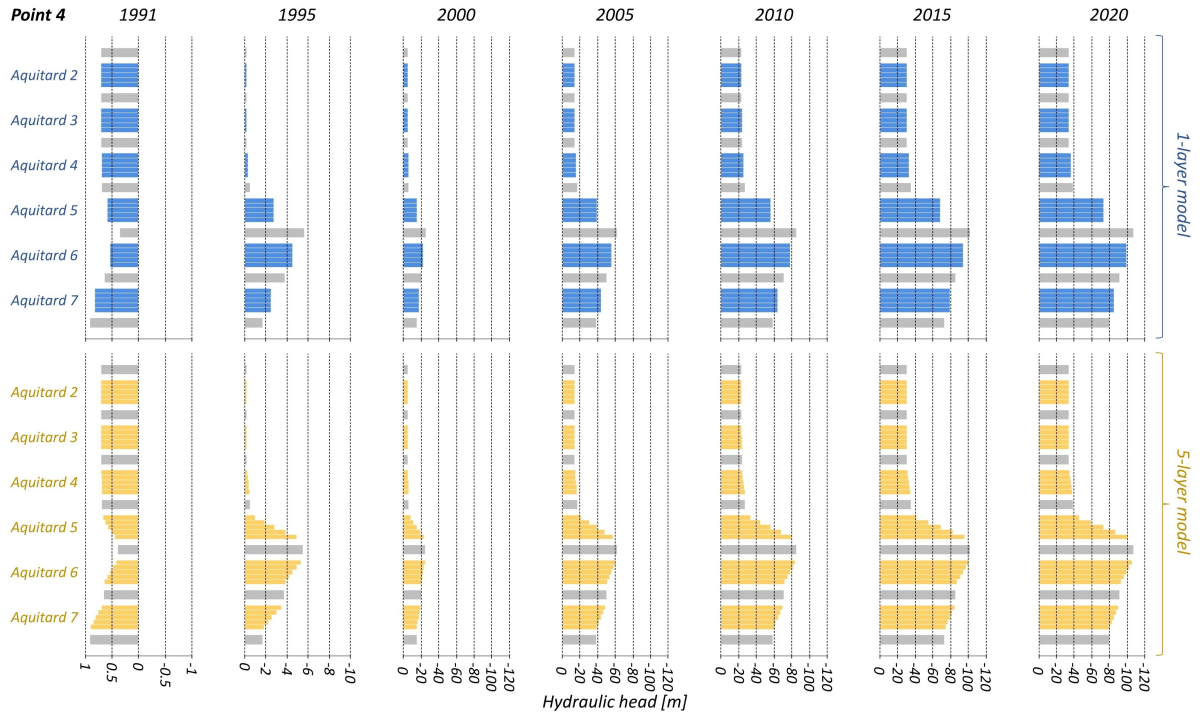


Figure S7: Hydraulic head distribution in particular aquitards as retrieved from the single (simulation A) and five-layer model (simulation C3) of the MKD between 1991 and 2020 in Point 4 (extreme groundwater head decline). See Figure 5 in the main text for Point 4 location.

Additional References

- [1] P S J Minderhoud, G Erkens, V H Pham, V T Bui, L Erban, H Kooi, and E Stouthamer. Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental Research Letters*, 12(6):064006, jun 2017.
- [2] P. S. J. Minderhoud, H. Middelkoop, G. Erkens, and E. Stouthamer. Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. *Environmental Research Communications*, 2(1):1–14, 2020.
- [3] Henk Kooi, Mahmoud Bakr, Ger de Lange, Evert den Haan, and Gilles Erkens. User guide to SUB-CR: a MODFLOW package for land subsidence and aquifer system compaction that includes creep, 2018.
- [4] H. Kooi and G. Erkens. Creep consolidation in land subsidence modelling; integrating geotechnical and hydrological approaches in a new modflow package (sub-cr). *Proceedings of the International Association of Hydrological Sciences*, 382:499–503, 2020.
- [5] Division for Water Resources Planning and Investigation for the South (DWRPIS). Report on the Results of the National Groundwater Monitoring Network for Nam Bo Plain. Unpublished report, Division of Water Resources Planning and Investigation of Vietnam, 2010.
- [6] Douglas Carlson. Estimate of Vertical Anisotropy of Hydraulic Conductivity for Northern Louisiana Aquifers from Grain-Size Data. In *Proceedings of the 57th Annual Convention of the Gulf Coast Association of Geological Societies (GCAGS)*, Texas, 2007.