

Supplementary information for “Revisiting hydraulic response times in regional multilayer groundwater systems: the role of aquitards and surface boundaries”

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S1 – Compilation of parameters and characteristics of major regional groundwater systems

Table S1: Compilation of orders of magnitudes of the geometric characteristics of some regional groundwater basins. The presented figures aim to provide a general overview of the orders of magnitude of basin extension, thickness, and maximum flow lengths. For detailed information about a specific basin, the reader is referred to the literature.

Aquifer system	Area [10 ³ km ²] a, b	Length [km] c *	Maximum thickness [m] b	Lithology aquifers b	Modern recharge rates [mm yr ⁻¹] b, d, e	Abstraction rates [km ³ yr ⁻¹] b **	Abstractions/ Recharge [%] **
Aquitaine Basin ^f	60	200	Cenozoique sequence: 2000 Mesozoic sequence: up to 10000	Unconsolidated sediments. Fractured and karstified limestones. Sandstones	100 – 300	0.29	3 - 8 %
Paris Basin ^g	190	320 - 420	3200	Sandstone, chalk	100 - 300	2.7	5 - 14 %
Great Artesian Basin _i	1700	400 - 1500	3000	Sandstones	Central region: 0 – 20 North-East region: 20 -100 Mean: 0.59	0.55	54 %
Guarani Aquifer ^j	1195	400	800	Sandstones and basalts	20 - 300	1	<1 - 5 %
Amazon Basin ^k	2000	3000	7000	Sandstones	>300	0.59	< 1 %
Nubian Aquifer System ^l	2199	750	3500	Sandstones	0 - 20	6.3	242 %
Lower Kalahari Basin ^m	350	780	10000	Sandstones, basalts, sands	2 - 100	0.04	2 %
North-Western Sahara Aquifer System ⁿ	1019	3000	500 – 1000	Sandstones, carbonates and clastic sediments	1 - 2	2.8	128 - 270 %
Arabian Aquifer System ^o	1485	-	6500	Sandstones and limestones	1.8	16	611 %
Floridan Aquifer System ^p	1150	-	9000 - 12000	Sands and gravels, carbonate rocks	130 - 200	30	13 - 20 %
North China Plains	320	770	600	Confined and unconfined alluvial deposits	130 - 200	37	60 - 92 %
Western Siberian Basin	3200	1750	6000	Sediments partly sub-permafrost	100 - 300	1.3	< 1 %

15 **Table S2: Compilation of orders of magnitudes of main hydraulic parameters of main hydrogeological units in some regional groundwater basins. The presented figures aim to provide a global overview of the orders of magnitude of the parameters of hydrogeological units. For detailed information about a specific basin, the reader is referred to the literature.**

Aquifer system	Aquifer horizontal hydraulic conductivity [m s ⁻¹]	Aquitard vertical hydraulic conductivity [m s ⁻¹]	Specific yield (Unconfined areas) [-]	Specific storage [m ⁻¹] *	Layer thickness [m]
Aquitaine Basin ^f	Plioquaternary: 1×10 ⁻⁴ – 1×10 ⁻² Miocene: 1×10 ⁻⁵ – 1×10 ⁻² Oligocene: 1×10 ⁻⁵ – 1×10 ⁻² Eocene: 1×10 ⁻⁶ – 3×10 ⁻⁴	Oligocene – Eocene aquitards: 1×10 ⁻¹² – 1×10 ⁻⁶	Plioquaternary: 0.05 – 0.34 Miocene: 0.01 – 0.1 Oligocene: 0.16 – 0.28 Eocene: 0.2 – 0.35	Miocene: 1×10 ⁻⁵ – 6×10 ⁻⁵ Oligocene: 1×10 ⁻⁶ – 1×10 ⁻⁴ Eocene: 1×10 ⁻⁶ – 3×10 ⁻⁶	Plioquaternary: ~10 - 100 Miocene: 50 - 120 Oligocene: ~200 Eocene: 50 - 250 Oligocene – Eocene aquitards: ~5 - 300
Paris Basin ^g	Dogger: 1×10 ⁻⁸ – 1×10 ⁻⁵ Albian: 1×10 ⁻⁶ – 1×10 ⁻³ Neocomian: ~ 1×10 ⁻⁶	1×10 ⁻¹² – 1×10 ⁻⁹	Dogger: 0.15 - 0.2 Albian: 0.12 – 0.3	Dogger: 5×10 ⁻⁵ – 5×10 ⁻⁴ Albian: 1×10 ⁻⁴ – 5×10 ⁻⁴	Dogger: ~ 70 - 250 Albian: 30 – 180 Neocomian: ~60
Great Artesian Basin ⁱ	Cadna-owie – Hooray: 2×10 ⁻⁷ – 9×10 ⁻⁴	Westbourne – Birkhead aquitards: 2.5×10 ⁻¹⁰ – 5×10 ⁻¹⁰	0.06 - 0.15	Cadna-owie – Hooray: ~5×10 ⁻⁶ Westbourne – Birkhead aquitards: ~6×10 ⁻⁷	Cadna-owie – Hooray: 73 - 824 Westbourne aquitard: 24 - 247
Guarani Aquifer ^j	Bauru group: 1×10 ⁻⁶ – 1×10 ⁻⁵ Serra Geral fractured basalts: ~5×10 ⁻⁵ – 8×10 ⁻³ Botucatu - Piramboia: 2×10 ⁻⁶ – 2×10 ⁻³	Serra Geral basalts: ~5×10 ⁻⁷ Passa Dois: 8×10 ⁻⁸	0.07 – 0.2	Botucatu aquifer: 4×10 ⁻⁷ – 1×10 ⁻⁵	Bauru group: ~200 Botucatu - Piramboia: 50 - 600 Serra Geral basalts: ~500 – 1000 Passa Dois: ~ 450
Amazon Basin ^k	Solimões/Alter do Chao group: 1×10 ⁻⁵ – 1×10 ⁻⁴ Tikuna Aquifer System: ~ 3×10 ⁻⁶	Solimões group clay layers: 1×10 ⁻⁸ – 1×10 ⁻⁶	0.1 – 0.25	Solimões group: 1×10 ⁻⁵ – 1×10 ⁻⁴	Solimões group: ~250 Tikuna Aquifer System: 250 – 700 Solimões group clay layers: 20 - 50
Nubian Aquifer System ^l	Nubian Sandstone Aquifer: 1×10 ⁻⁶ – 1×10 ⁻³	Clay layers: 1×10 ⁻⁹ – 1×10 ⁻⁷	0.01 – 0.365	Nubian Sandstone Aquifer: 1×10 ⁻⁶ – 1×10 ⁻⁴	Nubian Sandstone Aquifer: 260 - 2000

Lower Kalahari Basin ^m	Kalahari - Lebung Aquifers: $1 \times 10^{-6} - 1.7 \times 10^{-4}$ Ecca Aquifer: $1 \times 10^{-5} - 1.7 \times 10^{-4}$	Stormberg basalt aquitard: $\sim 3.5 \times 10^{-9}$ Inter Karoo Aquitard: $1 \times 10^{-12} - 1.4 \times 10^{-9}$	0.21 – 0.35	Stampriet Aquifer System: $1 \times 10^{-7} - 1 \times 10^{-5}$	Kalahari Aquifer: $\sim 6 - 200$ Stomberg basalt aquitard: ~ 200 Lebung Aquifer: ~ 230 Inter Karoo Aquitard: ~ 250 Ecca Aquifer: ~ 290
North-Western Sahara Aquifer System ⁿ	Complexe Terminal: $\sim 1 \times 10^{-3}$ Continental Intercalaire: $8 \times 10^{-6} - 1.3 \times 10^{-4}$	$1 \times 10^{-13} - 1.4 \times 10^{-10}$	0.01 – 0.1	Continental Intercalaire: $\sim 1 \times 10^{-5} - 1 \times 10^{-4}$	Complexe Terminal: ~ 340 Continental Intercalaire: ~ 350

^a (Margat and Gun, 2013) ^b (Gun, 2022) ^c (Rousseau-Gueutin et al., 2013) ^d (Richts et al., 2011) ^e (Döll and Flörke, 2005) ^f (Aissat et al., 2023; Biteau et al., 2006; BRGM, 1994, 2003, 2005, 2016, 2026; Curnelle et al., 1997; Douez, 2007; Larroque et al., 2008, 2013; Ortiz et al., 2020; Pédrón et al., 2006, 2008; Saltel et al., 2019; Thiéry et al., 2011) ^g (Amédéo and Matrimon, 2014; Bourgeois and Girard, 2010; Castro et al., 1998; Delmas et al., 2002; Gonçalves, 2002; Gonçalves et al., 2004b, a; Guillocheau et al., 2000; Humez et al., 2011; Jost, 2005; Jost et al., 2007; Mas et al., 2022; Seguin et al., 2015) ^h ⁱ (Bethke et al., 1999; Costelloe et al., 2020; Habermehl, 2020; Jiang, 2014; Smith and Welsh, 2011; Welsh, 2007) ^j (Aurelia et al., 1989; Bonotto, 2006; Gómez et al., 2010; Gonçalves et al., 2020; Hirata and Foster, 2021; Kirchheim et al., 2019; Rabelo and Wendland, 2009; Rodríguez et al., 2013; Sracek and Hirata, 2002; Wendland et al., 2006) ^k (Henrichs de Azevedo and Guimarães Campos, 2021; Hu et al., 2017; Rosário et al., 2016; Souza et al., 2013) ^l (Geresh et al., 2023; Hosseini et al., 2024; Sefelnasr, 2007; Voss and Soliman, 2014) ^m (Kinoti et al., 2024; Lekula et al., 2018; Mpuang et al., 2023; Stone and Edmunds, 2012; Wright and Hall, 1990) ⁿ (Gonçalves et al., 2013, 2020; Ould Baba, 2005; Petersen et al., 2014; Rafaâ Trigui et al., 2021) ^o (Schulz et al., 2017) ^p (Johnston, 1999; Williams and Kuniansky, 2015)

^{*} When storage properties are reported in the literature as storage coefficients, a specific storage is assumed to be two orders of magnitude lower.

^{*} The lengths here presented are taken as the total confined and unconfined lengths compiled by Rousseau-Gueutin et al. (2013) for each basin. For the Amazon Basin, Lower Kalahari Basin, North Western Sahara Aquifer System, Floridan Aquifer System, and the Arabian Aquifer System, the length is provided as an approximation of the major regional flow path length and the spatial limits of the systems after Richts et al. (2011); Margat and Gun (2013); and Gun (2022).

^{**} Abstraction data representative of the year 2010 and mean annual recharge compiled by Gun (2022). For the Aquitaine Basin and the Pannonian Basin, additional references where used. The abstraction rates in km^3/year are converted to mm/year over the approximated area of the basin for the calculation of abstraction to recharge ratios.

S2 – Validation of the two-dimensional analytical formulation

The proposed approach relies on the following considerations regarding boundary conditions: (i) In the horizontal direction, the system can be approximated as a one-dimensional flow domain of length L bounded by Dirichlet conditions, and (ii) in the vertical direction, the system can be approximated as a one-dimensional domain of thickness B bounded by a Dirichlet condition at the surface and a no-flow boundary at the base. This configuration implies a well-developed regional surface drainage system. Additionally, this implies the presence of a hard-rock basement or a low-permeability layer at the base of the system.

45 The transient perturbation is modelled through an instantaneous step-change boundary forcing, representing a regional recharge change that drives a rapid response in the unconfined areas. This formulation is valid when the shallow response of unconfined areas occurs on timescales much shorter than those associated with re-equilibration in the deeper parts of the groundwater basin. The transient problem is then simplified with a step-change boundary forcing and determined by the relaxation from the initial state. Additionally, the governing equation is linear and only considers compressible storage. These
50 assumptions are valid for *boundary-driven* unconfined response regimes, provided that water table changes remain small relative to the total saturated thickness. When the system departs from this response regime in unconfined areas, such as in *storage-driven* regimes, the analytical formulation would require accounting for specific yield through a full time-dependent boundary forcing.

55 Additionally, the magnitude of the hydrological change is relevant and must not alter or disrupt the surface boundaries at the regional scale over the long-term. Cuthbert et al. (2019) studied the mode of groundwater interactions with climate–surface systems and found that these interactions are relatively insensitive to a 50% change in recharge, which is considered important in the context of century-scale projections (Cuthbert et al., 2019; Döll et al., 2003). This does not mean that groundwater systems are unresponsive, instead it implies that the regime of surface–climate–groundwater interactions remains stable under
60 such changes. Consequently, in many basins worldwide, the dominant regional response regime is unlikely to shift over the coming century. A shift in regime would require long-term interruption of surface–groundwater interactions, as discussed for the Nubian, North-Western Sahara, or Arabian aquifer systems during the Late Pleistocene–Early Holocene climatic transitions (Schulz et al., 2017).

65 To assess the robustness of the proposed two-dimensional formulation for *unit-scale* and *basin-scale* response times, we use our synthetic numerical model to perform 500 simulations with randomly assigned parameter sets. Horizontal hydraulic conductivities of aquifer units were sampled from a log-normal distribution spanning from 1×10^{-7} to $1 \times 10^{-3} \text{ m s}^{-1}$. For aquitard units, horizontal hydraulic conductivities were sampled from a log-normal distribution spanning from 1×10^{-13} to $1 \times 10^{-8} \text{ m s}^{-1}$. Anisotropy ratios for each layer (k_v/k_h) ranging between 0.1 and 1, were drawn from a normal distribution,
70 ensuring that vertical hydraulic conductivity is lower than or equal to horizontal hydraulic conductivity in each unit. Specific storage for each layer was sampled from a log-normal distribution ranging from 10^{-6} to 10^{-4} , and specific yield in unconfined areas from a normal distribution between 0.1 and 0.3. This ensemble of simulations introduces varying degrees of heterogeneity and structural complexity into the multilayer system, relaxing the simplifying assumptions of the analytical formulation.

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For each parameter set, the 95th percentile of the simulated response time distribution within the deepest layer (Unit 5) was compared to the same analytical formulations discussed in the methods section, as shown in Fig. S1. The results show that the proposed two-dimensional unit-scale formulation provides the best agreement with the simulated response times for the

deepest confined aquifer in the multilayer system. The mean absolute error is approximately 0.24 log-years, corresponding to a deviation of about one-quarter of an order of magnitude from the simulated values. The one-dimensional confined-flow formulation still substantially overestimates response times in some cases, with a mean absolute error of 0.52 log-years, equivalent to approximately half an order of magnitude. The mixed-aquifer formulation consistently overestimates response times, by approximately two orders of magnitude on average.

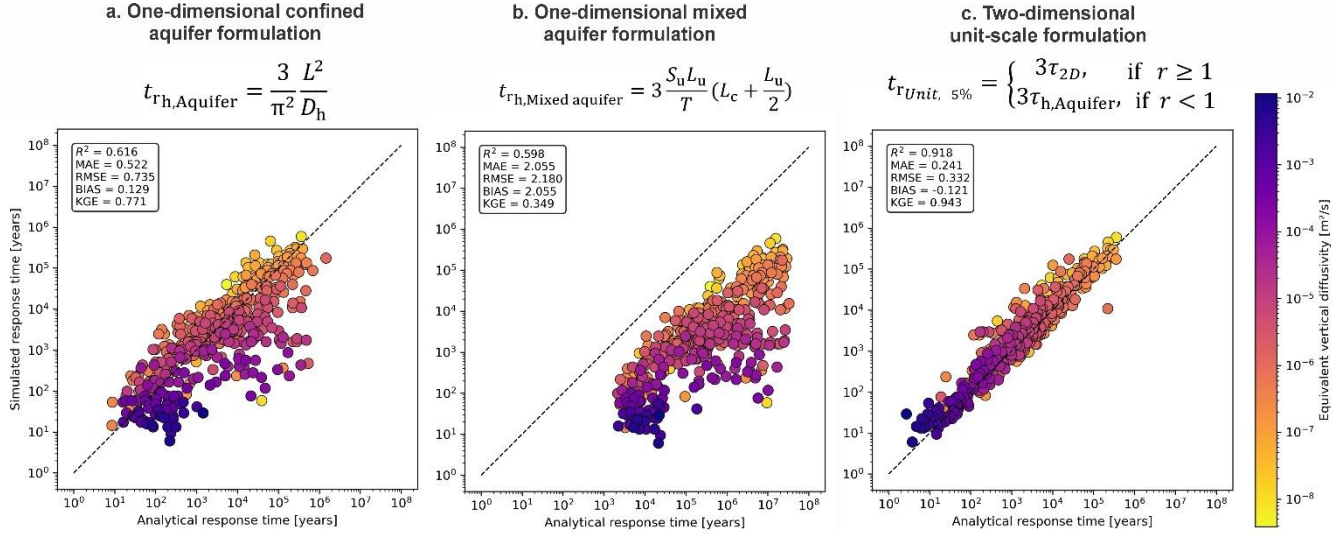
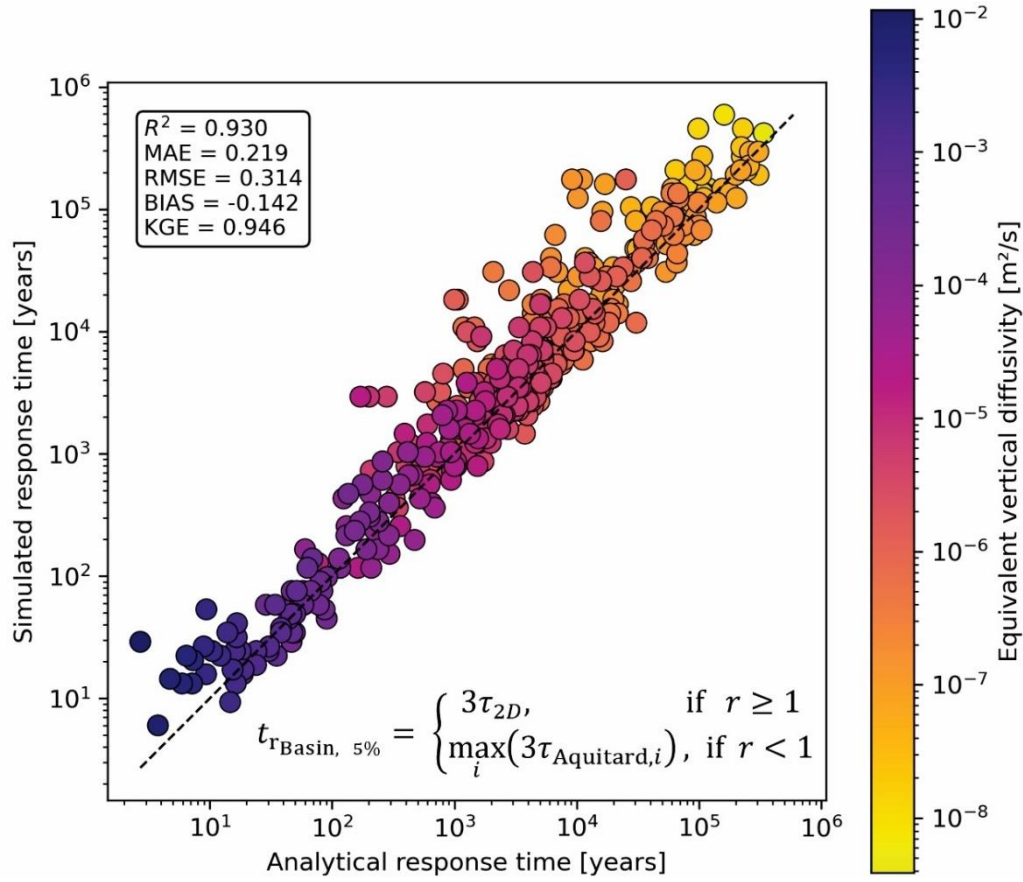


Figure S1. Scatter plot of unit-scale analytical formulations versus simulated 95th percentile response times for the deepest confined aquifer unit. R^2 : Coefficient of determination. MAE: Mean Absolute Error. RMSE: Root Mean Squared Error. KGE: Kling–Gupta efficiency.

Similarly, the 95th percentile of the simulated response time distribution over the whole model domain was compared with the analytical *basin-scale response time* derived using the two-dimensional formulation. Performance was evaluated in terms of orders of magnitude, using the base-10 logarithm of response times, as shown in Fig. S2. The results show that the method provides robust order-of-magnitude estimates, with a mean absolute error of 0.2 log years, corresponding to an average deviation of approximately a factor of 1.5 from the simulations. Moreover, 98% of the estimates are within an order of magnitude from the simulations, supporting its usefulness as a scoping estimation. The observed dispersion likely reflects additional factors influencing system response, such as layer anisotropy and contrasts in diffusivity over unconfined areas. Additionally, the analytical formulation assumes a rectangular basin with uniform thickness and length. Real basins have varying thickness and potentially different flow lengths across units. In practice, the approximation remains a robust order-of-magnitude estimate when representative flow lengths and basin thickness are used, as confirmed by numerical testing with our synthetic model. Overall, the largest uncertainties are expected to arise from the representative hydraulic parameters used, particularly hydraulic conductivities of low-permeability formations.



105 **Figure S2. Scatter plot of analytical versus simulated 95th percentile basin-scale response times. R^2 : Coefficient of determination. MAE: Mean Absolute Error. RMSE: Root Mean Squared Error. KGE: Kling–Gupta efficiency.**

Additionally, the proposed two-dimensional unit-scale and basin-scale analytical formulations were evaluated against different variations of the synthetic numerical model regarding number of layers, thickness, horizontal extension, and outcropping areas. Figure S3 presents cross-sections of each version of the numerical model used, and the scatter plots of unit-scale and basin-scale response times. In general, the proposed formulation reproduces well the simulated response times both at the unit-scale
 110 for the deepest confined aquifer unit within the multilayer system, and at the basin scale. In all cases, the mean absolute error is lower than 0.2 log-years, which implies deviations from the simulations by less than a factor of 1.5. This supports the robustness of the method as an order-of-magnitude estimate of response times in regional multilayer systems, provided that the discussed analytical assumptions are satisfied.

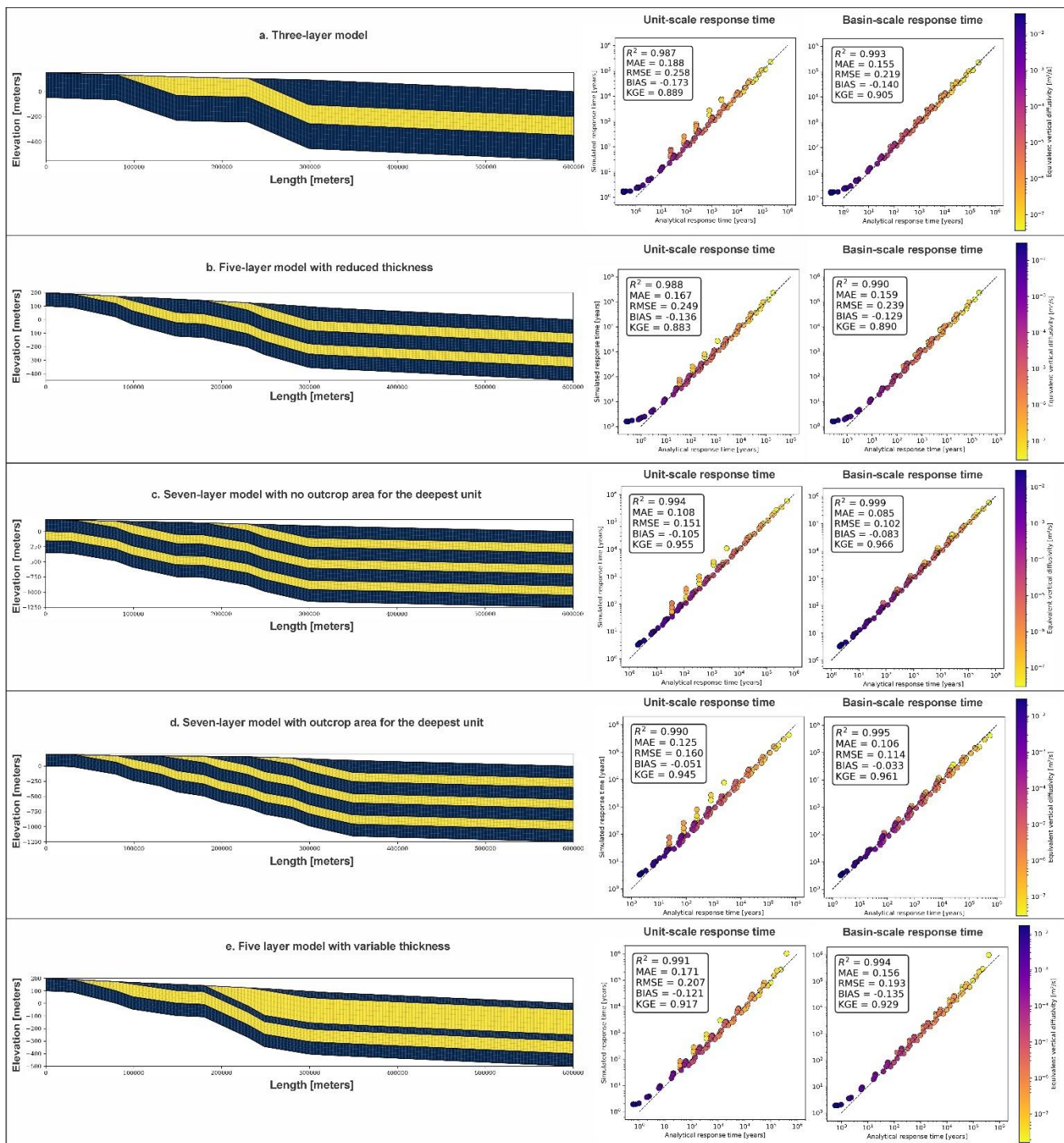


Figure S3. Evaluation of the two-dimensional *unit-scale* and *basin-scale* formulations for the estimation of response times against different versions of the numerical model.

S3 – Example application

120 The proposed two-dimensional analytical approach is implemented for the Aquitaine Basin, France, where annual groundwater recharge is approximately 200–300 mm. The presence of a well-developed surface drainage network makes this basin a suitable case study for applying the proposed two-dimensional analytical approach, as the response of unconfined areas is expected to be relatively rapid and predominantly boundary-driven. To characterize the system, we compiled data on the hydrodynamic parameters, thicknesses, and lengths of the hydrogeological units comprising the Cenozoic sedimentary sequence of the basin. A simplified stratigraphic column and the relevant parameter ranges are presented in Fig. S4.

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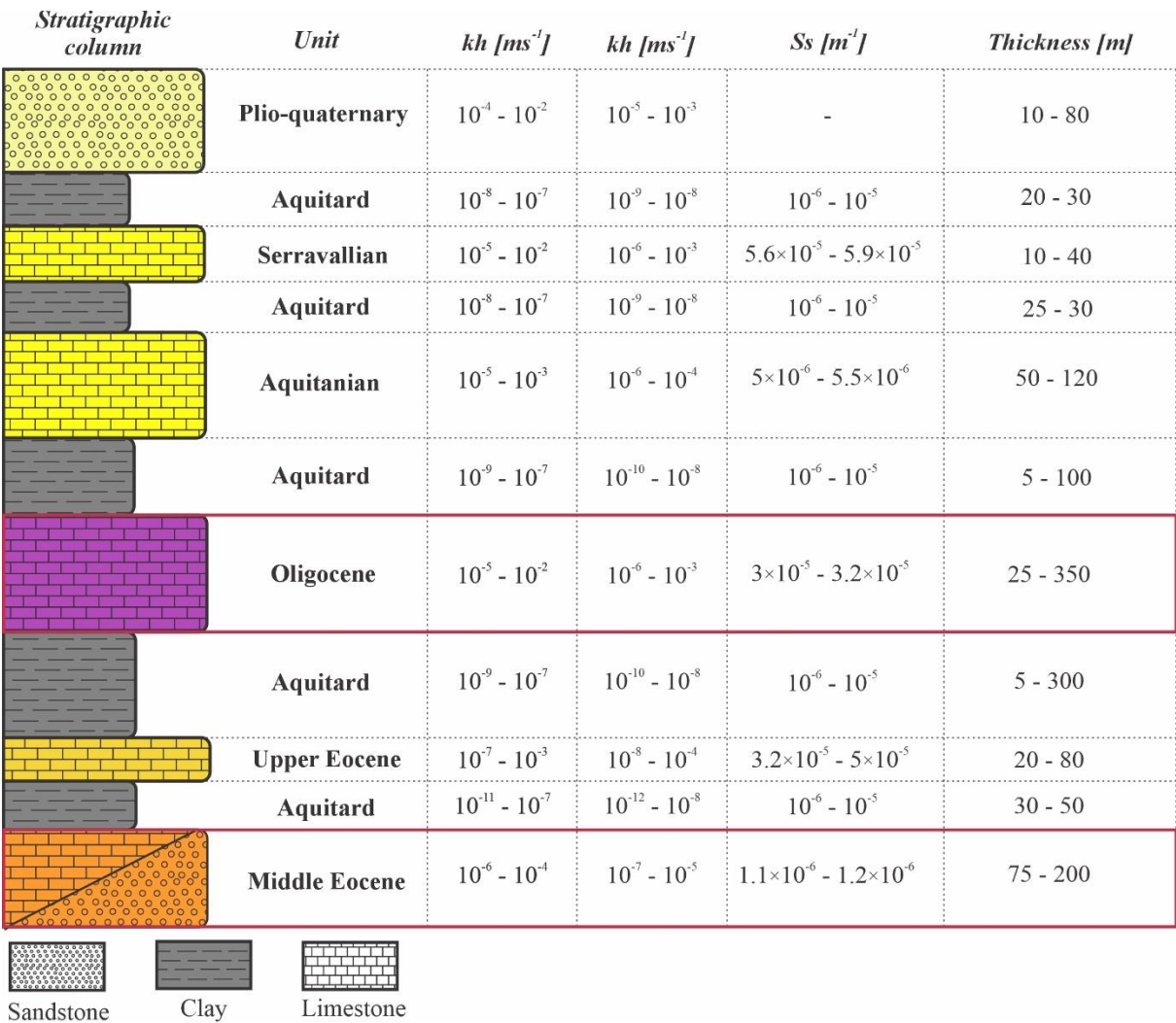


Figure S4. Generalized stratigraphic column of the Cenozoic sequence in the Aquitaine Basin France and representative parameters used in the response time estimation. Stratigraphic units as defined in the North-Aquitaine Groundwater Model and other studies (Aissat et al., 2023; Saltel et al., 2019; Thiéry et al., 2011).

130 To account for parameter uncertainty, we used a Monte Carlo approach (50,000 realizations) to derive probability distributions of unit-scale response times for the confined Oligocene and Middle Eocene aquifers, which are important for local water supply. For this we analyse the multilayer system formed by the target aquifer and all overlying units. Each realization determines the degree of hydraulic coupling, r , and applies the two-dimensional formulation for coupled cases ($r \geq 1$), and the one-dimensional confined aquifer formulation for uncoupled cases ($r < 1$).

135 Representative ranges of horizontal hydraulic conductivity and specific storage for the aquifer layers were derived from the calibrated parameter fields obtained by Aissat et al. (2023), as well as the ranges of vertical hydraulic conductivity for the aquitard layers. For the specific storage of aquitard units, a range of 10^{-6} to 10^{-5} m^{-1} was taken as representative following the estimates of Larroque et al. (2013). For the specific yield of the unconfined aquifers, we used a conservative range of 0.1–0.3.

140 Layer thicknesses were taken from maps and reports published by the French Geological Survey (BRGM, 1994, 2003, 2005, 2016, 2026). Lengths for each unit were obtained from measurements over official geological maps (BRGM, 2026), with 80 km for the Oligocene aquifer and 140 km for the Middle Eocene aquifer, with a log10-space standard deviation of 0.3 applied to represent the uncertainty.

145 For every parameter defined by a reported range, that range was interpreted as the 5th and 95th percentiles of the corresponding fitted distribution. Hydraulic conductivities and specific storage were sampled from a lognormal distribution spanning the given ranges, specific yield was sampled from a normal distribution, and layer thicknesses were sampled from a uniform distribution over the reported range. Parameters were sampled independently within each layer and were treated as spatially uniform, layer-representative values.

150 The results indicate that response times for the Oligocene aquifer are predominantly on the order of years, ranging from a few months to a few decades, with a median of 3 years. Around 99% of the Montecarlo estimations resulted in a well coupled system, ($r \geq 1$), suggesting that vertical diffusion through aquitards dominates the response. For the Middle Eocene aquifer, estimated response times are more likely on decadal timescales, ranging from a few years to centennial timescales, with a

155 median of 26 years. Similarly, around 90% of the realizations were classified as a well coupled system, implying that vertical diffusion through the aquitards remains relevant to the response, while localized uncoupling can occur in areas where aquitards are thicker and less diffusive. These estimates differ substantially from previous one-dimensional estimates for the Aquitaine Basin, which range from 10^3 to 10^6 years (Rousseau-Gueutin et al., 2013), as shown in Fig. S5.

160 Our results are consistent with recent studies of the hydrodynamic behaviour of confined aquifers in France, which show that groundwater levels in confined aquifers within major sedimentary basins are strongly influenced by annual to decadal hydroclimatic variability (Chidepudi et al., 2025a, b). A system can only track forcing that varies on timescales comparable to or slower than its own response time; forcing that varies much faster is damped rather than transmitted. This demonstrated

sensitivity to annual and decadal climatic forcing is therefore difficult to reconcile with response times at multimillennial scales, as it would imply near-complete damping of the signal. Hydraulic response times are consequently likely to be substantially shorter than those previously estimated by one-dimensional formulations, consistent with the annual-to-decadal timescales obtained here.

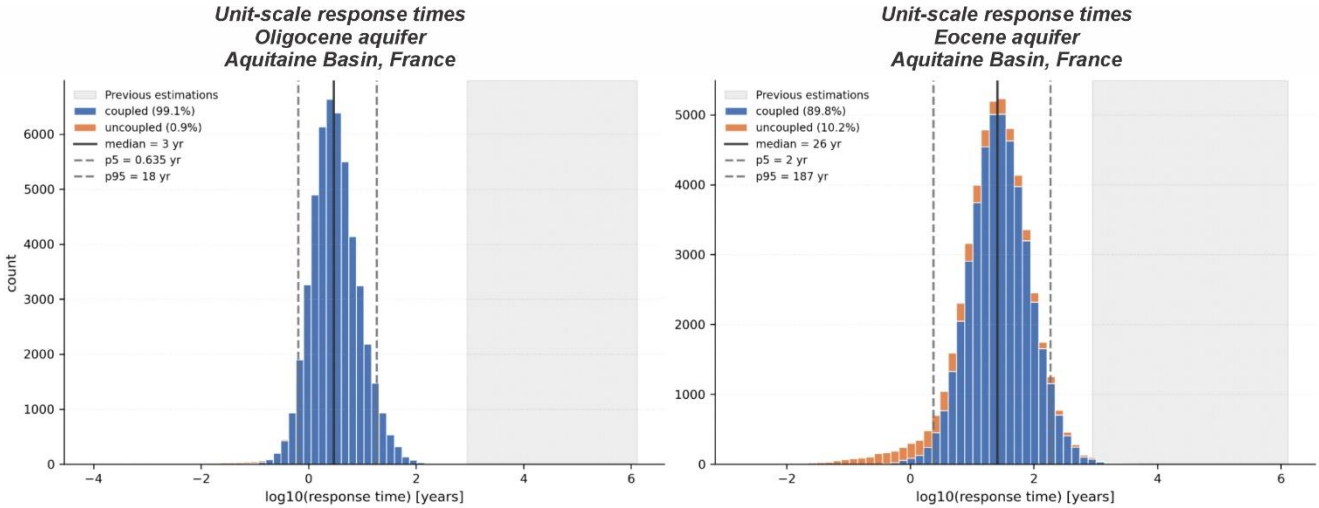


Figure S5. Unit-scale response time distributions from the Monte Carlo estimation for the Oligocene and Middle Eocene aquifers in the Aquitaine Basin, France.

This implies that these systems can be influenced by present-day climatic conditions and may be more vulnerable to climate change over the coming century than previously assumed. Additionally, these findings have important implications for groundwater management. Response times ranging from a few years to a few decades make groundwater abstraction from these aquifers directly relevant to management over typical planning horizons, which generally span 5–50 years. These timescales are also relevant for defining long-term management objectives and assessing the acceptable impacts of groundwater abstraction over intergenerational timeframes of approximately 100 years (Currell et al., 2016; Cuthbert et al., 2023; Gleeson et al., 2012).

References

Aissat, R., Pryet, A., Saltel, M., and Dupuy, A.: Comparison of different pilot point parameterization strategies when measurements are unevenly distributed in space, *Hydrogeol J*, 31, 2381–2400, <https://doi.org/10.1007/s10040-023-02737-z>, 2023.

Amédéo, F. and Matrimon, B.: L'étage Albien dans sa région-type, l'Aube (France) : une synthèse dans un contexte sédimentaire global, *Carnets Geol.*, 2014.

Aurelia, A., Silva, K. E., Rebouças, A. da C., Marlucia, M., and Santiago, F.: 14C Analyses of Groundwater From the Botucatu Aquifer System in Brazil, *Radiocarbon*, 31, 926–933, <https://doi.org/10.1017/S0033822200012546>, 1989.

- Bethke, C. M., Zhao, X., and Torgersen, T.: Groundwater flow and the 4He distribution in the Great Artesian Basin of Australia, *Journal of Geophysical Research: Solid Earth*, 104, 12999–13011, <https://doi.org/10.1029/1999JB900085>, 1999.
- 190 Biteau, J.-J., Le Marrec, A., Le Vot, M., and Masset, J.-M.: The Aquitaine Basin, *Petroleum Geoscience*, 12, 247–273, <https://doi.org/10.1144/1354-079305-674>, 2006.
- Bonotto, D. M.: Hydro(radio)chemical relationships in the giant Guarani aquifer, Brazil, *Journal of Hydrology*, 323, 353–386, <https://doi.org/10.1016/j.jhydrol.2005.09.007>, 2006.
- Bourgeois, B. and Girard, J. F.: First Modelling Results of the EM Response of a CO2 Storage in the Paris Basin, *Oil Gas Sci. Technol. – Rev. IFP*, 65, 597–614, <https://doi.org/10.2516/ogst/2009076>, 2010.
- 195 BRGM: Rapport de synthese du modèle regional multicouche du Bassin Nord Aquitain R-38006-SGN SP 94, R-38006-SGN SP 94, BRGM, <https://infoterre.brgm.fr/rapports/RR-38006-FR.pdf>, 1994.
- BRGM: Développements et maintenance du Modèle Nord-Aquitaine de gestion des nappes RP-52602-FR, *Gestion des eaux souterraines en Région Aquitaine*, RP-52602, BRGM, <https://infoterre.brgm.fr/rapports/RP-52602-FR.pdf>, 2003.
- 200 BRGM: Développements et maintenance du Modèle Nord-Aquitaine de gestion des nappes RP-53659-FR, *Gestion des eaux souterraines en Région Aquitaine*, RP-53659-FR, BRGM, <https://infoterre.brgm.fr/rapports/RP-53659-FR.pdf>, 2005.
- BRGM: Développements et maintenance du Modèle Nord-Aquitaine de gestion des nappes RP-65039-FR, *Gestion des eaux souterraines en Région Aquitaine*, RP-65039-FR, BRGM, <https://infoterre.brgm.fr/rapports/RP-65039-FR.pdf>, 2016.
- BRGM: Carte géologique de la France métropolitaine, <https://infoterre.brgm.fr/formulaire/telechargement-carte-geologique-metropolitaine-11-000-000> (last access: 23 February 2026), 2026.
- 205 Castro, M. C., Goblet, P., Ledoux, E., Violette, S., and de Marsily, G.: Noble gases as natural tracers of water circulation in the Paris Basin: 2. Calibration of a groundwater flow model using noble gas isotope data, *Water Resources Research*, 34, 2467–2483, <https://doi.org/10.1029/98WR01957>, 1998.
- Chidepudi, S. K. R., Massei, N., Jardani, A., Henriot, A., Fournier, M., and Dieppois, B.: Groundwater Level Projections for Aquifers Affected by Annual to Decadal Hydroclimate Variations: Example of Northern France, *Earth’s Future*, 13, e2024EF005251, <https://doi.org/10.1029/2024EF005251>, 2025a.
- 210 Chidepudi, S. K. R., Massei, N., Jardani, A., Fournier, M., Baulon, L., Zahy, A. E., and Thomas, A.: Sensitivity of Covered and Confined Aquifers to Climate Forcing in Metropolitan France, 2025b.
- Costelloe, J. F., Irvine, E. C., Western, A. W., Matic, V., Walker, J., and Tyler, M.: Quantifying Near-surface, Diffuse Groundwater Discharge along the South-West Margin of the Great Artesian Basin, in: *Proceedings of Water Down Under 2008*, 831–840, <https://doi.org/10.3316/informit.570721630661697>, 2020.
- 215 Curnelle, R., Dubois, P., Seguin, J. C., Whitaker, D., Matthews, D. H., Laughton, A. S., Kholief, M. M., Kent, P. E., Kent, P., Bott, M. H. P., McKenzie, D. P., and Williams, C. A.: The Mesozoic-Tertiary evolution of the Aquitaine Basin, *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 305, 63–84, <https://doi.org/10.1098/rsta.1982.0026>, 1997.
- 220 Currell, M., Gleeson, T., and Dahlhaus, P.: A New Assessment Framework for Transience in Hydrogeological Systems, *Groundwater*, 54, 4–14, <https://doi.org/10.1111/gwat.12300>, 2016.

- Cuthbert, M. O., Gleeson, T., Moosdorf, N., Befus, K. M., Schneider, A., Hartmann, J., and Lehner, B.: Global patterns and dynamics of climate–groundwater interactions, *Nature Clim Change*, 9, 137–141, <https://doi.org/10.1038/s41558-018-0386-4>, 2019.
- 225 Cuthbert, M. O., Gleeson, T., Bierkens, M. F. P., Ferguson, G., and Taylor, R. G.: Defining Renewable Groundwater Use and Its Relevance to Sustainable Groundwater Management, *Water Resources Research*, 59, e2022WR032831, <https://doi.org/10.1029/2022WR032831>, 2023.
- Delmas, J., Houel, P., and Vially, R.: Paris Basin, Petroleum potential (IFP regional report), IFP, 2002.
- Döll, P. and Flörke, M.: Global-scale estimation of diffuse groundwater recharge, *Frankfurt Hydrology Paper* 03, 2005.
- 230 Döll, P., Kaspar, F., and Lehner, B.: A global hydrological model for deriving water availability indicators: model tuning and validation, *Journal of Hydrology*, 270, 105–134, [https://doi.org/10.1016/S0022-1694\(02\)00283-4](https://doi.org/10.1016/S0022-1694(02)00283-4), 2003.
- Douez, O.: Réponse d’un système aquifère multicouche aux variations paléoclimatiques et aux sollicitations anthropiques - Approche par modélisation couplée hydrodynamique, thermique et géochimique, phdthesis, Université Michel de Montaigne - Bordeaux III, 2007.
- 235 Geriesh, M. H., Abouelmagd, A., and Mansour, B. M. H.: Major Groundwater Reservoirs of Egypt, in: *The Phanerozoic Geology and Natural Resources of Egypt*, edited by: Hamimi, Z., Khozyem, H., Adatte, T., Nader, F. H., Oboh-Ikuenobe, F., Zobaa, M. K., and El Atfy, H., Springer International Publishing, Cham, 613–635, https://doi.org/10.1007/978-3-030-95637-0_21, 2023.
- Gleeson, T., Alley, W. M., Allen, D. M., Sophocleous, M. A., Zhou, Y., Taniguchi, M., and VanderSteen, J.: Towards Sustainable Groundwater Use: Setting Long-Term Goals, Backcasting, and Managing Adaptively, *Groundwater*, 50, 19–26, <https://doi.org/10.1111/j.1745-6584.2011.00825.x>, 2012.
- 240 Gómez, A. A., Rodríguez, L. B., and Vives, L. S.: The Guarani Aquifer System: estimation of recharge along the Uruguay–Brazil border, *Hydrogeol J*, 18, 1667–1684, <https://doi.org/10.1007/s10040-010-0630-0>, 2010.
- Gonçalvès, J.: Modélisation 3D de l’évolution géologique du bassin de Paris : implications diagénétiques et hydrogéologiques, thesis, Paris 6, 2002.
- 245 Gonçalvès, J., Violette, S., and Wendling, J.: Analytical and numerical solutions for alternative overpressuring processes: Application to the Callovo-Oxfordian sedimentary sequence in the Paris basin, France, *Journal of Geophysical Research: Solid Earth*, 109, <https://doi.org/10.1029/2002JB002278>, 2004a.
- Gonçalvès, J., Violette, S., Guillocheau, F., Robin, C., Pagel, M., Bruel, D., De Marsily, G., and Ledoux, E.: Contribution of a three-dimensional regional scale basin model to the study of the past fluid flow evolution and the present hydrology of the Paris basin, France, *Basin Research*, 16, 569–586, <https://doi.org/10.1111/j.1365-2117.2004.00243.x>, 2004b.
- 250 Gonçalvès, J., Petersen, J., Deschamps, P., Hamelin, B., and Baba-Sy, O.: Quantifying the modern recharge of the “fossil” Sahara aquifers, *Geophysical Research Letters*, 40, 2673–2678, <https://doi.org/10.1002/grl.50478>, 2013.
- Gonçalvès, J., Deschamps, P., Hamelin, B., Vallet-Coulomb, C., Petersen, J., and Chekireb, A.: Revisiting recharge and sustainability of the North-Western Sahara aquifers, *Reg Environ Change*, 20, 47, <https://doi.org/10.1007/s10113-020-01627-4>, 2020.
- 255

- Gonçalves, R. D., Teramoto, E. H., and Chang, H. K.: Regional Groundwater Modeling of the Guarani Aquifer System, *Water*, 12, 2323, <https://doi.org/10.3390/w12092323>, 2020.
- Guillocheau, F., Robin, C., Allemand, P., Bourquin, S., Brault, N., Dromart, G., Friedenber, R., Garcia, J.-P., Gaulier, J.-M., Gaumet, F., Grosdoy, B., Hanot, F., Le Strat, P., Mettraux, M., Nalpas, T., Prijac, C., Rigoltet, C., Serrano, O., and Grandjean, G.: Meso-Cenozoic geodynamic evolution of the Paris Basin: 3D stratigraphic constraints, *Geodinamica Acta*, 13, 189–245, <https://doi.org/10.1080/09853111.2000.11105372>, 2000.
- Gun, J. van der: Large Aquifer Systems Around the World, The Groundwater Project, <https://doi.org/10.21083/978-1-77470-020-4>, 2022.
- 265 Habermehl, M. A.: Review: The evolving understanding of the Great Artesian Basin (Australia), from discovery to current hydrogeological interpretations, *Hydrogeol J*, 28, 13–36, <https://doi.org/10.1007/s10040-019-02036-6>, 2020.
- Henrichs de Azevedo, J. and Guimarães Campos, J. E.: Flow patterns and aquifer recharge controls under Amazon rainforest influence: The case of the Alter do Chão aquifer system, *Journal of South American Earth Sciences*, 112, 103596, <https://doi.org/10.1016/j.jsames.2021.103596>, 2021.
- 270 Hirata, R. and Foster, S.: The Guarani Aquifer System – from regional reserves to local use, *Quarterly Journal of Engineering Geology and Hydrogeology*, 54, qjehg2020-091, <https://doi.org/10.1144/qjehg2020-091>, 2021.
- Hosseini, Z., Raeisi, E., Abdollahifard, I., and Teatini, P.: Comprehensive hydrogeological study of the Nubian aquifer System, Northeast Africa, *Journal of Hydrology*, 636, 131237, <https://doi.org/10.1016/j.jhydrol.2024.131237>, 2024.
- 275 Hu, K., Awange, J. L., Khandu, Forootan, E., Goncalves, R. M., and Fleming, K.: Hydrogeological characterisation of groundwater over Brazil using remotely sensed and model products, *Science of The Total Environment*, 599–600, 372–386, <https://doi.org/10.1016/j.scitotenv.2017.04.188>, 2017.
- Humez, P., Audigane, P., Lions, J., Chiaberge, C., and Bellenfant, G.: Modeling of CO₂ Leakage up Through an Abandoned Well from Deep Saline Aquifer to Shallow Fresh Groundwaters, *Transp Porous Med*, 90, 153–181, <https://doi.org/10.1007/s11242-011-9801-2>, 2011.
- 280 Jiang, Z.: Analysis and modelling of the hydraulic conductivity in aquitards application to the Galilee Basin and the Great Artesian Basin, Queensland University of Technology, 2014.
- Johnston, R. H.: Hydrologic budgets of regional aquifer systems of the United States for predevelopment and development conditions, rev., U.S. Geological Survey, Reston, Va, 34 pp., 1999.
- 285 Jost, A.: Caractérisation des forçages climatiques et géomorphologiques des cinq derniers millions d’années et modélisation de leurs conséquences sur un système aquifère complexe: le bassin de Paris, 2005.
- Jost, A., Violette, S., Gonçalves, J., Ledoux, E., Guyomard, Y., Guillocheau, F., Kageyama, M., Ramstein, G., and Suc, J.-P.: Long-term hydrodynamic response induced by past climatic and geomorphologic forcing: The case of the Paris basin, France, *Physics and Chemistry of the Earth, Parts A/B/C*, 32, 368–378, <https://doi.org/10.1016/j.pce.2006.02.053>, 2007.
- 290 Kinoti, I., Leblanc, M., Lekula, M., Tweed, S., Kenabatho, P. K., Oliso, A., and Lubczynski, M. W.: Hydrogeological conceptual model of Stampriet transboundary aquifer system in Southern Africa, *Groundwater for Sustainable Development*, 26, 101301, <https://doi.org/10.1016/j.gsd.2024.101301>, 2024.

- Kirchheim, R. E., Gastmans, D., Chang, H. K., and Gilmore, T. E.: The use of isotopes in evolving groundwater circulation models of regional continental aquifers: The case of the Guarani Aquifer System, *Hydrological Processes*, 33, 2266–2278, <https://doi.org/10.1002/hyp.13476>, 2019.
- 295 Larroque, F., Treichel, W., and Dupuy, A.: Use of unit response functions for management of regional multilayered aquifers: application to the North Aquitaine Tertiary system (France), *Hydrogeol J*, 16, 215–233, <https://doi.org/10.1007/s10040-007-0245-2>, 2008.
- Larroque, F., Cabaret, O., Atteia, O., Dupuy, A., and Franceschi, M.: Vertical heterogeneities of hydraulic aquitard parameters: preliminary results from laboratory and in situ monitoring, *Hydrological Sciences Journal*, 58, 912–929, 300 <https://doi.org/10.1080/02626667.2013.783215>, 2013.
- Lekula, M., Lubczynski, M. W., and Shemang, E. M.: Hydrogeological conceptual model of large and complex sedimentary aquifer systems – Central Kalahari Basin, *Physics and Chemistry of the Earth, Parts A/B/C*, 106, 47–62, <https://doi.org/10.1016/j.pce.2018.05.006>, 2018.
- Margat, J. and Gun, J. van der: *Groundwater around the World: A Geographic Synopsis*, CRC Press, London, 376 pp., 305 <https://doi.org/10.1201/b13977>, 2013.
- Mas, P., Calcagno, P., Caritg-Monnot, S., Beccaletto, L., Capar, L., and Hamm, V.: A 3D geomodel of the deep aquifers in the Orléans area of the southern Paris Basin (France), *Sci Data*, 9, 781, <https://doi.org/10.1038/s41597-022-01876-4>, 2022.
- Mpuang, A. P., Shibutani, T., and Ntibinyane, O.: New insights into the tectonics and geodynamics of Botswana from intracrustal structures revealed by receiver function analysis, *Geophysical Journal International*, 235, 1086–1101, 310 <https://doi.org/10.1093/gji/ggad291>, 2023.
- Ortiz, A., Guillocheau, F., Lasseur, E., Briais, J., Robin, C., Serrano, O., and Fillon, C.: Sediment routing system and sink preservation during the post-orogenic evolution of a retro-foreland basin: The case example of the North Pyrenean (Aquitaine, Bay of Biscay) Basins, *Marine and Petroleum Geology*, 112, 104085, <https://doi.org/10.1016/j.marpetgeo.2019.104085>, 2020.
- Ould Baba, M.: RECHARGE ET PALEORECHARGE DU SYSTEME AQUIFERE DU SAHARA SEPTENTRIONAL, 315 Université de Tunis El Manar, Tunis, 2005.
- Pédrón, N., Platel, J., and Bourguine, B.: Développements et maintenance du Modèle Nord-Aquitaine de gestion des nappes RP-55242-FR, Gestion des eaux souterraines en Région Aquitaine, RP-55242-FR, BRGM, <https://infoterre.brgm.fr/rapports/RP-55242-FR.pdf>, 2006.
- Pédrón, N., Platel, J., and Bourguine, B.: Développements et maintenance du Modèle Nord-Aquitaine de gestion des nappes 320 RP-56614-FR, RP-56614-FR, BRGM, <https://infoterre.brgm.fr/rapports/RP-56614-FR.pdf>, 2008.
- Petersen, J. O., Deschamps, P., Gonçalves, J., Hamelin, B., Michelot, J. L., Guendouz, A., and Zouari, K.: Quantifying paleorecharge in the Continental Intercalaire (CI) aquifer by a Monte-Carlo inversion approach of $^{36}\text{Cl}/\text{Cl}$ data, *Applied Geochemistry*, 50, 209–221, <https://doi.org/10.1016/j.apgeochem.2014.04.014>, 2014.
- Rabelo, J. L. and Wendland, E.: Assessment of groundwater recharge and water fluxes of the Guarani Aquifer System, Brazil, 325 *Hydrogeol J*, 17, 1733–1748, <https://doi.org/10.1007/s10040-009-0462-y>, 2009.
- Rafaâ Trigui, M., Trabelsi, R., Zouari, K., and Agoun, A.: Implication of hydrogeological and hydrodynamic setting on water quality of the Complex Terminal Aquifer in Kebili (southern Tunisia): The use of geochemical indicators and modelling, *Journal of African Earth Sciences*, 176, 104121, <https://doi.org/10.1016/j.jafrearsci.2021.104121>, 2021.

- 330 Richts, A., Struckmeier, W. F., and Zaepke, M.: WHYMAP and the Groundwater Resources Map of the World 1:25,000,000, in: *Sustaining Groundwater Resources: A Critical Element in the Global Water Crisis*, edited by: Jones, J. A. A., Springer Netherlands, Dordrecht, 159–173, https://doi.org/10.1007/978-90-481-3426-7_10, 2011.
- Rodríguez, L., Vives, L., and Gomez, A.: Conceptual and numerical modeling approach of the Guarani Aquifer System, *Hydrology and Earth System Sciences*, 17, 295–314, <https://doi.org/10.5194/hess-17-295-2013>, 2013.
- 335 Rosário, F. F. do, Custodio, E., and Silva, G. C. da: Hydrogeology of the Western Amazon Aquifer System (WAAS), *Journal of South American Earth Sciences*, 72, 375–386, <https://doi.org/10.1016/j.jsames.2016.10.004>, 2016.
- Rousseau-Gueutin, P., Love, A. J., Vasseur, G., Robinson, N. I., Simmons, C. T., and De Marsily, G.: Time to reach near-steady state in large aquifers: Time to Reach Near-Steady State in Large Aquifers, *Water Resour. Res.*, 49, 6893–6908, <https://doi.org/10.1002/wrcr.20534>, 2013.
- 340 Saltel, M., Rebeix, R., Thomas, B., Franceschi, M., Lavielle, B., and Bertran, P.: Paleoclimate variations and impact on groundwater recharge in multi-layer aquifer systems using a multi-tracer approach (northern Aquitaine basin, France), *Hydrogeol J*, 27, 1439–1457, <https://doi.org/10.1007/s10040-019-01944-x>, 2019.
- Schulz, S., Walther, M., Michelsen, N., Rausch, R., Dirks, H., Al-Saud, M., Merz, R., Kolditz, O., and Schüth, C.: Improving large-scale groundwater models by considering fossil gradients, *Advances in Water Resources*, 103, 32–43, <https://doi.org/10.1016/j.advwatres.2017.02.010>, 2017.
- 345 Sefelnasr, A.: Development of groundwater flow model for water resources management in the development areas of the western desert, Egypt, *Methodology*, 44, 61, 2007.
- Seguin, J. J., Castillo, C., and Arnaud, L.: Modélisation des nappes de l’Albien et du Néocomien du Bassin de Paris, RP-64873-FR, BRGM, 2015.
- 350 Smith, A. and Welsh, W.: Review of groundwater models and modelling methodologies for the Great Artesian Basin, CSIRO Water for a Healthy Country, Flagship, Australia, 2011.
- Souza, E. L. de, Galvão, P. H. F., Pinheiro, C. do S. da S., Baessa, M. P. M., Demétrio, J. G. A., and Brito, W. R. R.: Síntese da hidrogeologia nas bacias sedimentares do Amazonas e do Solimões: Sistemas Aquíferos Içá-Solimões e Alter do Chão, *Geologia USP. Série Científica*, 13, 107–117, <https://doi.org/10.5327/Z1519-874X2013000100007>, 2013.
- 355 Sracek, O. and Hirata, R.: Geochemical and stable isotopic evolution of the Guarani Aquifer System in the state of São Paulo, Brazil, *Hydrogeology Journal*, 10, 643–655, <https://doi.org/10.1007/s10040-002-0222-8>, 2002.
- Stone, A. E. C. and Edmunds, W. M.: Sand, salt and water in the Stampriet Basin, Namibia: Calculating unsaturated zone (Kalahari dunefield) recharge using the chloride mass balance approach, *Water SA*, 38, 367–378, <https://doi.org/10.4314/wsa.v38i3.2>, 2012.
- 360 Thiéry, D., Amraoui, N., Gomez, E., Pédrón, N., and Seguin, J. J.: Regional Model of Groundwater Management in North Aquitania Aquifer System: Water Resources Optimization and Implementation of Prospective Scenarios Taking into Account Climate Change, in: *Water Security in the Mediterranean Region*, edited by: Scozzari, A. and El Mansouri, B., Springer Netherlands, Dordrecht, 275–290, https://doi.org/10.1007/978-94-007-1623-0_19, 2011.
- 365 Voss, C. I. and Soliman, S. M.: The transboundary non-renewable Nubian Aquifer System of Chad, Egypt, Libya and Sudan: classical groundwater questions and parsimonious hydrogeologic analysis and modeling, *Hydrogeol J*, 22, 441–468, <https://doi.org/10.1007/s10040-013-1039-3>, 2014.

Welsh, W. D.: Groundwater balance modelling with Darcy's Law, 2007.

Wendland, E., Rabelo, J., and Roehrig, J.: Guarani Aquifer System – The Strategical Water Source In South America, Institut für Tropentechnologie, 2006.

Williams, L. J. and Kuniansky, E. L.: Revised Hydrogeologic Framework of the Floridan Aquifer System in Florida and Parts
370 of Georgia, Alabama, and South Carolina, Professional Paper, 1807, USGS, 2015.

Wright, J. A. and Hall, J.: Deep Seismic profiling in the Nosop Basin, Botswana: cratons, mobile belts and sedimentary basins, Tectonophysics, 173, 333–343, [https://doi.org/10.1016/0040-1951\(90\)90228-Z](https://doi.org/10.1016/0040-1951(90)90228-Z), 1990.