

Supplementary Material

Linking groundwater abstraction to anthropogenic land subsidence in Northern Madrid, Spain:
a numerical modelling perspective

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Purpose of this supplement. This document provides the technical background for the poster contribution. It describes the observational data, the construction of the three-dimensional model domain, the hydro-mechanical formulation, the boundary condition derived from piezometric head decline, the post-processing convention used for displacement, and the comparison with satellite-derived surface deformation.

S1 Scientific context

Groundwater abstraction modifies the hydraulic state of aquifer systems. A decline in piezometric head reduces pore pressure, increases effective stress, and may lead to compaction of compressible sediments. Where compaction propagates to the land surface, the process becomes measurable as land subsidence. This mechanism has been documented in several aquifer systems worldwide and is particularly relevant where urban infrastructure overlies heavily exploited groundwater resources.

The present work focuses on the northern Madrid aquifer system, where previous studies linked groundwater-level variations to satellite-observed ground deformation. The poster extends this interpretation through a three-dimensional hydro-mechanical numerical model. The model is not intended as a full operational groundwater-management model at this stage. Rather, it provides a physically consistent numerical framework to test whether the observed piezometric decline can produce the observed magnitude and timing of subsidence.

Main modelling question. Can a three-dimensional hydro-mechanical model reproduce the groundwater-abstraction-induced subsidence observed by InSAR during the 1999–2000 extraction cycle in northern Madrid?

S2 Study area and observational constraints

The study area lies within the Tertiary Detritic Aquifer of Madrid (TDAM), in the northern extraction field of the Madrid basin. This region has been monitored using piezometric measurements and satellite radar interferometry. The numerical model was constrained using groundwater-level data and evaluated against satellite-derived displacement.

Two observational data types are used:

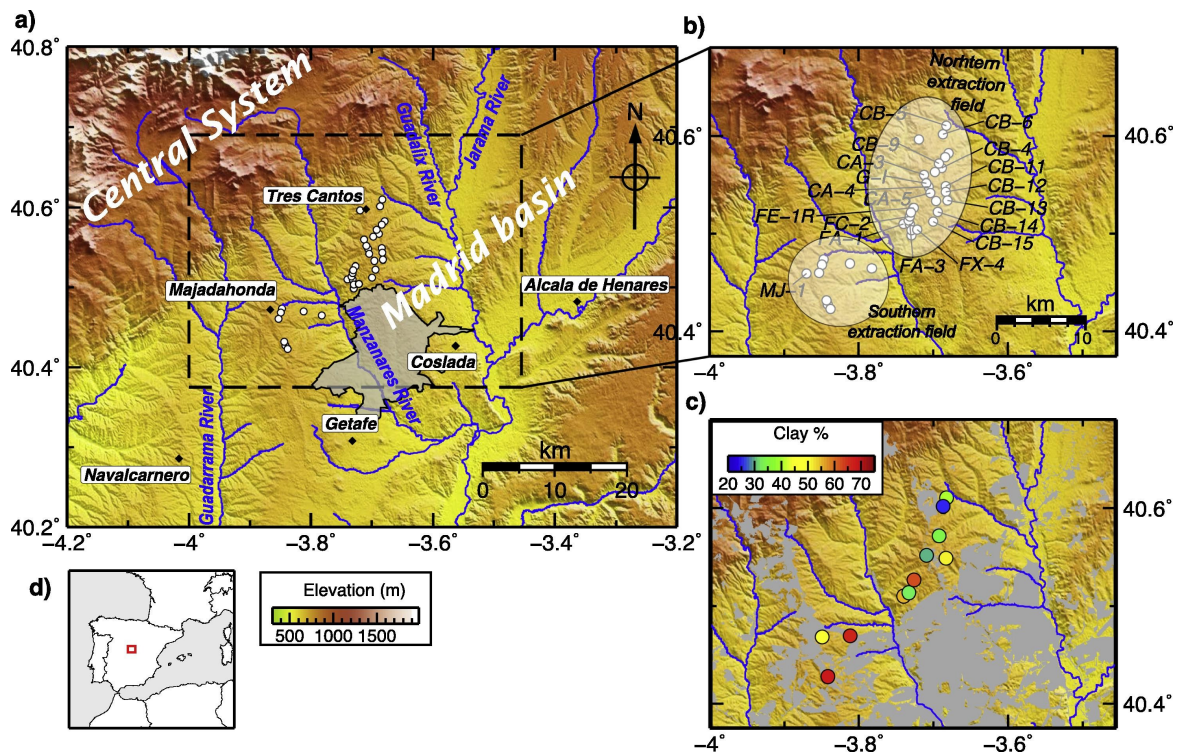


Figure 1: Regional and local context of the Madrid aquifer system. The northern extraction field contains monitoring wells and persistent-scatterer InSAR observations used to compare groundwater-level changes with surface deformation. The figure is included to show the spatial context of the model domain and the observation network.

- **Piezometric data:** the FE-1 well is used as a representative hydraulic forcing time series for the selected extraction cycle.
- **Satellite displacement data:** ERS/InSAR persistent-scatterer observations are used to evaluate the simulated surface deformation.

The selected modelling period corresponds to the intense 1999–2000 extraction phase. This interval is useful because it contains a strong piezometric decline and a clearly detectable deformation signal in the ERS/InSAR record.

S3 Construction of the 3D numerical model

The numerical domain was built as a simplified three-layer hydrostratigraphic representation of the northern Madrid aquifer system. The horizontal model footprint was based on the spatial extent of the northern extraction field and available well/piezometer locations. The real-world coordinates were transformed into a local COMSOL coordinate system so that the geometry could be built and meshed efficiently.

The model uses three main units:

S4 Hydraulic forcing from FE-1 piezometric data

The FE-1 piezometric record was imported into COMSOL as an interpolation function, $h_{FE1}(t)$. The model is driven by the change in piezometric head relative to the beginning of the selected extraction cycle. This avoids applying an arbitrary absolute pressure and instead treats the simulation as a perturbation problem around the cycle-start state.

Table 1: Hydrostratigraphic units represented in the numerical model. Depths are given relative to the model top surface.

Unit	Depth interval	Thickness	Role	Description
Clay / overburden	0 to -300 m	300 m	Upper confining unit	Represents the over-consolidated Miocene clay and shallow overburden.
TDAM aquifer	-300 m to -454 m	154 m	Water-bearing unit	Main aquifer interval where piezometric decline is interpreted to affect pore pressure.
Bedrock	-454 m to -700 m	246 m	Lower stiff unit	Represents the lower mechanical and hydraulic boundary region of the model.

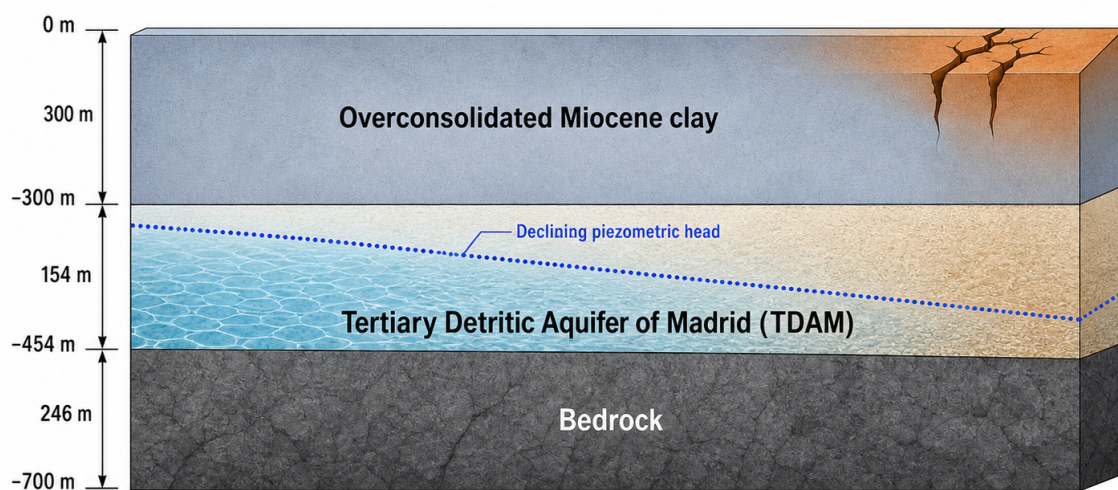


Figure 2: Conceptual three-layer model geometry used to communicate the numerical setup. The blue middle interval represents the water-bearing aquifer layer, not a surface-water body. The dotted blue line indicates the declining piezometric condition during groundwater abstraction. The vertical scale is visually exaggerated for clarity.

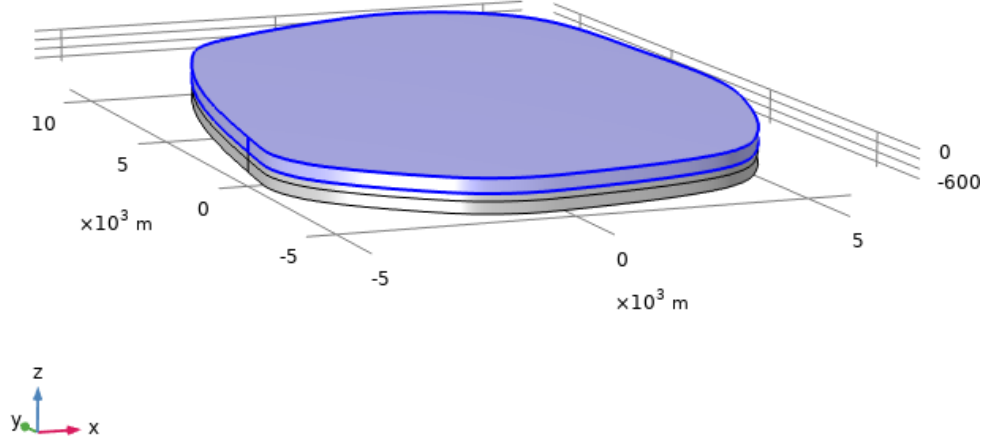


Figure 3: COMSOL view of the actual three-dimensional model geometry. The model appears thin in side view because the horizontal length scale is several kilometres, whereas the total model depth is 700 m. This geometric aspect ratio is expected and should not be interpreted as an error in the layer assignment.

The pressure-change boundary condition is defined as

$$\Delta p(t) = \rho_w g [h_{\text{FE1}}(t) - h_{\text{FE1}}(t_0)], \quad (1)$$

where ρ_w is the density of water, g is gravitational acceleration, $h_{\text{FE1}}(t)$ is the FE-1 piezometric head, and t_0 is the start of the selected extraction cycle.

In COMSOL syntax, the expression is written as

$$\text{rho_w*g*(piez_FE1(t)-piez_FE1(5e7[s]))}. \quad (2)$$

This expression is zero at $t = t_0$ by construction. A negative head change therefore produces a negative pressure perturbation, representing pore-pressure depletion during abstraction.

S5 Hydro-mechanical coupling

The numerical model couples groundwater-pressure change to mechanical deformation through poroelasticity. In simplified terms, pressure depletion increases effective stress and causes compaction of the porous skeleton. The conceptual relation is

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \alpha p \mathbf{I}, \quad (3)$$

where $\boldsymbol{\sigma}'$ is effective stress, $\boldsymbol{\sigma}$ is total stress, p is pore pressure, α is the Biot–Willis coefficient, and \mathbf{I} is the identity tensor. When pore pressure decreases, the effective stress increases, leading to elastic compaction if the material remains within a recoverable range.

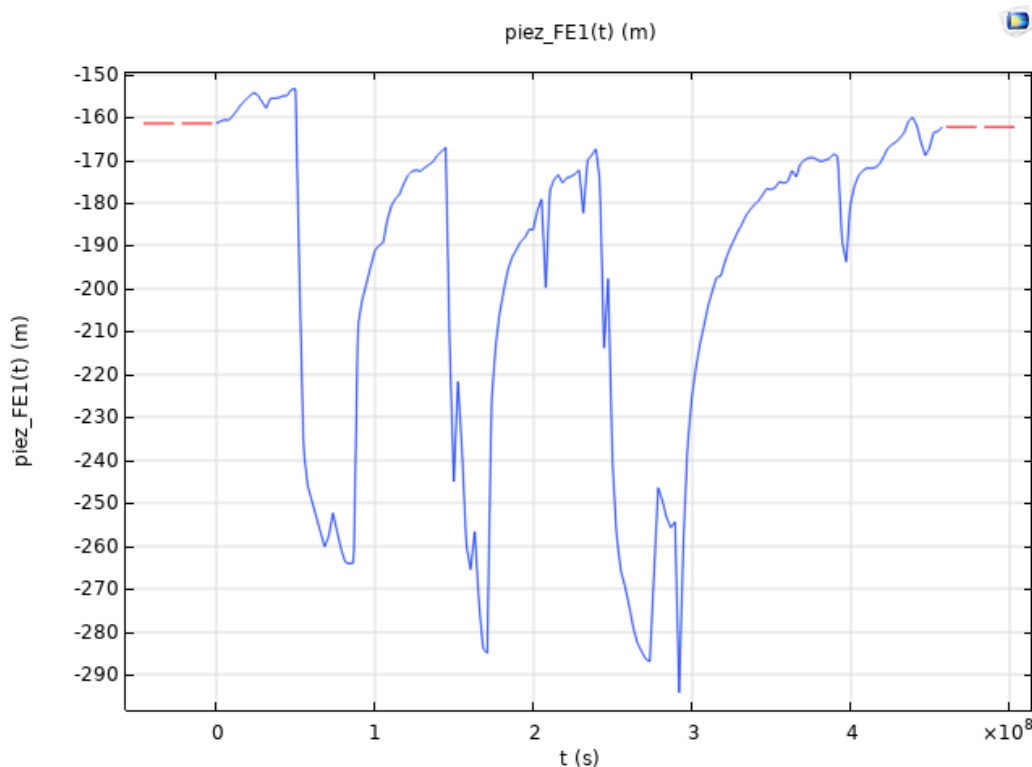


Figure 4: FE-1 piezometric time series imported into COMSOL. The sharp drawdown and recovery phases reflect groundwater extraction and partial recovery. The numerical experiment focuses on the 1999–2000 extraction cycle, where the head decline is large and the InSAR deformation signal is well expressed.

The model therefore follows the chain

piezometric decline → *pore-pressure drop* → *effective-stress increase* → *aquifer-system compaction*
→ *surface subsidence*.

The model solves the hydraulic and mechanical response in three dimensions, allowing the pressure field and the resulting surface displacement to be evaluated spatially rather than only as a one-dimensional analytical response.

S6 Material parameterization

The final parameter set used in the poster is summarized in table 2. Values should be interpreted as effective model parameters at the scale of the numerical domain. The elastic stiffness of the aquifer was calibrated within the range implied by published skeletal storage estimates, while the clay and bedrock were treated as mechanically stiffer units.

Parameter interpretation. The parameter values are not presented as a unique inversion of the aquifer system. They are effective numerical parameters selected to test whether the observed head decline can generate the observed order of magnitude of surface deformation. A full parameter-inversion study would require distributed pumping records, multiple piezometers, and spatially resolved calibration against InSAR displacement fields.

Table 2: Key material and hydraulic parameters used in the final numerical setup.

Parameter	Clay / overburden	TDAM aquifer	Bedrock
Thickness	300 m	154 m	246 m
Young's modulus, E	2×10^{10} Pa	2.5×10^9 Pa	5×10^{10} Pa
Poisson's ratio, ν	0.35	0.25	0.20
Biot coefficient, α	0.9	0.7	0.5
Intrinsic permeability, κ	1×10^{-15} m ²	1×10^{-11} m ²	model-test value
Porosity, n	0.35	0.10	0.05

Table 3: Main geometrical, mechanical, and hydraulic parameters used in the COMSOL hydro-mechanical model.

Group	Parameter	Symbol	Value	Unit
Model geometry				
Geometry	Total model depth	H	700	m
Geometry	Clay / overburden thickness	H_{clay}	300	m
Geometry	Aquifer thickness	H_{aq}	154	m
Geometry	Bedrock thickness	H_{bed}	246	m
Mechanical parameters				
Clay / overburden	Young's modulus	E_{clay}	2.0×10^{10}	Pa
Clay / overburden	Poisson's ratio	ν_{clay}	0.35	–
Clay / overburden	Biot–Willis coefficient	α_{clay}	0.90	–
TDAM aquifer	Young's modulus	E_{aq}	2.5×10^9	Pa
TDAM aquifer	Poisson's ratio	ν_{aq}	0.25	–
TDAM aquifer	Biot–Willis coefficient	α_{aq}	0.70	–
Bedrock	Young's modulus	E_{bed}	5.0×10^{10}	Pa
Bedrock	Poisson's ratio	ν_{bed}	0.20	–
Bedrock	Biot–Willis coefficient	α_{bed}	0.50	–
Hydraulic parameters				
Clay / overburden	Intrinsic permeability	κ_{clay}	1.0×10^{-15}	m ²
TDAM aquifer	Intrinsic permeability	κ_{aq}	1.0×10^{-11}	m ²
Bedrock	Intrinsic permeability	κ_{bed}	1.0×10^{-12}	m ²
Clay / overburden	Porosity	n_{clay}	0.35	–
TDAM aquifer	Porosity	n_{aq}	0.10	–
Bedrock	Porosity	n_{bed}	0.05	–
Fluid properties and forcing				
Water	Density	ρ_w	1000	kg m ⁻³
Water	Dynamic viscosity	μ	1.0×10^{-3}	Pa s
Forcing	Gravitational acceleration	g	9.81	m s ⁻²
Forcing	Reference time for extraction cycle	t_0	5.0×10^7	s

Note. The parameters are treated as effective model-scale values. The final hydraulic forcing was applied through the FE-1 piezometric head change, converted into a pressure perturbation using $\Delta p(t) = \rho_w g [h_{\text{FE1}}(t) - h_{\text{FE1}}(t_0)]$.

S7 Post-processing convention for displacement

The vertical displacement variable in COMSOL is denoted by w . Subsidence is represented as $-w$, so that downward motion is plotted as positive in some COMSOL maps. For comparison with InSAR, where subsidence is commonly plotted as negative displacement, the sign convention can be adjusted during plotting.

For the numerical results shown in the poster, displacement is evaluated relative to the beginning of the selected cycle:

$$\Delta(-w) = [-w(t)] - [-w(t_0)]. \quad (4)$$

In COMSOL, the relative displacement expression is

$$-(w - \text{withsol}('sol1', w, \text{setval}(t, 5e7))). \quad (5)$$

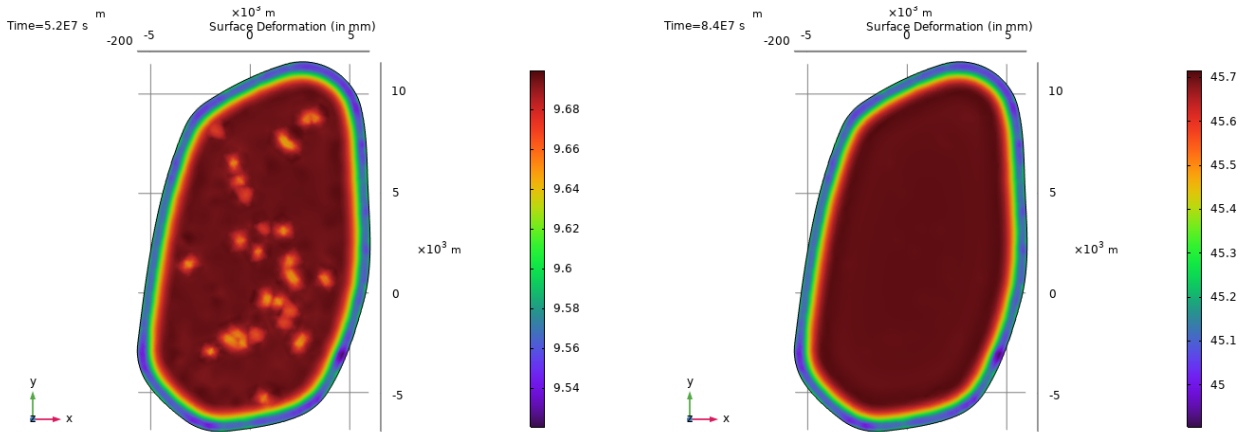
This subtraction removes any small numerical offset at the start of the time-dependent simulation and ensures that the plotted deformation corresponds to cycle-induced displacement rather than absolute displacement from the full model initialization.

Similarly, the relative pressure field can be plotted as

$$p - \text{withsol}('sol1', p, \text{setval}(t, 5e7)). \quad (6)$$

S8 Surface deformation results

The surface deformation maps show the simulated vertical response during the selected extraction cycle. The field is spatially smooth and relatively uniform over much of the model domain. This is consistent with the broad hydraulic forcing used in the present version of the model. Local variations mainly appear near domain boundaries or where the numerical field contains small spatial heterogeneities.



(a) Early response at $t = 5.2 \times 10^7$ s.

(b) Late response at $t = 8.4 \times 10^7$ s.

Figure 5: Simulated surface deformation during the selected extraction cycle. The maps show relative vertical displacement in millimetres. The late-stage result indicates a domain-scale subsidence response of approximately several tens of millimetres, comparable in order of magnitude to the ERS/InSAR deformation signal used for validation.

The near-uniform colour in the late-stage deformation map should not be interpreted as a failed visualization. It reflects the fact that the current forcing is spatially broad. A more localized displacement bowl would require spatially variable pumping or explicit well-source terms.

S9 Comparison with satellite-derived displacement

The satellite comparison uses ERS/InSAR persistent-scatterer displacement data from the northern extraction field. The main comparison shown in the poster uses a northern-field average rather than a single isolated point. This is appropriate because the numerical model is forced by a representative piezometric decline and produces a broad surface response.

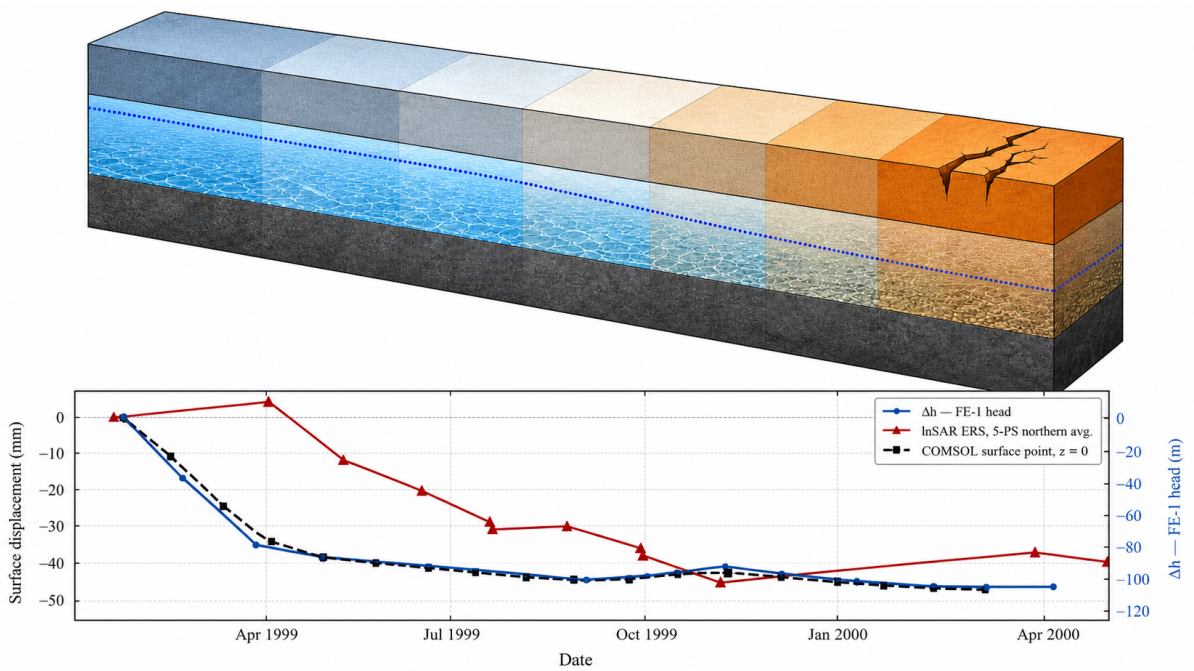


Figure 6: Time-series comparison between FE-1 head decline, ERS/InSAR surface displacement, and COMSOL-simulated surface deformation at $z = 0$. The FE-1 head decline provides the hydraulic forcing, while the InSAR series provides an observational constraint on the surface response. The comparison is used to assess whether the model reproduces the timing and order of magnitude of the observed subsidence during the 1999–2000 extraction cycle.

The comparison should be interpreted cautiously. The model is not fitted directly to every InSAR point. Instead, it tests whether a physically plausible hydro-mechanical response can be obtained from the observed piezometric decline. Agreement in the order of magnitude and general timing supports the proposed abstraction–subsidence link, while remaining differences point to simplifications in the present setup.

S10 Model interpretation

The numerical results support the following interpretation:

1. The FE-1 piezometric decline provides a physically meaningful transient hydraulic forcing.
2. The imposed head decline produces pore-pressure depletion in the model domain.
3. Through poroelastic coupling, pressure depletion increases effective stress and generates vertical compaction.

4. The resulting surface deformation is comparable in order of magnitude to the ERS/InSAR observations during the selected extraction cycle.

The model therefore provides a three-dimensional numerical extension of earlier one-dimensional interpretations of the Madrid aquifer deformation response. Its main added value is not only the prediction of a single settlement value, but also the possibility of examining pressure and displacement fields in space.

S11 Limitations and assumptions

The present model is intentionally simplified. The main assumptions are:

- FE-1 is used as a representative forcing time series for the selected extraction cycle.
- Individual pumping wells are not explicitly simulated in the final poster configuration.
- The pressure boundary condition is spatially broad rather than locally imposed at well locations.
- Material properties are effective parameters at model scale.
- Spatial variability in lithology, permeability, pumping intensity, and boundary conditions is simplified.
- Only one major extraction cycle is emphasized in the poster comparison.

These assumptions are acceptable for a first hydro-mechanical consistency test, but they should be addressed in future work if the model is extended towards predictive groundwater-management scenarios.

S12 Future development

Future work should focus on extending the present proof-of-concept model towards a more predictive framework. The most important developments are:

- simulation of multiple abstraction and recovery cycles;
- spatially variable forcing using several piezometers and pumping records;
- distributed calibration against InSAR deformation fields;
- improved representation of lateral hydraulic boundaries and aquifer heterogeneity;
- development of machine-learning surrogate models trained on numerical simulations for rapid scenario testing.

A surrogate model would be particularly useful for policy applications. Once trained on a set of physically based simulations, it could rapidly estimate subsidence under different groundwater abstraction scenarios without rerunning the full finite-element model for every management option.

S13 Summary

The supplementary material documents a three-dimensional hydro-mechanical modelling workflow for groundwater-abstraction-induced subsidence in northern Madrid. FE-1 piezometric head decline is converted into a transient pressure forcing, which drives pore-pressure depletion and poroelastic compaction in a three-layer COMSOL model. The resulting surface deformation is compared with ERS/InSAR observations for the 1999–2000 extraction cycle. The current model reproduces the observed order of magnitude of deformation and provides a basis for future multi-cycle and policy-oriented scenario modelling.

References

References

- [1] Ezquerro, P., Herrera, G., Marchamalo, M., Tomás, R., Béjar-Pizarro, M., Martínez, R., and Bonì, R.: A quasi-elastic aquifer deformational behavior: Madrid aquifer case study, *Journal of Hydrology*, 519, 1192–1204, 2014.
- [2] Béjar-Pizarro, M., Ezquerro, P., Herrera, G., Tomás, R., Guardiola-Albert, C., Hernández, J. M., and Fernández-Merodo, J. A.: Mapping groundwater level and aquifer storage variations from InSAR measurements in the Madrid aquifer, Central Spain, *Journal of Hydrology*, 547, 678–689, 2017.