Modeling Historical Subsidence Due to Groundwater Withdrawal in The Alto Guadalentín Aquifer-system (Spain)

Fernández-Merodo, J. A., Ezquerro, P., Manzanal, D., Béjar-Pizarro, M.,
Mateos, R. M., Guardiola-Albert, C., … Herrera, G. (2021).
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OUTLINE

01 Introduction

Motivations / Objectives / Study area / Conceptual model

Introduction / Motivation

- The geomechanical frameworks commonly describe subsidence based on **Terzaghi's 1D consolidation theory** or **Biot's 3D consolidation theory**.

Reliable predictive tool ➡ Complexity

1) Mixed formulations for solid-fluid interaction
2) Realistic non-linear constitutive models for soil compressibility
3) The numerical methods for solving mixed formulations (Ex: Finite Element Method)

Regional studies ➡ Difficulty

1) Heterogeneity of the 3D geology
2) Boundary conditions / Historical pumping rates & aquifer recharges
3) Realistic initial states
4) Soil parameters

- This paper presents a new numerical methodology to calculate historical subsidence in the Alto Guadalentín Basin, based on realistic **hydro-mechanical coupling behavior** and **advanced mechanical stress-strain relationships**.

Fig. Geographical location of the study area.

Introduction / Study area – geological description

- The Alto Guadalentín Basin is an intermountain tectonic depression in Spain.

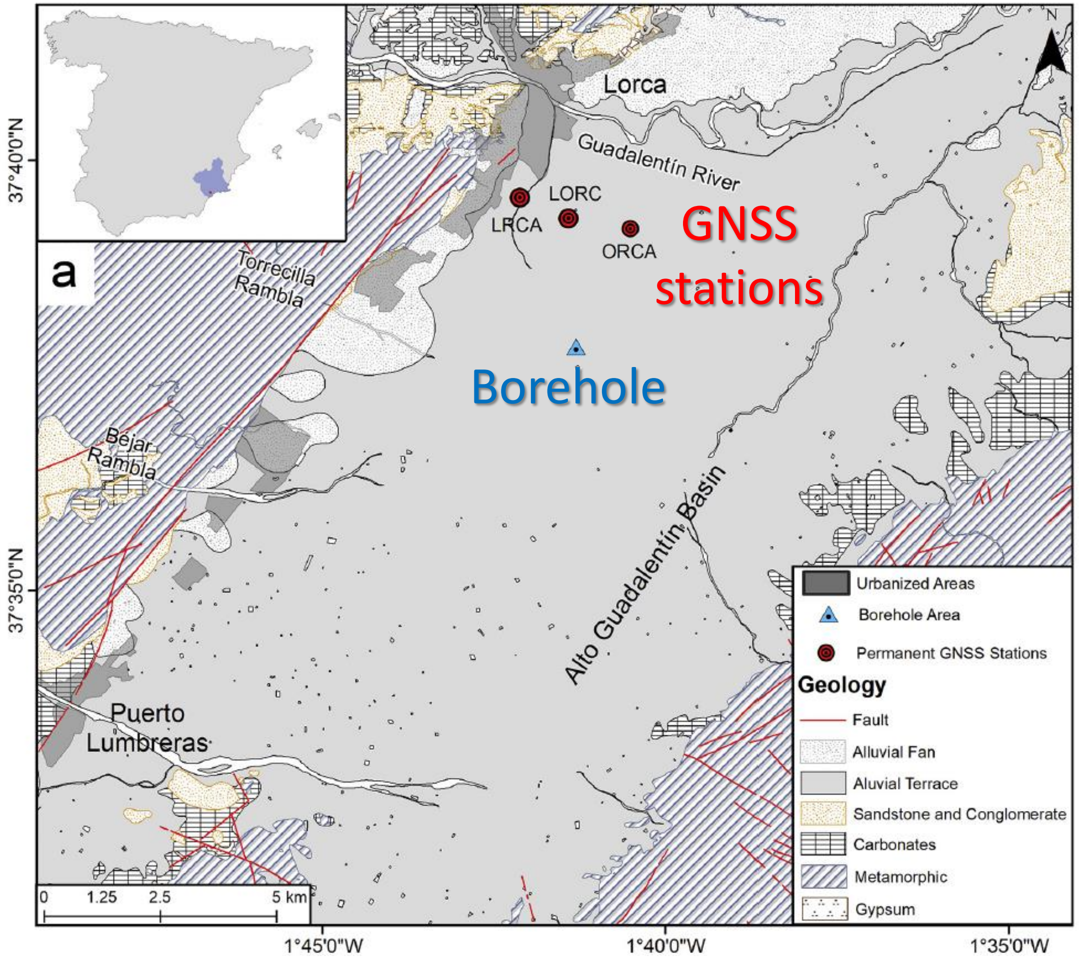


Fig. Geologic map

Main aquifer system

Plio-Quaternary sediments (from alluvial fan systems)

300 - 900 m depth

Miocene deposits (conglomerates / sandstones / marls)

Low permeability

impervious limit

- The upper part of the Plio-Quaternary sediments are continuous fine sediments.

magnitude of subsidence

↑

Aquitard
(Clay / Silt)

Confined aquifer
(Sand / Gravel)

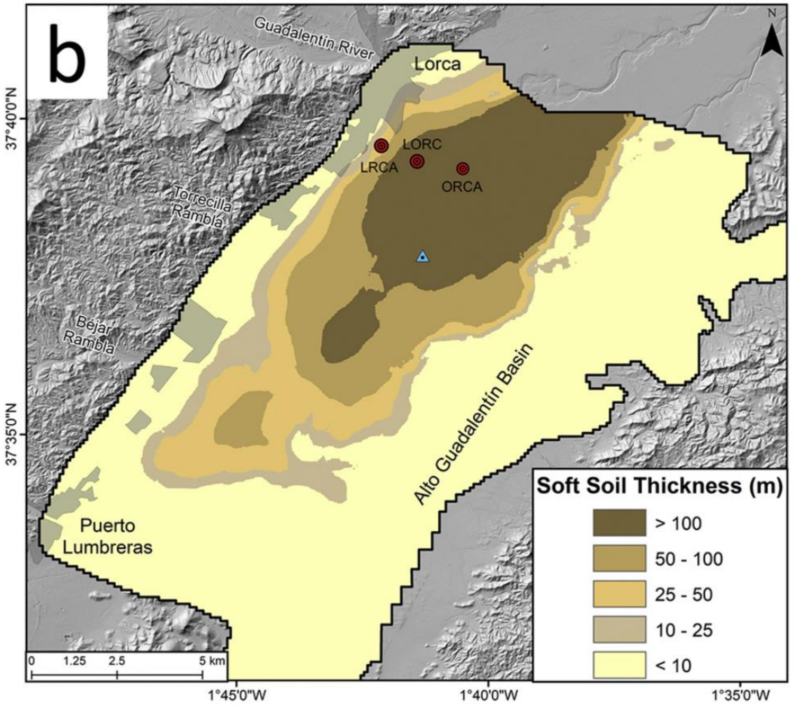


Fig. Soft soil thickness distribution

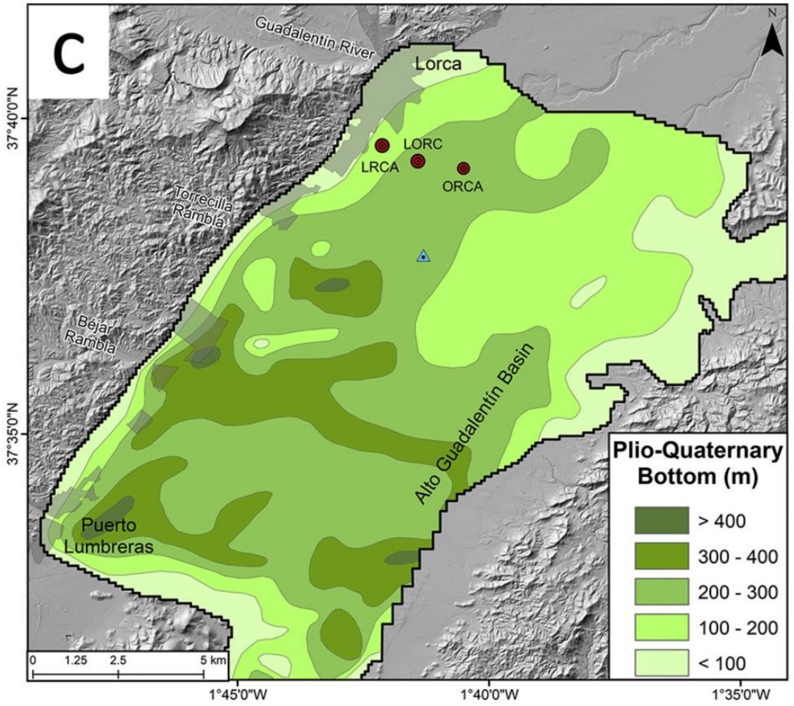


Fig. Plio-quaternary bottom

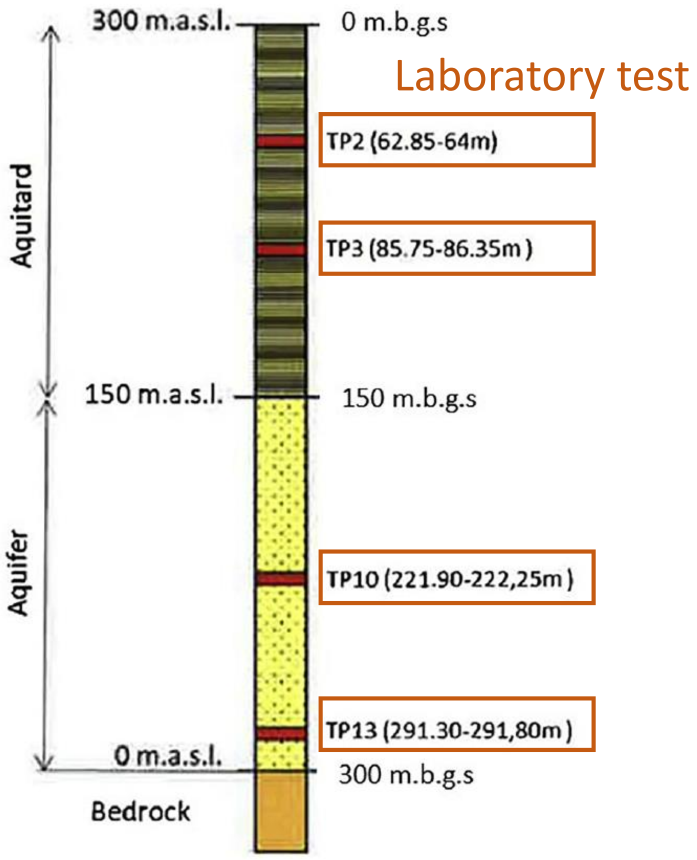


Fig. Simplified stratigraphic column

Introduction / Study area – subsidence

- Since 1960, limited natural recharge and intensive use of the aquifer resources lead to 150m drop of average groundwater level in 50 years.
- The aquifer was officially declared overexploited in 1988.

13 cm/yr (1992-2000) | 11.9 cm/yr (2003-2010) | 10.55 cm/yr (2011-2017)

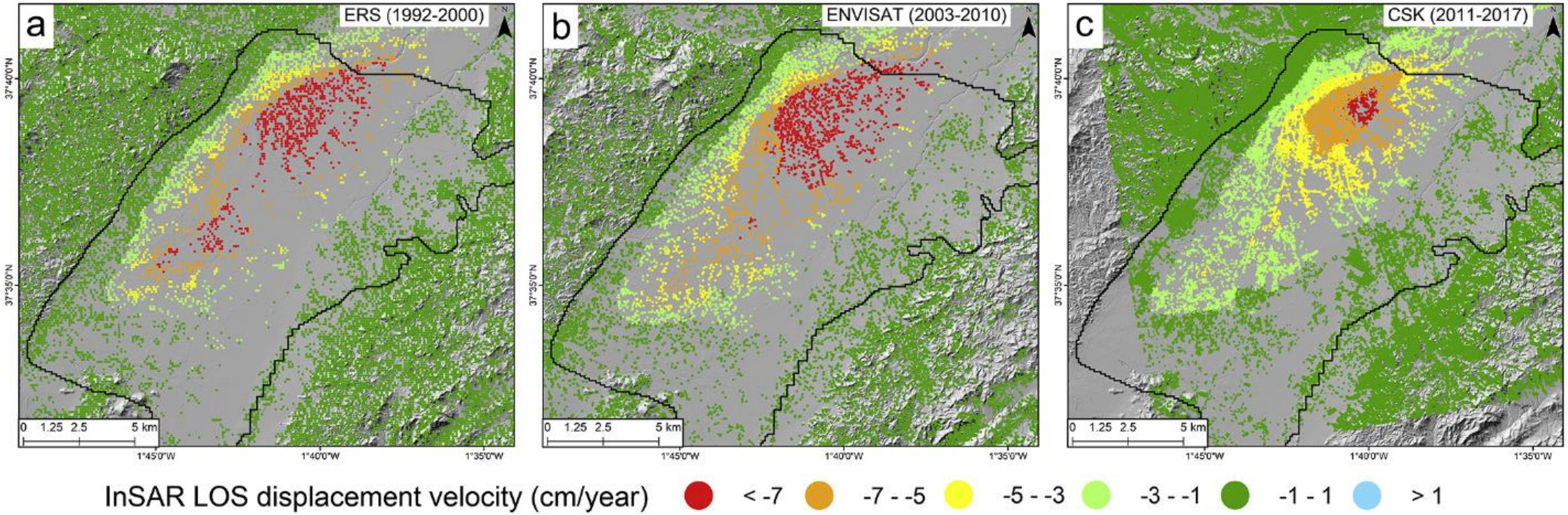


Fig. The displacement velocities in the Alto Guadalentín Basin.

Introduction / Study area – subsidence

- The accumulated subsidence recorded is around 3.1 m over the last 27 years.
- Surface subsidence monitoring indicates the deformation trend has been nearly constant since 1995.

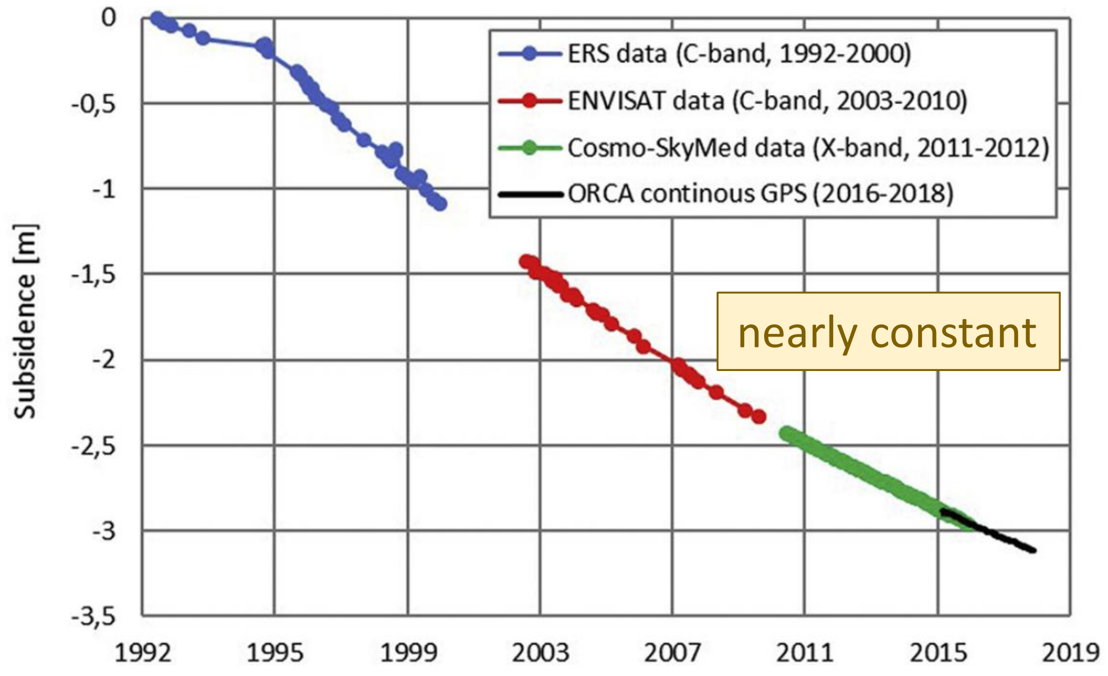
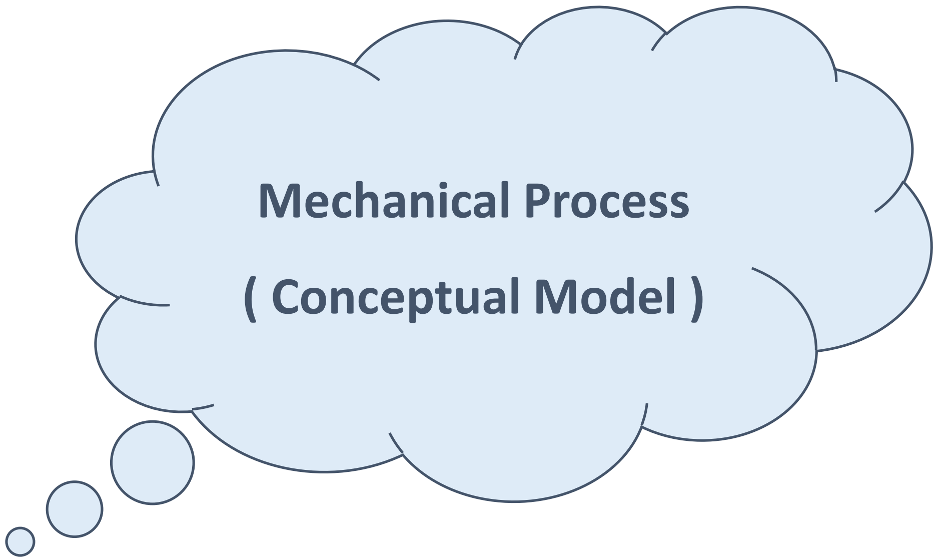


Fig. Subsidence recorded by different techniques since 1992 in the area of maximum subsidence.



Mechanical Process:

- Slow consolidation due to slow downward percolation of water in the 150-m-thick clay layer.

The aquifer is confined in equilibrium	Pumping period with no surface recharge	No pumping and no recharge

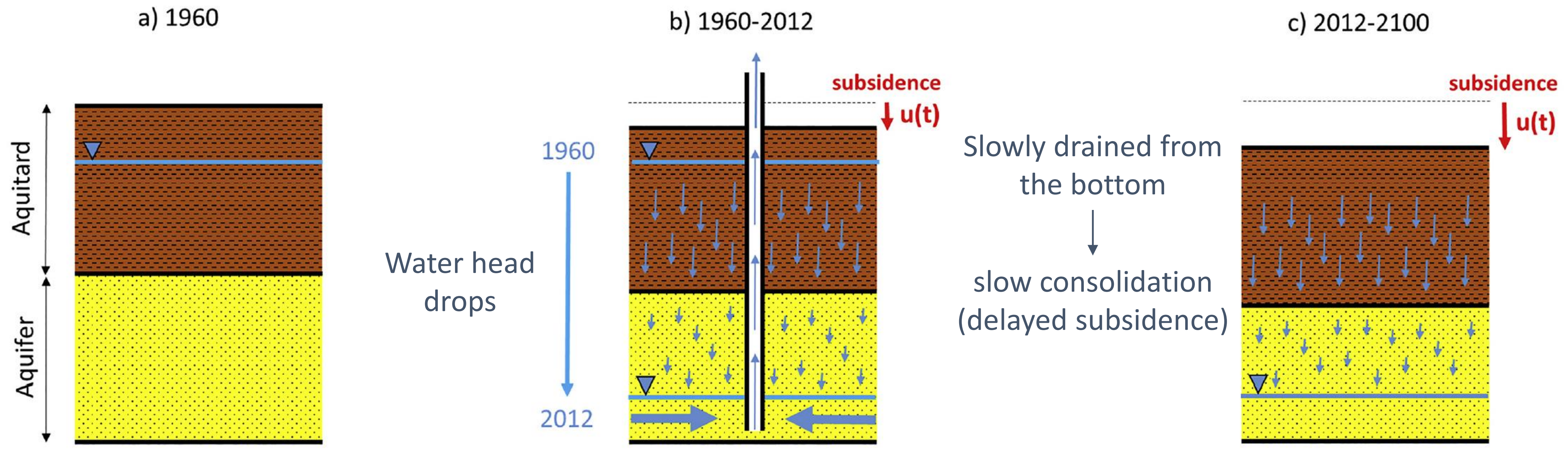


Fig. Conceptual model

02 Methodology

Groundwater model / Constitutive model / Subsidence model

Methodology

- The new numerical methodology in this paper aims to use advantages of each model.

(1) **Groundwater model** (3D MODFLOW) → The groundwater evolution in the regional Alto Guadalentín aquifer system since 1960.

Groundwater observation data

(2) **Constitutive model** (state parameter-based) → The mechanical behavior of soil

Experimental data from laboratory test

Subsidence model (1D GEHOMADRID) → Slow vertical percolation and associated vertical consolidation in the aquitard.

ERS, ENVISAT, CSM and GNSS

Methodology / Groundwater model

- The regional trend of water flows and changes in the hydraulic head of the aquifer.
- Water flows are basically horizontal, driven by recorded yearly water discharge and recharge.

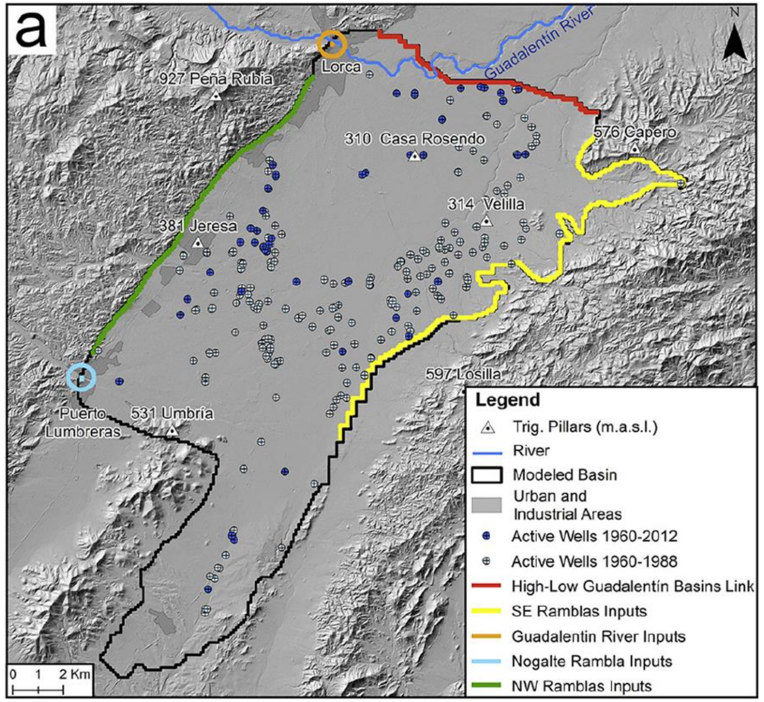


Fig. Lateral boundary conditions
(discharge: pump / recharge: streams)

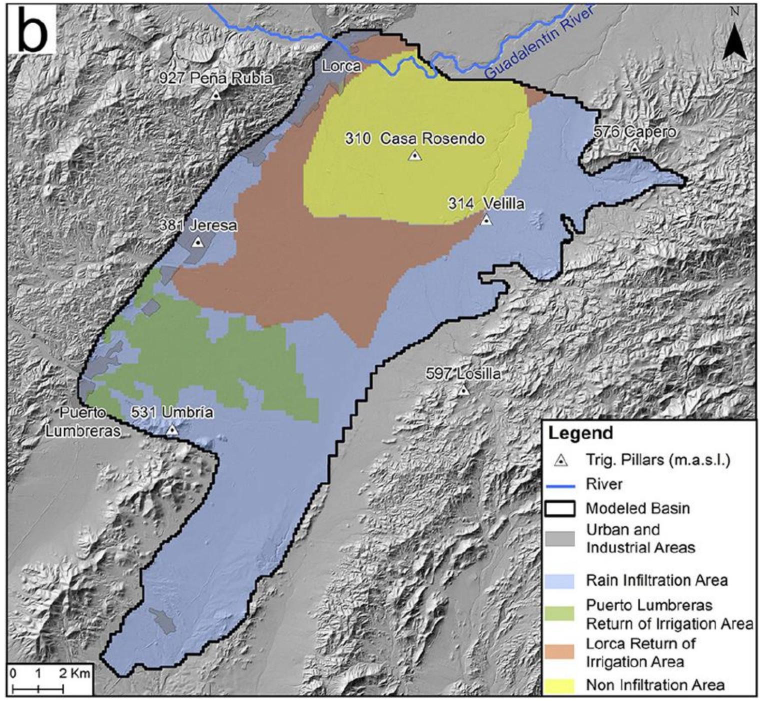


Fig. Superficial boundary conditions
(ex: infiltration and irrigation area)

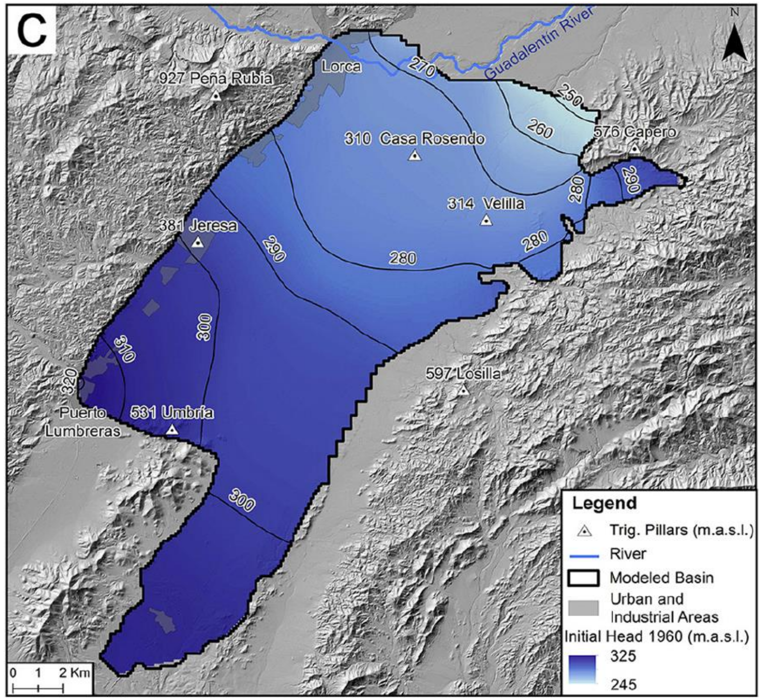


Fig. Initial state
(1960 data → steady state solution)

Methodology / Constitutive model

- By defining a state parameter, single set of material parameters can be used to reproduce the mechanical behavior of soils under different confining pressures and void ratios.
- It can be used at different depth, and the model automatically stiffens the material in the simplified stratigraphic column.

Table 3
Calibrated model parameters.

	Parameter	Value
Elasticity	G_{eso} (kPa)	49.
	ν	0.25
Critical State	M_g	0.9
	e_Γ	0.63
	λ	0.0085
	ζ_C	0.6
Plastic flow	d_0	1.
	m	0.9
	h_1 / h_2	1. / 0.
Plastic modulus	H_0'	1.
	β_0'	0.
	β	1.8
	H_{v0}	21.
	β_v	7.
	β_0	20.
	β_1	5.
	γ	8.

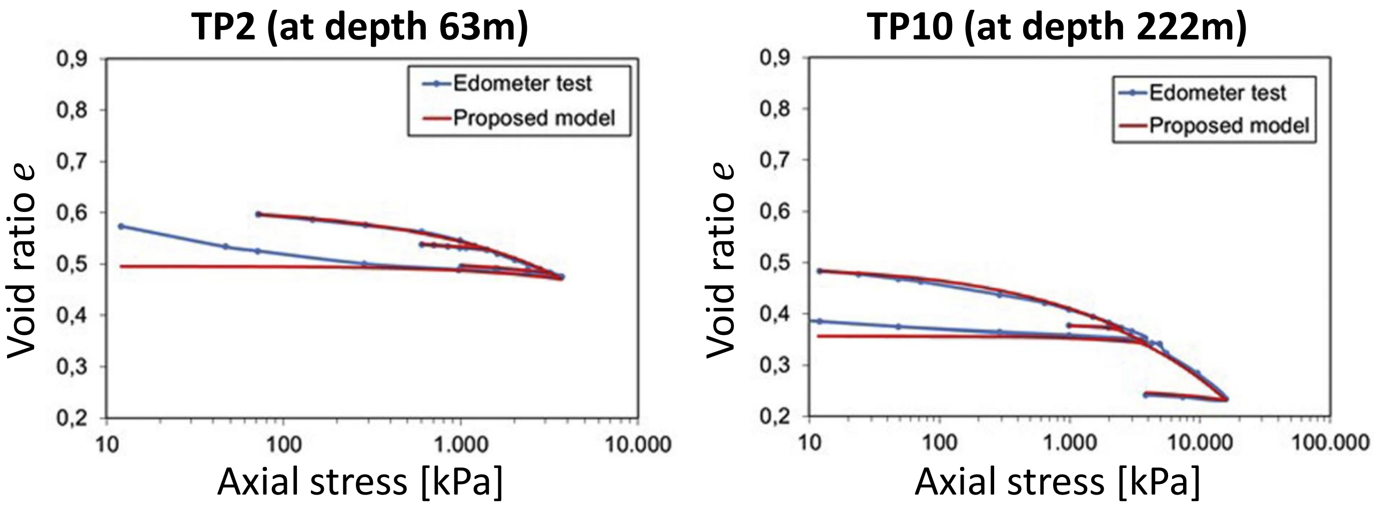
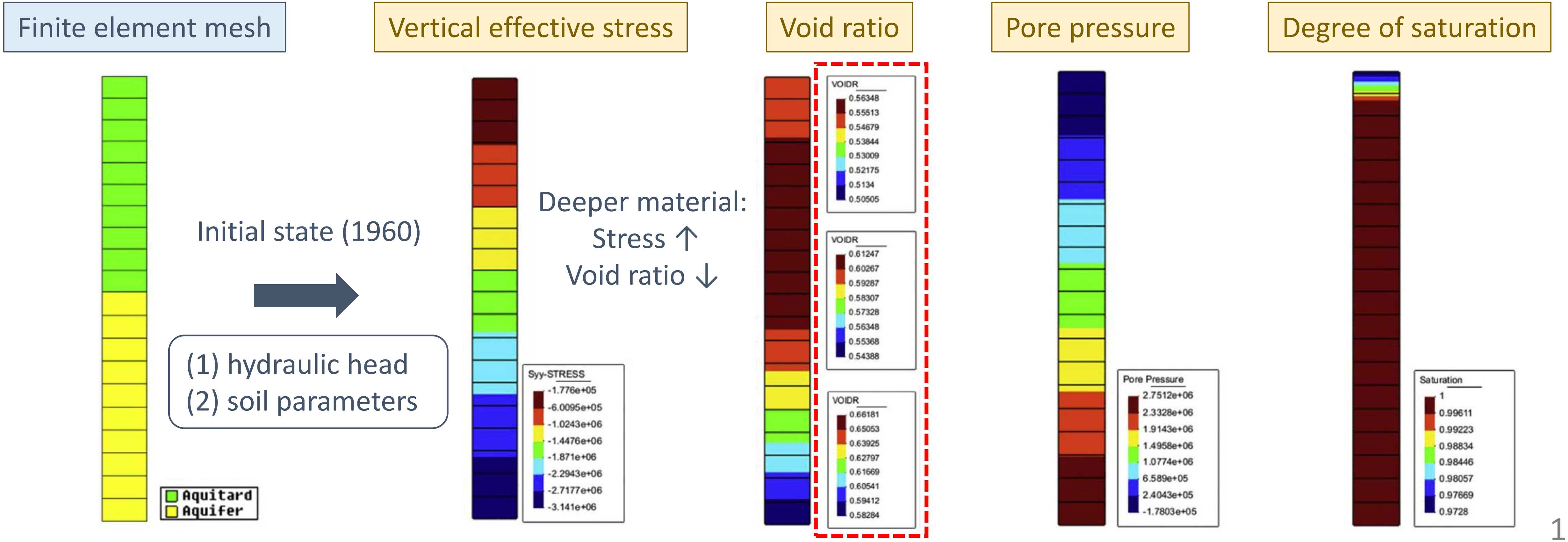


Fig. Comparisons between model predictions and experimental data in oedometer tests.

Methodology / Subsidence model

- Hydro-mechanical coupling between pore fluids (air and water) and the soil skeleton is represented by the Biot equations.
- Initial equilibrium state: the effective stress increases with depth and the void ratio decreases with depth. That is, a more compacted state for deeper materials is considered.



03 Results & Discussion

The results of groundwater model and subsidence model

- The groundwater model calculates a 160 m head drop over the period 1960 – 2012.

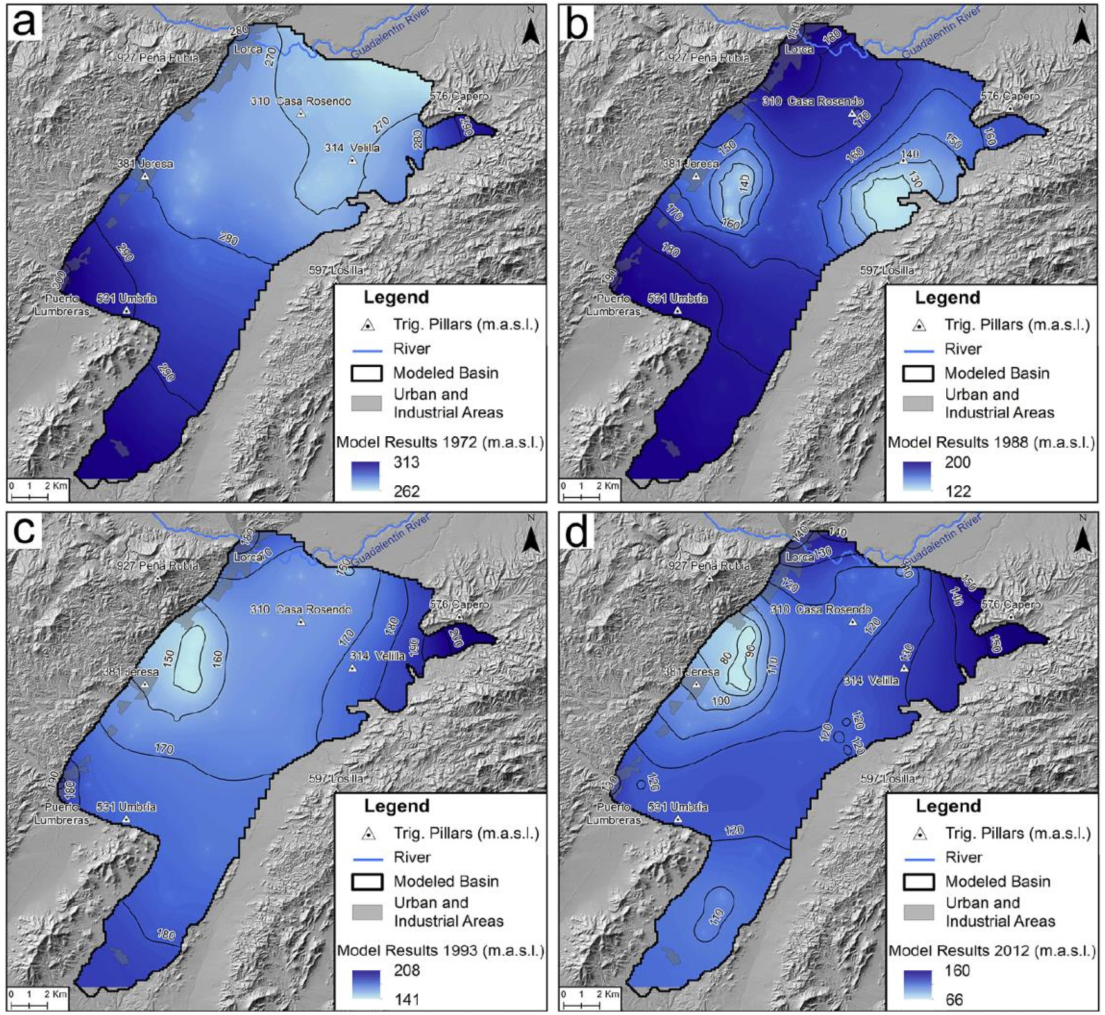


Fig. Computed hydraulic head spatial distribution in (a) 1972 (b) 1988 (c) 1993 (d) 2012

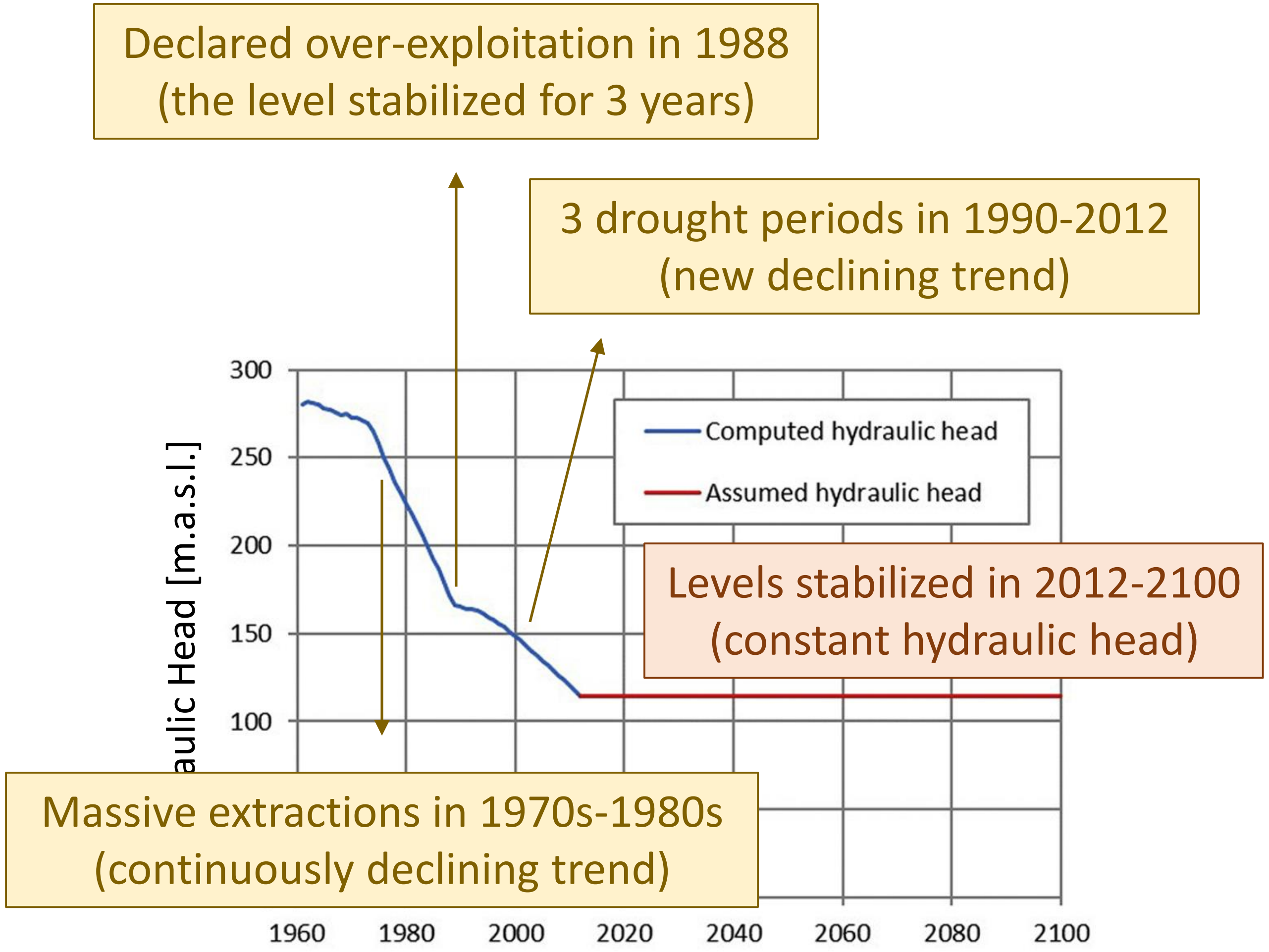


Fig. The time evolution of the hydraulic head in the borehole cell.

Results & Discussion / Subsidence model results

- The figure shows the time evolution of the computed subsidence for the three different initial states.
- The computed subsidence is larger for higher void ratio in initial state. (i.e. lower initial compacted materials)

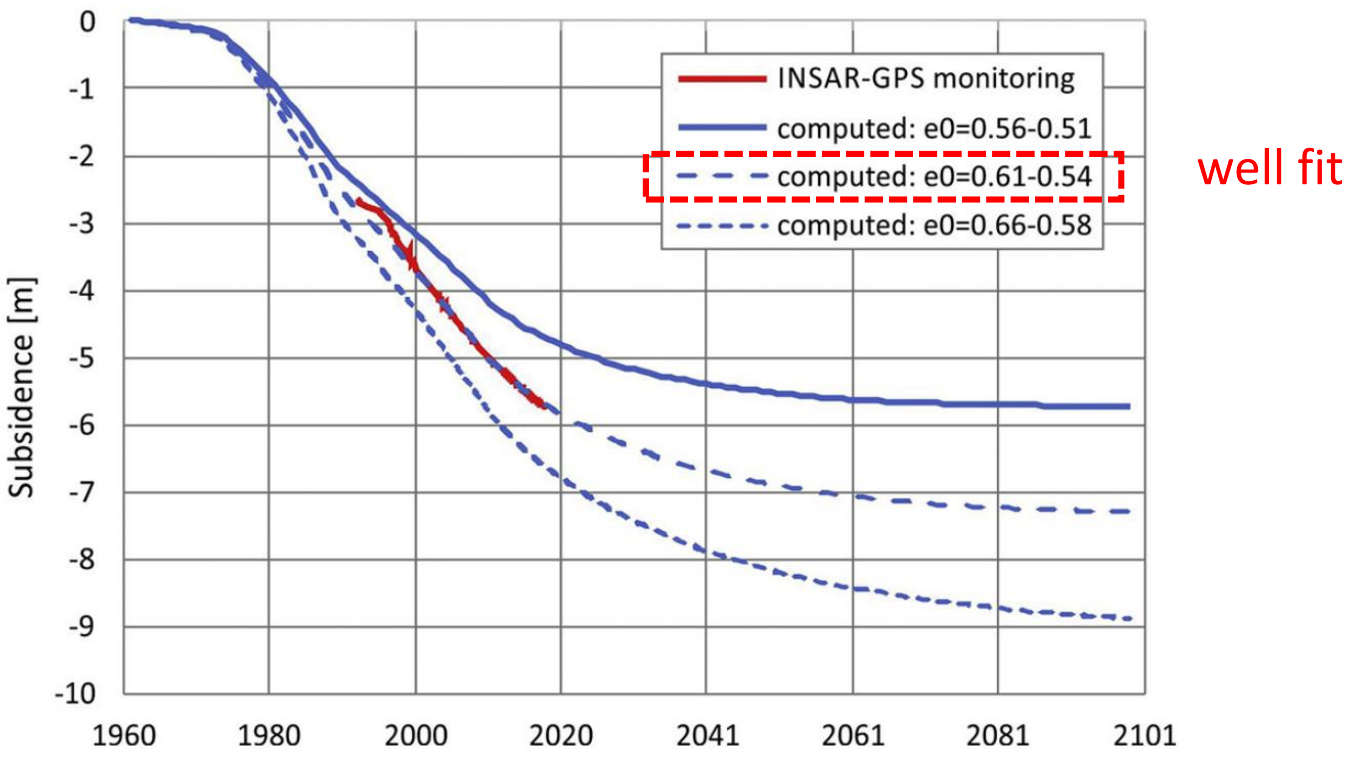
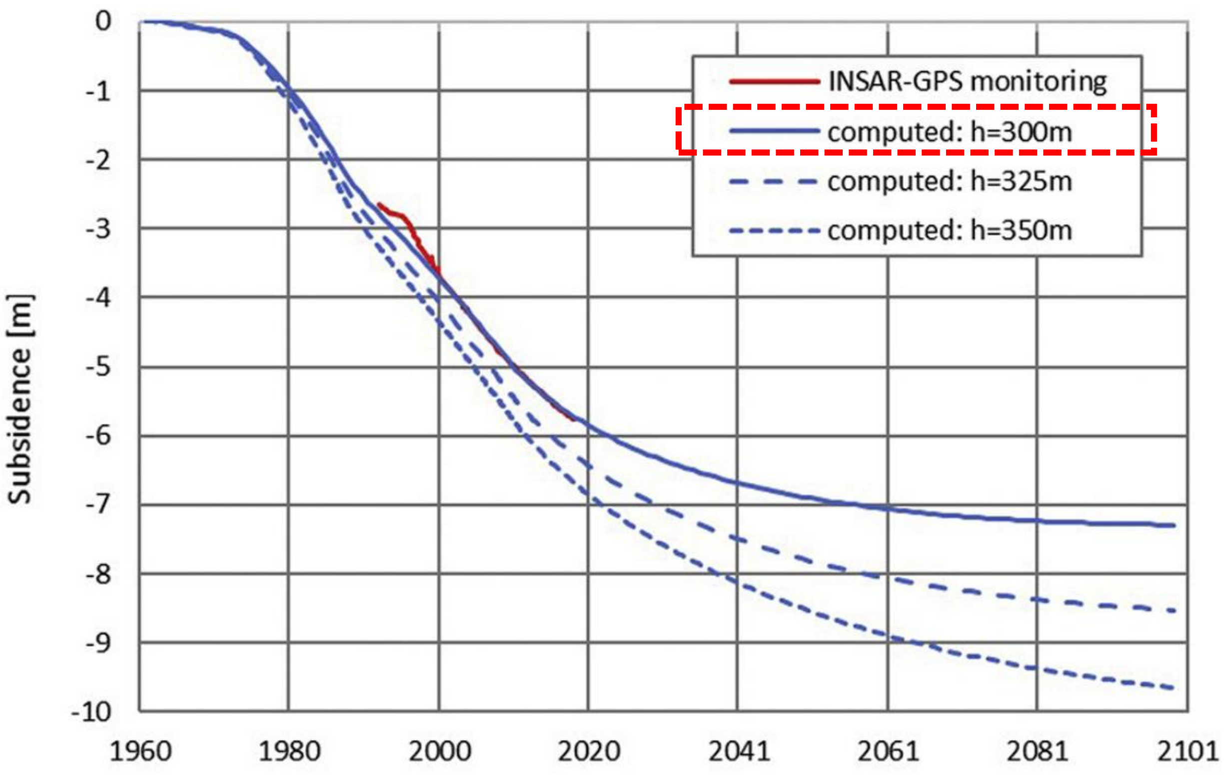


Fig. Subsidence computation. Influence of initial states.

Results & Discussion / Subsidence model results

- The assumed thickness of the compressible material should have an influence on the final subsidence results.
- Because the depth of the bedrock was not determined in the 300-m-depth borehole, the influence of aquifer system thickness is analyzed.

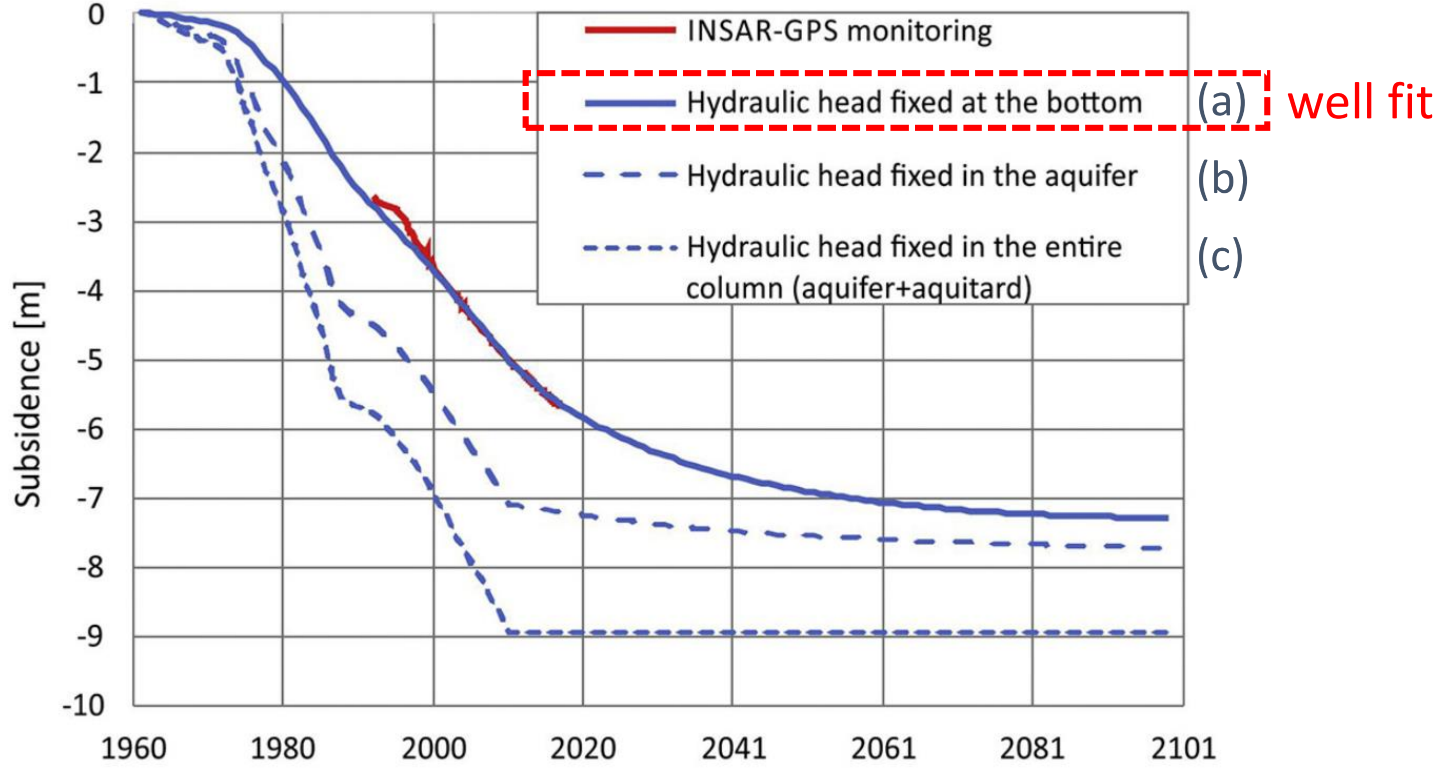


well fit

Fig. Subsidence computation. Influence of aquifer system thickness.

Results & Discussion / Subsidence model results

- The hydraulic head is set in three different ways in the subsidence model.
- The subsidence fits well with observed subsidence trend when the hydraulic head fixed at the bottom.



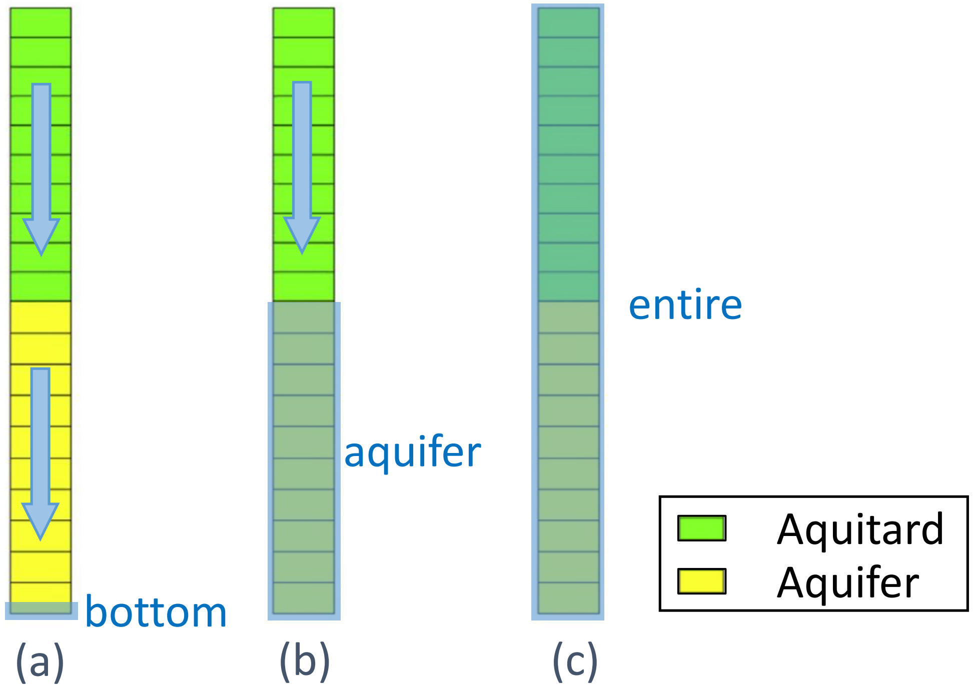
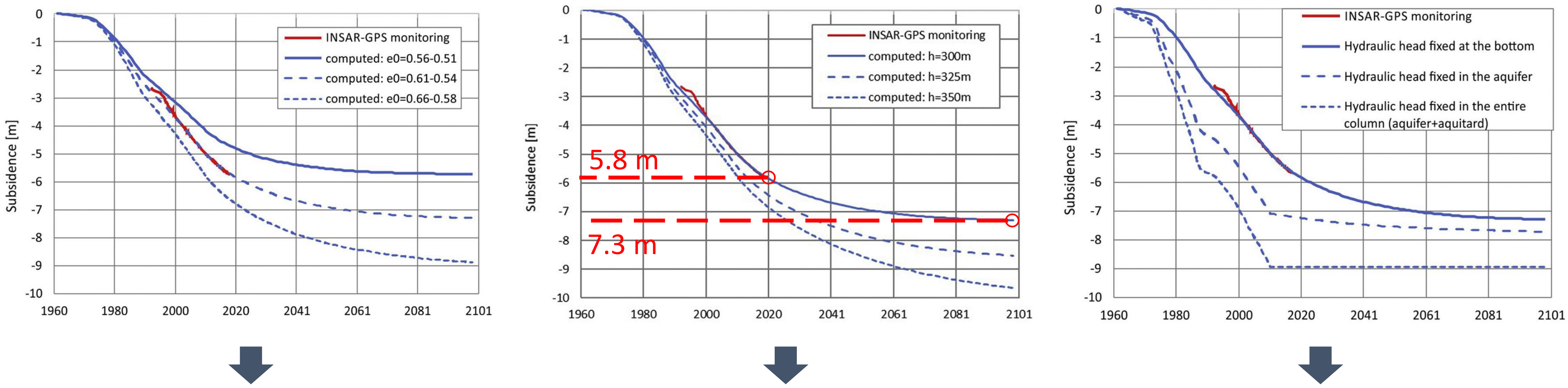


Fig. Subsidence computation. Influence of hydraulic boundary conditions.

Results & Discussion / Subsidence model results

- Overall, the best results can fit well with subsidence observed for the period 1995-2012.
- This calibrated solution leads to a historical subsidence of 5.8 m from 1960 to 2020, and a prediction of up to 7.3 m in 2100 (for an assumed constant hydraulic head since 2012).



e_0: 0.61 – 0.54

300-m-depth column

Hydraulic head fixed at the bottom

- It should be emphasized that the pore pressure profiles are realistic because of the non-linearity of permeability.
- Although the material stiffens with depth due to the constitutive model, the material deforms at deep depth.
- Deformation mainly occurred in the aquifer from 1960-2012 and also at the bottom of the aquitard after 2012.

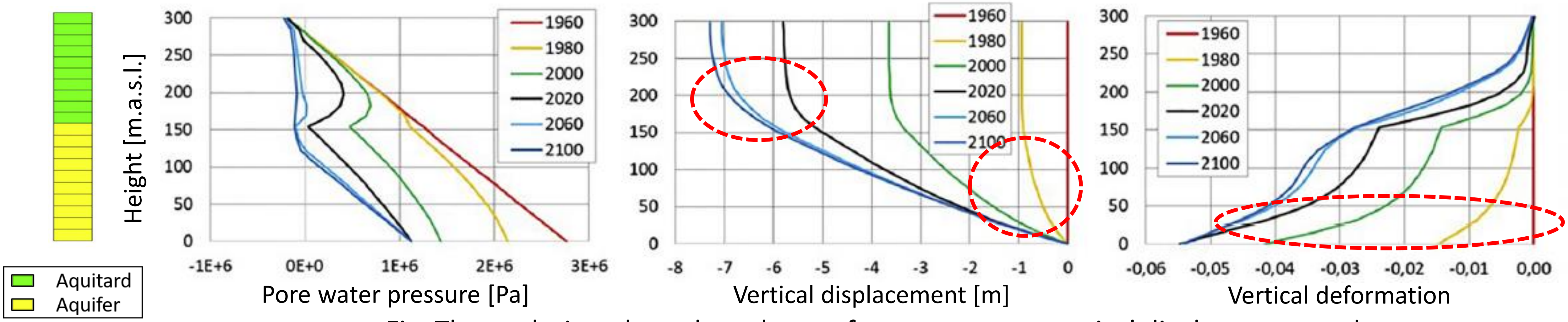


Fig. The evolution along the column of pore pressure, vertical displacement and vertical deformation.

04 Conclusions

Conclusions

- Numerically simulating subsidence due to groundwater withdrawal at a regional scale is a complex problem that can be approached through different models.
  - A rough 3D groundwater model reproduces horizontal flow due to pumping in the confined aquifer at the regional scale.
  - A coupled hydro-mechanical 1D subsidence model reproduces in detail the slow vertical flow and desaturation process in the aquitard due to bottom drainage.
  - Moreover, a constitutive model of state parameter is proposed to reproduce inelastic soil compressibility across the column in a uniform way.

THANK YOU
FOR YOUR ATTENTION