SALT WATER INTRUSION IN A GROUNDWATER SYSTEM AT THE BASILICATA REGION, SOUTH ITALY

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Abstract. Working package 5 (WP5) of the EU-project CRYSTECHSALIN (fifth framework programme) is considered in this article. CRYSTECHSALIN stands for *Crystallisation technologies for prevention of salt water intrusion*. The project is focused on the development of a new cost efficient and environmental-friendly technology to reduce the permeability of soil formations that are threatened by the intrusion of saline groundwater. WP5 is focused on the creation of a hydrogeological and hydrogeochemical numerical model. The specific field test site of the working package under consideration is located in the coastal plain of the Italian region of Basilicata, South Italy, nearby the city of Scanzano. A regional density dependent groundwater flow model is developed to investigate the regional effects of permeability reductions. The computer code MOCDENS3D (Oude Essink, 1998, 2001) is used for that purpose. This code is a version of MOC3D that has been adapted to simulate transient density-driven groundwater flow and solute transport. It appears that a physical barrier is only effective from a hydraulic point of view when the permeability reduction is relative high.

Keywords: CRYSTECHSALIN, Italian test site in the Basilicata region, prevention of salt water intrusion, permeability reduction, numerical modelling of variable-density groundwater flow, MOCDENS3D.

INTRODUCTION

The main task of working package 5 of the EU project CRYSTECHSALIN is to develop a mathematical model that describes the mixing processes in a porous media. The relevant hydrogeological processes are analysed and described mathematically. A numerical concept will be worked out that will describe the flow of calcium carbonate leading to the formation of slightly soluble minerals after in-situ mixing with sea water. The field test site is located in the coastal plain of the Italian region of Basilicata, South Italy, nearby the Torre di Scanzano: viz. Idrovora 4-Torre (Figure 1a and b).

Two density dependent groundwater models of the field test site are constructed in order to analyse the existing flow processes in the hydrogeologic system: one coarse model of the whole regional area and one fine model of the field test site. In this article, only the coarse regional model is discussed. The regional large-scale model has been constructed to determine: 1. the natural groundwater flow in seaward direction; 2. the salt water intrusion in the coastal plain; 3. the boundary conditions of the local model; and finally, 4. the regional effect of the hydraulic conductivity reduction. The computer code MOCDENS3D is applied to take into account variable-density flow.

The geometry of the hydrogeologic system at the field test site will be modelled in three dimensions, as injection of grouting material in the real field test site is typically a three dimensional problem. Interaction of different grouting materials and in-situ minerals will be considered. Based on the variable-density flow field, multi-species reactive transport in the saturated porous medium will be superimposed, taking into account the relevant geochemical processes in the subsoil: viz. precipitation and dissolution of calcium carbonate which are under influence of an inhibitor. For this purpose, reactive flow and transport of calcium carbonate are coupled with groundwater flow, as changes in porosity and permeability are considered. As such, a reduction in permeability influences the variable-density flow field and the groundwater flow will be recalculated repeatedly to get an up-to-date flow situation. Eventually, an effective methodology to implement a physical barrier will be proposed.

GEOMETRY OF THE TEST SITE

The following hydrogeological parameters of the coastal plain of the Italian region of Basilicata have been considered (derived from the extensive report of Polemio et al , 2002): geometry of the site, depth of the impervious basement, boundary and initial conditions, natural groundwater recharge, groundwater extractions (rate and positions of wells), river fluxes, position, thickness, hydraulic conductivity and porosity of layers, piezometric heads at different levels (corrected for density differences, if applicable), observation wells (position and head of the screen), geochemical data of the observation wells, total dissolved solids in the observation wells and salinity concentration distribution in the system.

Two models will be constructed in this working package: a regional model and a local model. The large-scale regional model of the whole coastal plain between the two rivers Cavone and Agri is developed to construct a reliable calibrated model which takes into account all relevent regional physical processe and to check whether the boundary conditions in the fine model are far enough from our field test site to not influence groundwater flow and solute transport. In both cases density dependent groundwater flow and solute transport will be considered.

Figure 1: a. Position of the Italian field test site, **b.** Map of the regional model, including the rivers Agri and Cavone

CHARACTERISTICS NUMERICAL CODE

MOCDENS3D (Oude Essink, 1998, 2001) is used to simulate the transient groundwater system. It is based on the United States Geological Survey three-dimensional public domain finite difference computer code MOC3D (Konikow et al.,1996). As density differences are considered in the coastal plain, the code has been adapted to simulate variable-density flow in porous media.

Groundwater flow equation

The (adapted) MODFLOW module solves the density driven groundwater flow equation [McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996]. It combines the continuity equation with the equation of motion. Under the given circumstances in the Dutch coastal aquifers, the Oberbeck-Boussinesq approximation is valid as it is suggested that the density variations (due to concentration changes) remain small to moderate in comparison with the reference density ρ throughout the considered hydrogeologic system:

$$\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}=S_s\frac{\partial \phi_f}{\partial t}+W \qquad (1)$$

$$q_x=-\frac{\kappa_x}{\mu}\frac{\partial p}{\partial x} \qquad\qquad q_y=-\frac{\kappa_y}{\mu}\frac{\partial p}{\partial y}$$

$$q_z=-\frac{\kappa_z}{\mu}\left(\frac{\partial p}{\partial z}+\rho g\right) \qquad (2)$$

where q_x, q_y, q_z = Darcian specific discharges in the principal directions [L T^{-1}]; S_s = specific storage of the porous material [L^{-1}]; W = source function, which describes the mass flux of the fluid into (negative sign) or out of (positive sign) the system [T^{-1}]; κ_x, κ_y, κ_z = principal intrinsic permeabilities [L^2]; μ = dynamic viscosity of water [M L^{-1} T^{-1}]; p = pressure [M L^{-1} T^{-2}]; ρ= the density of the groundwater [M L^{-3}]; and g = gravitational acceleration [L T^{-2}]. A so-called freshwater head ϕ_f is introduced to take into account differences in density in the calculation of the head:

$$\phi_f = \frac{p}{\rho_f \, g} + z \qquad (3)$$

where ϕ_f is the freshwater head [L], ρ_f is the reference density, usually the density of fresh groundwater at reference chloride concentration C_0 [M L^{-3}], p is the pressure [M L^{-1} T^{-2}], and z is the elevation head [L]. Rewriting the Darcian specific discharge in terms of freshwater head gives:

$$q_x = -\frac{\kappa_x \rho_f g}{\mu}\frac{\partial \phi_f}{\partial x} \qquad q_y = -\frac{\kappa_y \rho_f g}{\mu}\frac{\partial \phi_f}{\partial y}$$

$$q_z = -\frac{\kappa_z \rho_f g}{\mu}\left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f}\right) \qquad (4)$$

In many cases small viscosity differences can be neglected if density differences are considered in normal hydrogeologic systems [Verruijt, 1980; Bear and Verruijt, 1987].

$$\frac{\kappa_i \rho_f g}{\mu} = k_i \qquad (5)$$

$$q_x = -k_x \frac{\partial \phi_f}{\partial x} \qquad q_y = -k_y \frac{\partial \phi_f}{\partial y}$$

$$q_z = -k_z\left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho}\right) \qquad (6)$$

The basic water balance used in MODFLOW is given below [McDonald and Harbaugh, 1988]:

$$\sum Q_i = S_s \frac{\Delta \phi_f}{\Delta t}\Delta V \qquad (7)$$

where Q_i = total flow rate into the element (L^3 T^{-1}) and ΔV = volume of the element (L^3). The MODFLOW basic equation for density dependent groundwater flow becomes as follows [Oude Essink, 1998, 2001]:

$$\begin{aligned}
&CV_{i,j,k-1/2}\,\phi^{t+\Delta t}_{i,j,k-1} + CC_{i-1/2,j,k}\,\phi^{t+\Delta t}_{i-1,j,k} + CR_{i,j-1/2,k}\,\phi^{t+\Delta t}_{i,j-1,k} \\
&+ (-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} \\
&- CR_{i,j+1/2,k} - CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k})\phi^{t+\Delta t}_{i,j,k} \\
&+ CR_{i,j+1/2,k}\,\phi^{t+\Delta t}_{i,j+1,k} + CC_{i+1/2,j,k}\,\phi^{t+\Delta t}_{i+1,j,k} + CV_{i,j,k+1/2}\,\phi^{t+\Delta t}_{i,j,k+1} = RHS_{i,j,k}
\end{aligned} \qquad (8)$$

$$HCOF_{i,j,k} = P_{i,j,k} - SC1_{i,j,k}/(\Delta t) \qquad (9)$$

$$\begin{aligned}
RHS_{i,j,k} = &-Q_{i,j,k} - SC1_{i,j,k}\,\phi^{t}_{i,j,k}/(\Delta t) \\
&- CV_{i,j,k-1/2}\,\Psi_{i,j,k-1/2}(d_{i,j,k-1} + d_{i,j,k})/2 \\
&+ CV_{i,j,k+1/2}\,\Psi_{i,j,k+1/2}(d_{i,j,k} + d_{i,j,k+1})/2
\end{aligned} \qquad (10)$$

$$SC1_{i,j,k} = SS_{i,j,k}\Delta V \qquad (11)$$

$$\begin{aligned}
\Psi_{i,j,k-1/2} &= \left(\frac{(\rho_{i,j,k-1} + \rho_{i,j,k})/2 - \rho_f}{\rho_f}\right) \\
\Psi_{i,j,k+1/2} &= \left(\frac{(\rho_{i,j,k} + \rho_{i,j,k+1})/2 - \rho_f}{\rho_f}\right)
\end{aligned} \qquad (12)$$

where $CV_{i,j,k}$, $CC_{i,j,k}$, $CR_{i,j,k}$ = the so-called MODFLOW hydraulic conductances between elements in respectively vertical, column and row directions (L^2 T^{-1}) [McDonald and Harbaugh, 1988]; $P_{i,j,k}$, $Q_{i,j,k}$ = factors which account for the combined flow of all external sources and stresses into an element (L^2 T^{-1}); $SS_{i,j,k}$ = specific storage of an element (L^{-1}); $d_{i,j,k}$ = thickness of the model layer k (L) and $\psi_{i,j,k-1/2}$, $\psi_{i,j,k+1/2}$ = buoyancy terms (-). The two buoyancy terms $\psi_{i,j,k}$ are subtracted from the so-called right head side term $RHS_{i,j,k}$ to take into account variable density. See Oude Essink [1998, 2001] for a detailed description of the adaptation of MODFLOW to density differences.

The advection-dispersion equation

The MOC module using the method of characteristics solves the advection-dispersion equation, which simulates the solute transport [Konikow and Bredehoeft, 1978; Konikow et al., 1996]. Advective transport of solutes is modelled by means of the method of particle tracking and dispersive transport by means of the finite difference method.

$$R_d \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i}(CV_i) + \frac{(C-C)'W}{n_e} - R_d \lambda C \qquad (13)$$

The used reference solute is chloride that is expected to be conservative. MOCDENS3D takes into account hydrodynamic dispersion.

The equation of state

A linear equation of state couples groundwater flow and solute transport:

$$\rho_{i,j,k} = \rho_{\mathrm{f}} [1 + \beta_{\mathrm{C}} (C - C_0)] \qquad (14)$$

where $\rho_{i,j,k}$ is the density of groundwater (M L^{-3}), C is the chloride concentration (M L^{-3}), and β_C is the volumetric concentration expansion gradient (L^3 M^{-1}). During the numerical simulation, changes in solutes, transported by advection, dispersion and molecular diffusion, affect the density and thus the groundwater flow. The groundwater flow equation is recalculated regularly to account for changes in density.

MODEL DESIGN

Numerical geometry and model grid

The regional model of the entire regional plain between the two rivers Cavone and Agri consists of a 3D grid of 10.0 km by 12.0 km by 100 m depth. The grid contains about 360000 elements: n_x=100, n_y=120, n_z=50, where n_i denotes the number of elements in the i direction (~60% of the elements is active). Each element is 100 m by 100 m long. In vertical direction the thickness of the elements equals 1 m for the lower 40 layer and 6 m for the upper 10 layers. Even those elements that are situated far into the sea are taken into account. Each element contains eight particles to solve the advection term of the solute transport equation. As such, some 2.9 million particles are used initially. On the applied time scale, the specific storativity S_s [L^{-1}] can be set to zero, as only a stationary groundwater flow model is generated. Later, a non-steady state model for the solute transport on the local scale will be deduced. The flow time step Δt to recalculate the groundwater flow equation equals one month. The convergence criterion for the groundwater flow equation (freshwater head) is equal to 10^{-3} m. The groundwater flow equation is solved with the preconditioned conjugate gradient procedure.

Boundary conditions

Boundary conditions are implemented at four sides. At the seaside a so-called general head boundary is implemented, as outflow of fresh groundwater from the land to the sea is difficult to implement in the model. The general head boundary (it is in fact a mixed or Cauchy boundary condition) is typically a MODFLOW-feature which models the in or outflow to an element through the difference between the head in the element itself and an external fixed head. A resistance (‘conductance’) attenuates the effect of the external fixed head. In case of implementing the sea, the resistance should be low (or the conductance high). The two rivers Agri and Cavone appear to intersect the groundwater system. As such, these two rivers act as Dirichlet ‘fixed head’ boundaries with interfere with the groundwater flow system through a resistance. The river package of the code MODFLOW is applied to account for this feature, as well as for some other rivers in the area. In addition, the drain package is implementetd at the coastal plain. It takes into account the features of this drained agricultural area. The well package of MODFLOW is used to account for small extractions. At the uphill part, a constant fixed head is inserted in the model. The bottom of the system, at –30 m M.S.L., is considered to be a no-flux boundary.

As little is known about hydrodynamic dispersion in the system, a brief sensitivity analysis will be executed to assess the mixing effect on the overall modelling. Initially, the longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1.

The phreatic water level in the so-called ‘idrovoras’ is modelled by the drain package of MODFLOW. The constant natural groundwater recharge is in this regional model for the time being set equal to 0 mm/d. In the updated version of the regional model, seasonal fluctuations in the natural groundwater recharge will be considered.

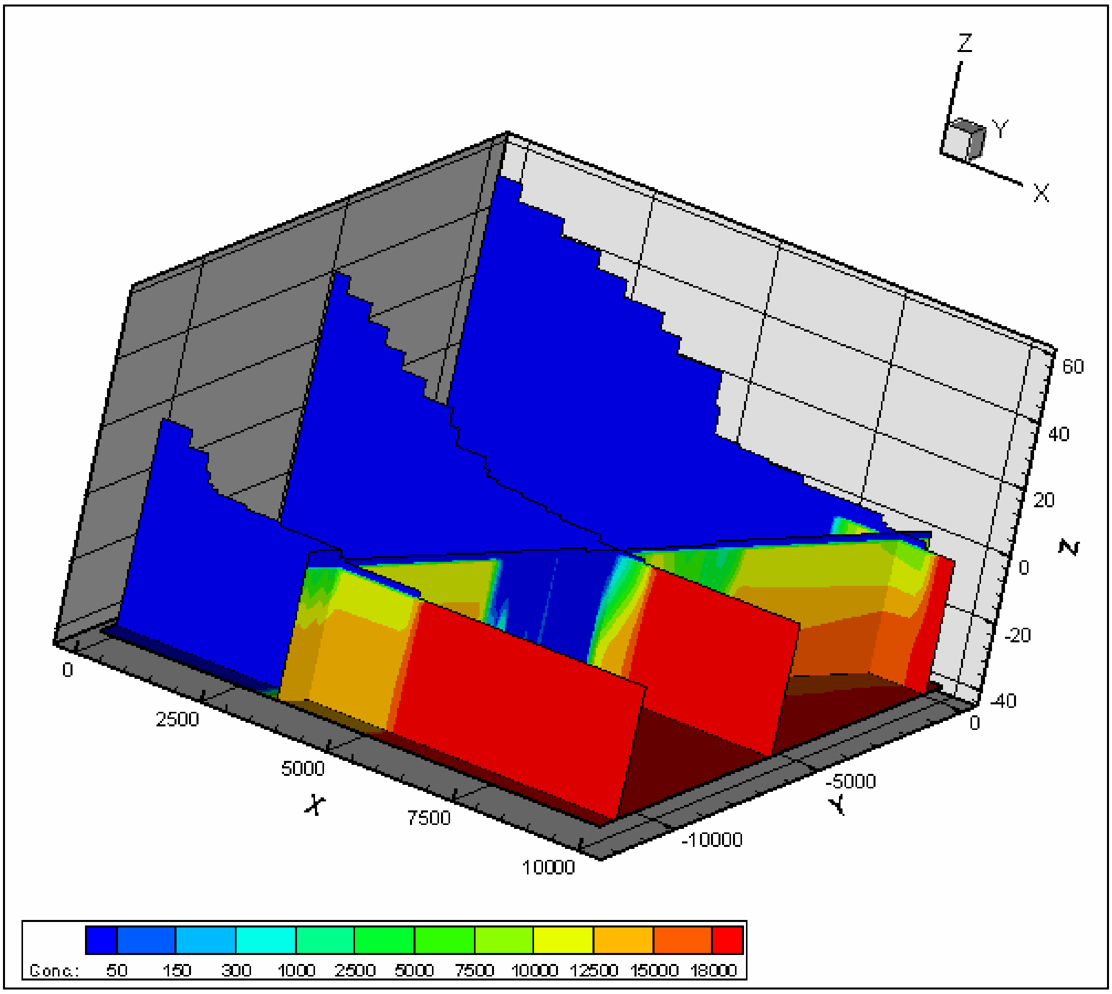

Figure 2: Initial chloride distribution in the subsoil: display of some slices.

At the initial situation (2000 AD), the coastal groundwater system contains some brackish but mostly fresh groundwater (Figure 2 and 3). On the average, the salinity increases with depth (Polemio et al, 2002). The groundwater system is overall a fresh groundwater system, except near the sea where TDS up to a number of hundreds of mg/l are found. In addition, more inland, some upconing of light brackish water is occurring, which might suggest inflow of brackish water into the aquifer system: salt water intrusion. The volumetric concentration expansion gradient β_C is 1.34 x 10^{-6} l/mg Cl^-. Saline groundwater at the sea does probably not exceed 22000 mg Cl^-/l, as sea water from the Mediterranean has a density somewhat higher than ocean water. The corresponding density of that saline groundwater equals 1029.5 kg/m^3.

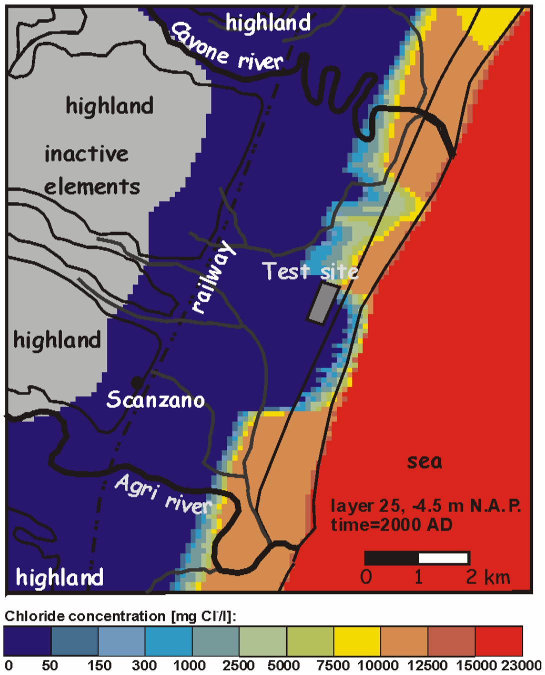

Figure 3: Regional concentration at a horizontal scale, at –5 m M.S.L.

Subsoil parameters

The groundwater system can be subdivided into two regions: the hilly marine terraces and the deposits at the coastal plain (Figure 4 and 5). At ground surface, the system can be divided into three lithological units (Polemio et al., 2002): 1. the coastal deposits,with low hydraulic conductivities (less then 0.2 m/day); 2. the alluvial, transitional and marine deposits; and 3. the marine terraces. Some marine terraced scarps are also present at the highland. At the field test site the top unit consists of soil (less then 2 m thick), followed by grey and/or yellow clays which thickness, viz. 0.5 m, appears to increase landwards. The second unit consists mainly of grey sands, fine-grained to coarse-grained, with a thickness of about 20 m. Hydraulic conductivities k_x varies from 2 to 20 m/day. Pebbly sands and clays intersect this unit. Throughout the large-scale model, the thickness of the second unit varies a lot (Polemio et al., 2002). The third unit is of grey clays.

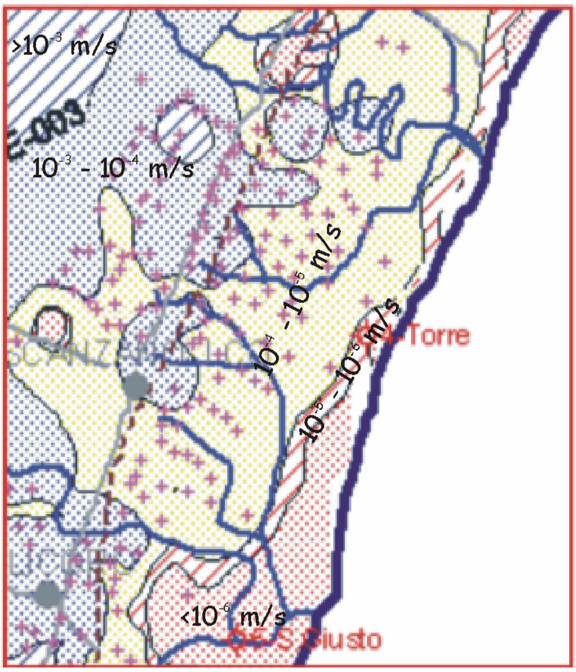

Figure 4: Hydraulic conductivity map (m/s) of the large-scale model area (from Polemio et al, 2002).

The following subsoil parameters are assumed: the anisotropy ratio k_z/k_x equals 0.1 for all layers. The effective porosity n_e is 0.25. The longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1. For a conservative solute as chloride, the molecular diffusion for porous media is taken equal to 10^{-9} m^2/s.

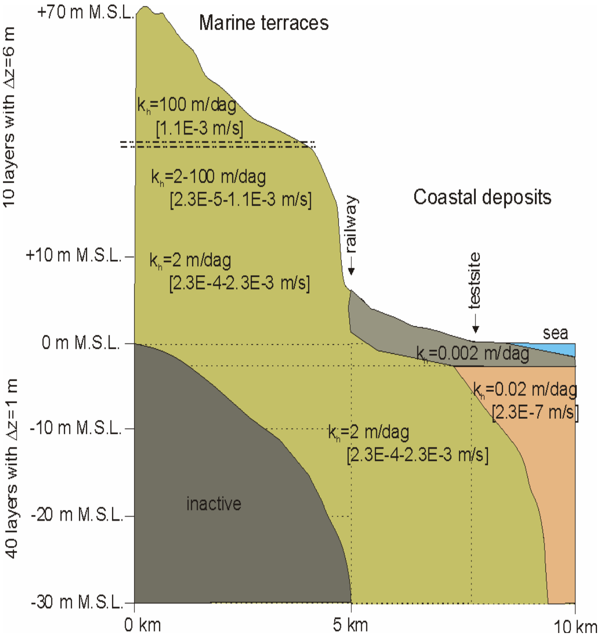

Figure 5: Simplified subsoil composition of the regional model.

Model parameters

The bottom of the system at –30 m M.S.L. is considered to be no-flux boundaries. At the vertical seaside borders, a so-called general head boundary is implemented with freshwater heads equal to hydrostatic pressure. At the inland hills side, a constant water level (viz. a Dirichlet boundary condition) is inserted. At the top of the system, the ground surface is +70 m M.S.L. The maximum and minimum measured head in the regional model is +54.20 m and -0.40 m M.S.L.

DISCUSSION

Calibration of the model: freshwater head distribution

Calibration of the numerical regional groundwater flow model was focused on the freshwater heads in the hydrogeologic system. There were 327 observation wells present in the Large Scale Area, of which only 208 were useful for the regional model. Freshwater head calibration was executed by comparing those 208 measured and simulated (freshwater) heads, which were corrected for density differences (Figures 6 and 7). The mean error was -0.36 m,

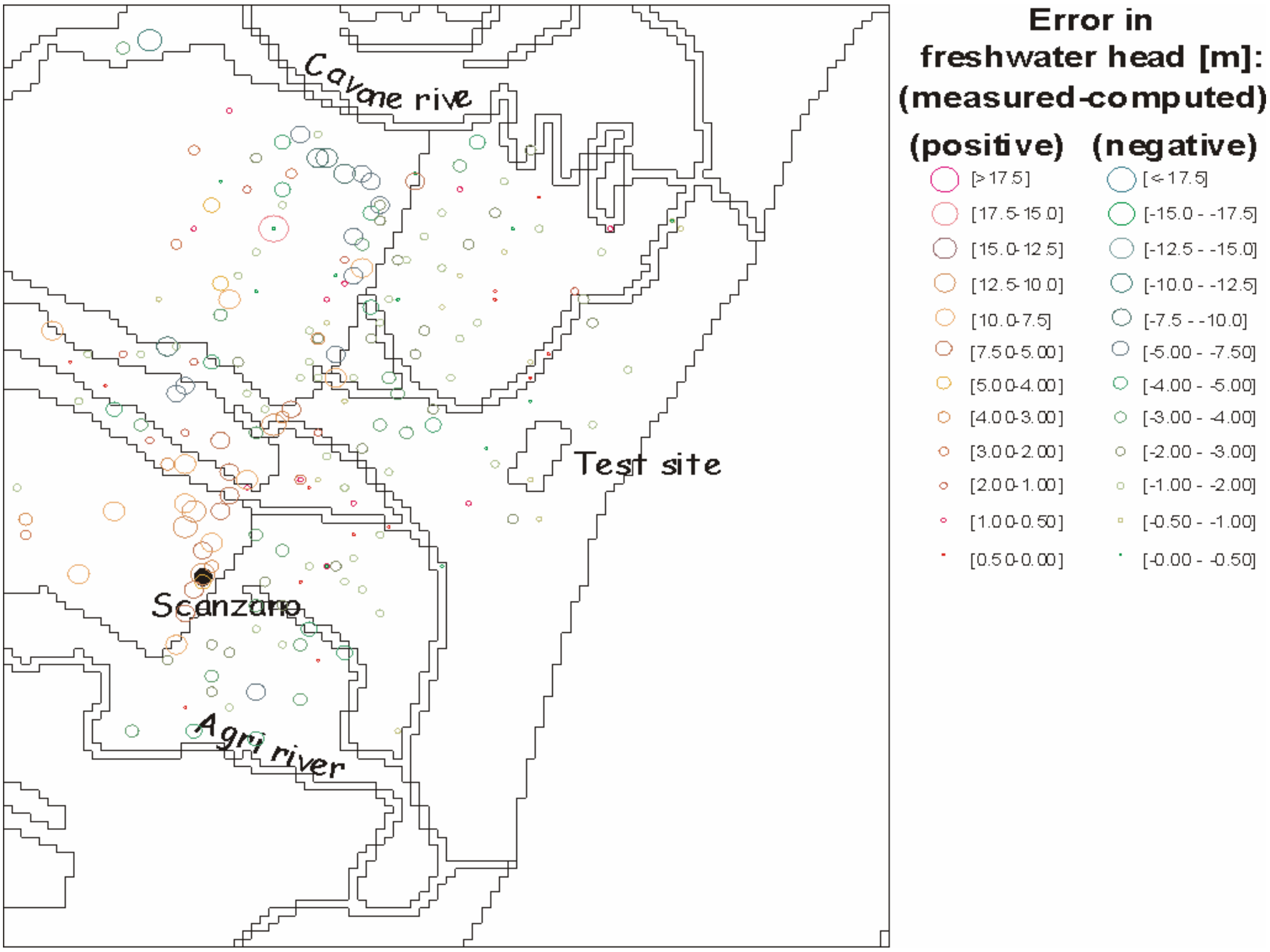

Figure 6: Spatial distribution of the errors: measured versus computed values at a horizontal scale.

the mean absolute error 3.01 m and the standard deviation 4.09 m. Seasonal variations in natural recharge obstruct easy calibration of the density dependent groundwater flow model. In the next phase, seasonal variation will be included.

Figure 8 shows the regional freshwater head distribution in the system. Obviously, the hills at the inland side of the hydrogeologic system generate high heads. Groundwater will flow from this upland up towards the coastal plain at a high pace.

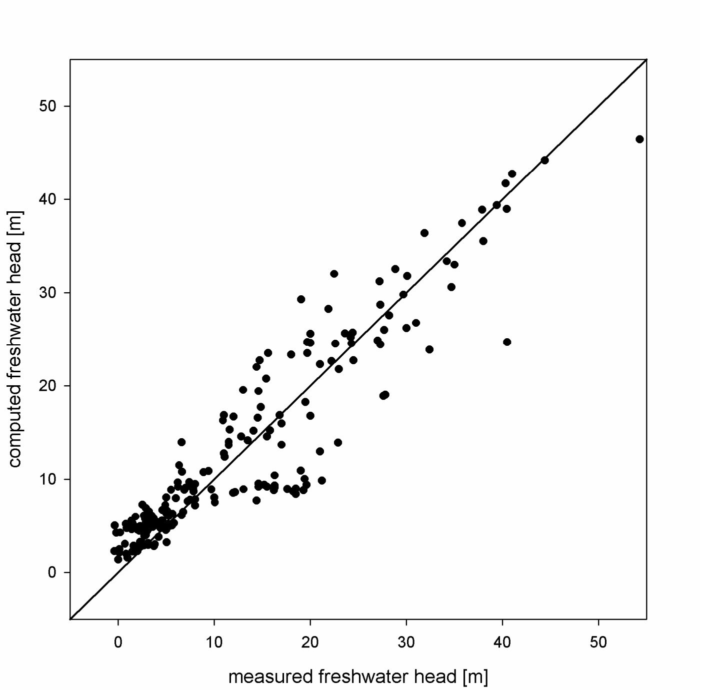

Figure 7: Calibration of the freshwater head: computed versus 'measured' freshwater heads.

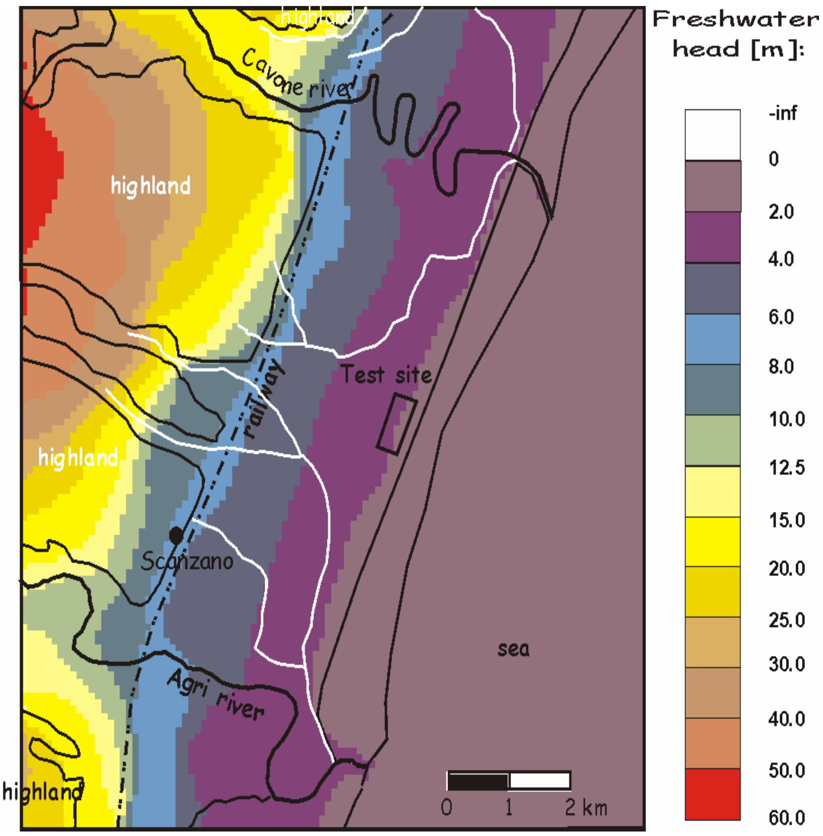

Figure 8: Regional freshwater head at a horizontal scale, at layer 20 (0 -+1 m M.S.L.).

CREATION OF A PHYSICAL BARRIER

The regional model is used to assess the effect of a physical barrier on the groundwater flow regime and the head distribution. Different scenarios of hydraulic conductivity reduction are simulated: 1. a factor 10 reduction; 2. a factor 100; and 3. a factor 1000. The length of the barrier in this numerical experiment is about 1200 m long, and is positioned parallel to the coast, exactly at the field test site. In the regional model, elements have sizes of 100*100*1 m. As such, this barrier geometry implies hydraulic conductivity reductions at blocks with these dimensions. This is not completely realistic for the real field test site situation, where much smaller widths of the barrier will be generated. Nevertheless, this exercise will provide an idea of the possible head changes. Note that in the local model, much smaller elements will be used and a more realistic situation will be computed. Figure 8 shows that the largest drop in head at the landside of the barrier is 1.08 m, for a hydraulic conductivity reduction equal to a factor of 1000. The zone of influence is at least some hundreds of meters.

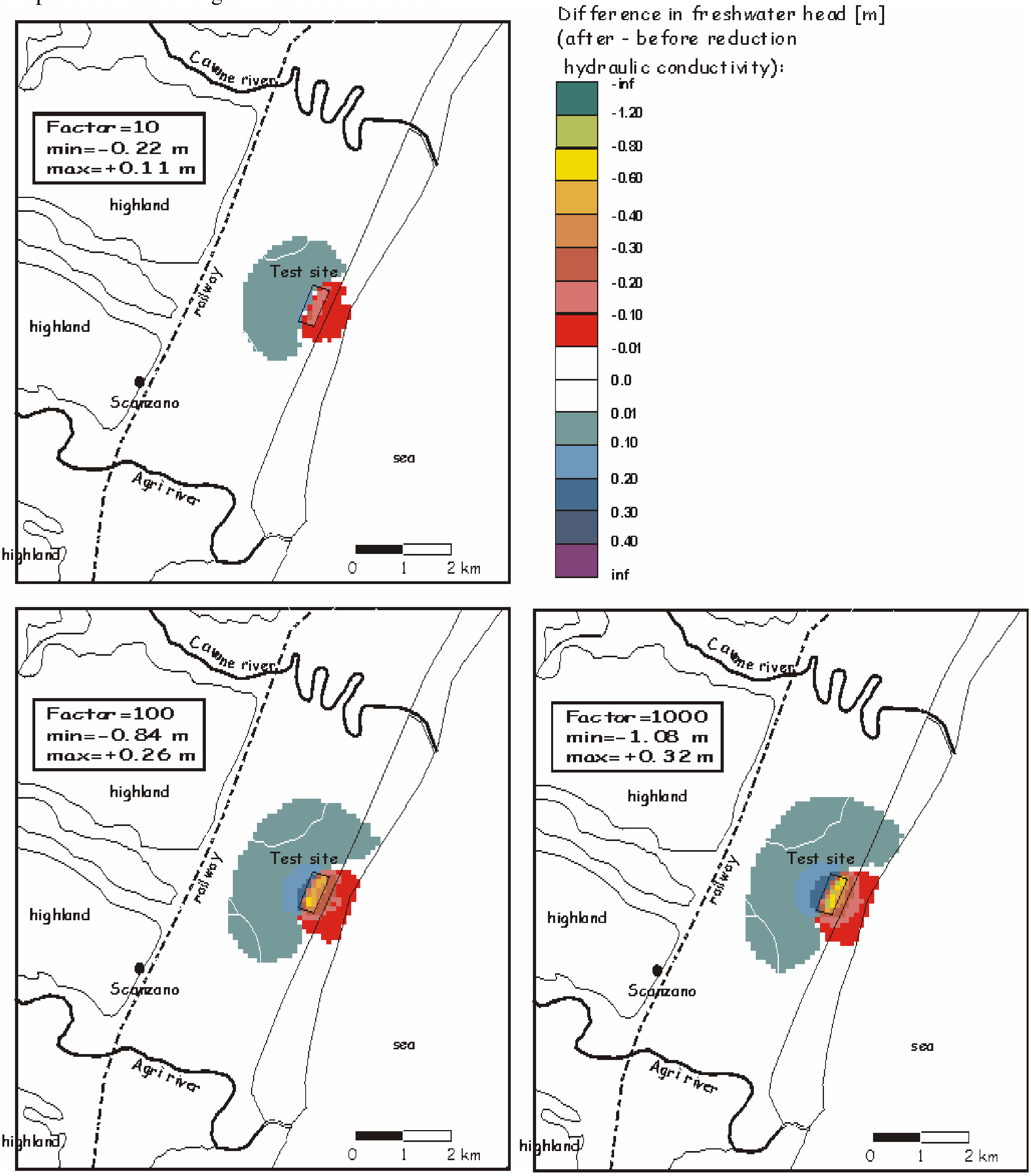

Figure 9: Effect of the reduction of the hydraulic conductivity on the head distribution at layer 20 (0 -+1 m M.S.L.).

CONCLUSIONS

The regional model of density dependent groundwater flow and solute transport in the coastal plain of the Italian region of Basilicata, South Italy, nearby the city of Scanzano, is ready, though seasonal fine-tuning is essential. A change in freshwater heads is only detectable if hydraulic conductivity reduction is large and the length of the barrier is substantial. A local model is necessary to simulate multicomponent solute transport in a variable-density groundwater system at the field test site.

FUTURE RESEARCH

Scenarios of injection/extraction well schemes will be tested numerically to determine the possibility of in-situ mixing of solutions. A local model will be constructed to consider the relevant hydrogeological and geochemical processes in the subsoil: viz. precipitation and dissolution of solutes that is under influence of an inhibitor, which eventually will lead to the formation of slightly soluble minerals. For this purpose, reactive flow and solute transport are coupled with groundwater flow, as also changes in porosity and permeability are considered.

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