Modelling Possible Structural Instabilities Of The Po River Embankment, Italy, Due To Groundwater Pumping In The Ferrara Province

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EXTENDED ABSTRACT

Land subsidence due to groundwater pumping is a major environmental problem in flat alluvial coastal plains. In the eastern Po River plain, Italy, CADF, a local Water Distribution Company serving a 1300 km^2 territory, is producing water from a well-field established since the 1930s at the Ro Ferrarese village. The 10^7 m^3/year current pumping rate is withdrawn from a 20-60 m deep confined aquifer. In order to cope with the increasing water demand, CADF has planned in 2006 the development a new field 5 km east of the old one. The new field is made of 9 wells located in the Po River overbank and produces from the same shallow aquifer.

To provide the establishment authorization, the Regional Environmental Agency has required the evaluation of the environmental impact in terms of land subsidence and possible structural instability of the Po River embankment (that is more than 10 m above the surrounding farmland) due to differential displacements.

In order to comply with the previous requirements, a modeling study supported by in situ investigations has been performed. Advanced three-dimensional finite element flow and poro-elastic models have been implemented with a realistically detailed lithostratigraphic sequence obtained by integrating a number of borehole stratigraphies and 2D electrical resistivity tomographies. The models have been calibrated against the outcome of available pumping tests and records of land settlement taken at the old well-field. A "best fit" scenario along with other three plausible scenarios have been simulated in order to account for the major data uncertainties of the hydrologic parameters, i.e. hydraulic conductivity of the pumped aquifer and sand and clay vertical compressibility.

The models have been used to simulate the anthropogenic land subsidence from the establishment of the Ro well-field (1930) to the present time (2005), and to predict the expected occurrence up to 2035.

The results show a cumulative maximum land settlement of 15 ± 4 cm at the Ro well-field over the simulated 105 years (Figure 1). A value of 6 ± 2 cm of land subsidence may be expected from 2005 to 2035 at the new well-field. The displacement gradient is of the order of 10^{-4}-10^{-5}. Hence, it may be concluded that the activation of the new well-field and the joint groundwater pumping from the old one should not generate any instability of the Po River embankment.

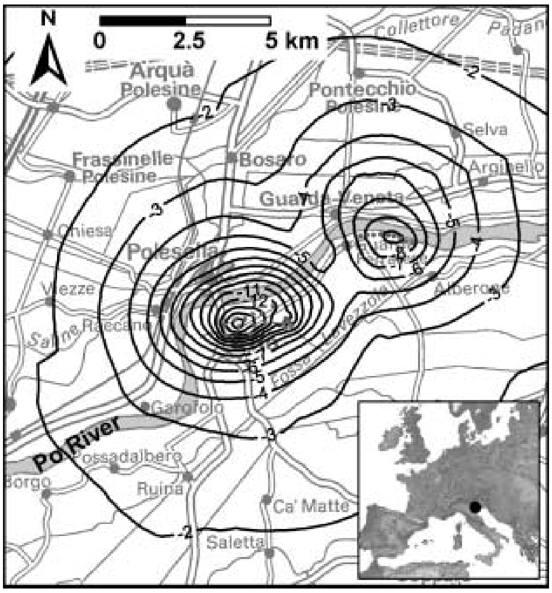

Figure 1. Land subsidence (cm) from 1930 to 2035 due to CADF groundwater withdrawals as computed by the FE model with the "best fit" scenario.

1. INTRODUCTION

In the eastern Po River plain, Ro Ferrarese village, Italy, CADF, a local Water Distribution Company serving an area of 1300 km^2, withdraws yearly about 10^7 m^3 from a 70 year old well-field tapping a 20-60 m deep confined aquifer underlying the Po River. To cope with the increasing water demand a new well-field in the village of Guarda Ferrarese, 5 km east of Ro, is planned (Figure 2). The design of the new field comprises 9 wells which are located in the Po River overbank and are supposed to produce from the same aquifer as the old ones. To release the authorization to open the new wells the REA (Regional Environmental Agency) requires the evaluation of the environmental impact in terms of both anthropogenic land subsidence and levee stability because of the possible differential displacements. To cope with the above requirements CADF has committed the task to perform a number of field and lab soil tests and carry out numerical simulations of the pumping process in relation to the expected past and future land subsidence and embankment stability:

1. in the area where the old field is located because of the previous groundwater pumping;
2. in the areas hosting both the old and the new field because of the new withdrawals possibly added to the old ones.

To meet the CADF requests and provide a satisfactory response the investigation should address the following points:

- an improved hydro-geological soil characterization through ad hoc field and lab analyses enlightening in particular the actual aquifer and confining bed geometry;
- the connection between the river and the aquifer and the presence of highly compressible intervening peat horizons;
- the pumping distribution both in the past and in the future with proper reference to the average seasonal variations;
- the geo-mechanical soil behaviour in loading and unloading to predict more accurately the land subsidence in the light of the complex history of the old Ro well-field;
- an appropriately large simulation area to reduce the influence of the porous medium boundaries in view of the extended simulation time (105 years overall) and the simultaneous activation of the two fields;
- the evaluation of the land subsidence experienced since 1930 when the first wells became operative.

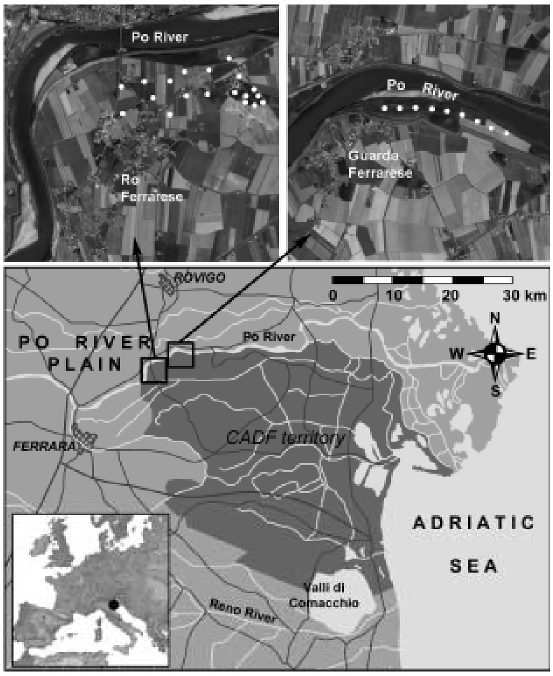

Figure 2. Map of the eastern Po River plain with the area managed by CADF in dark grey. The upper zooms show the well-fields in Ro and Guarda Ferrarese with the well locations depicted by white dots.

The present hydro-geological information suggests the existence of a thick clay layer overlying the aquifer, thus pumping should not affect the position of the water table within the levee and hence should not induce water siphoning. The levee stability will therefore be addressed by computing the settlement experienced by the levee itself due to the consolidation of the underlying pumped units and by check for differential displacements that should compromise the embankment structure. All the available hydro-geological and geo-mechanical data have been implemented into a mathematical hydrological model for the prediction of the drawdown and a geo-mechanical model for the prediction of the land subsidence. The codes used are the Finite Element (FE) codes MED-FLOW3D and MED-SUB-3D that solve the 3D flow and poro-elastic PDE (Partial Differential Equation), respectively, in a heterogeneous and anisotropic porous medium in transient conditions. The models have been developed at the DMMMSA (Department of Mathematical Models and Methods for Scientific Applications) of the University of Padova (Teatini *et al.* 2006) and engineered by MED Ingegneria. The flow model calibration has been done using a few ad hoc pumping tests performed in 2003 and 2005 while the geo-mechanical model has been calibrated against subsidence records collected over the period 1994-2004. Both models have then been used in their predictive capacity for simulating the overall future occurrence up to 2035.

In the sequel the hydro-geological and geo-mechanical data are first briefly reviewed. The calibration and application of the flow and structural model follow, with the most salient results shown and discussed. Finally some considerations are made concerning the effects of the expected land subsidence and differential ground displacements on the stability of the Po River levee and the buildings of the Ro and Guarda villages.

2. HYDROGEOLOGICAL AND GEOMECHANICAL CHARACTERIZATION OF THE AQUIFER SYSTEM

The location of both the old and the new well-fields is shown in Figure 2. Being close to the Po River delta this area is presently experiencing a natural land subsidence that can be estimated at 20 cm from 1930 to 2005 (Gambolati and Teatini 1998). Figure 3 shows the elevation of the area above the mean sea level (a.m.s.l.) as reconstructed using a quite accurate digital elevation model. It is worth noticing the relative flatness of the zone, the relative large depth of the Po River bed (down to -11 m a.m.s.l.) and the altitude of its major levees on the order of 13 m a.m.s.l.

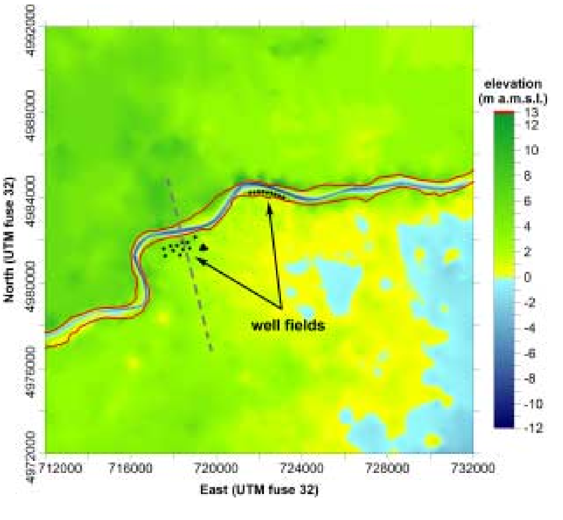

Figure 3. Digital elevation model of the study area around the well-fields. The dashed line represents the trace of the vertical section shown in Figure 4 and Figure 6.

The exploited aquifer exhibits a variable thickness and depth from the ground surface, and is overlain and underlain by two aquitards as is schematically shown in Figure 4 providing a vertical cross section through the aquifer system down to -70 m a.m.s.l. in a North-South direction. The actual geometry of the aquifer has been accurately reconstructed, including the top and bottom aquitards.

Pumping tests carried out since 1983 have allowed to draw a map of the regional horizontal hydraulic conductivity k_h that varies within the aquifer between 10^{-3} and 10^{-4} m/s with the vertical conductivity k_z ten times smaller. As far as the aquitards are concerned, a representative value of k_z turned out to be on the order of 10^{-8} m/s (Bariani *et al.* 2007). Based on laboratory tests performed on soil samples from a pilot well drilled in the Guarda area a value for the vertical soil compressibility c_M on the order of 3×10^{-3} and 3×10^{-2} cm^2/kg for the aquifer sand and the overlying aquitard clay, respectively, is derived. Remembering that $c_M \approx S_s/\gamma_w$, with S_s the aquifer specific elastic storage and γ_w the water specific weight, the c_M estimate of 3×10^{-3} cm^2/kg is in good agreement with the value $S_s=2.8\times10^{-4}$ m^{-1} provided by the pumping tests executed in the Ro and Guarda areas. Concerning the peat layer, this has been incorporated within the upper aquitard with a c_M twice as much as the clay c_M.

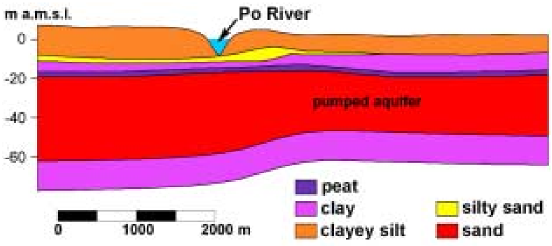

Figure 4. Schematic lithological cross section of the simulated aquifer system along the trace given in Figure 3. The vertical exaggeration is 25.

3. FINITE ELEMENT MODEL IMPLEMENTATION

Modeling of land subsidence has been carried out by a two-step uncoupled approach (Gambolati and Freeze 1973), with the hydrodynamics of the pumped aquifer first simulated by a groundwater flow model and the land displacement then computed with the aid of a poro-mechanical model with the pore pressure field specified as an external distributed source of strength within the porous medium.

The classical groundwater flow equation (e.g, Bear 1972):

$$\nabla(k\nabla h) = S_s \frac{\partial h}{\partial t} + q , \tag{1}$$

and the equilibrium equations for a mechanically isotropic elastic medium (e.g., Verruijt 1969):

$$G\nabla^2 u_i + (\lambda + G)\frac{\partial \varepsilon}{\partial i} = \frac{\partial p}{\partial t} \qquad i = x, y, z , \tag{2}$$

have been solved in space by linear finite elements (tetrahedra) and in time by a finite different scheme. The following notation is used: h is the hydraulic head, p the pore pressure variation (i.e., $p=\gamma\Delta h$ with γ the groundwater specific weight), u_i the displacement component along the i-th coordinate direction (x, y, z), ε the volumetric strain, q the source/sink, and t is time. Well known relationships relate the Lamé constant λ and the shear modulus G to c_M .

3.1. 3D FE grid

The pumped aquifer and the underlying and overlying geological units have been discretized by tetrahedral finite elements. The horizontal projection of the 3D FE model is a 40×40 km^2 square while the vertical depth goes down to the bottom of the clay unit underlying the aquifer of interest (about -70 m a.m.s.l.). Horizontally the area is divided into 29 sub-regions in relation to the extent of the identified different geological formations, the aquifer hydraulic conductivity and the trace of the Po River.

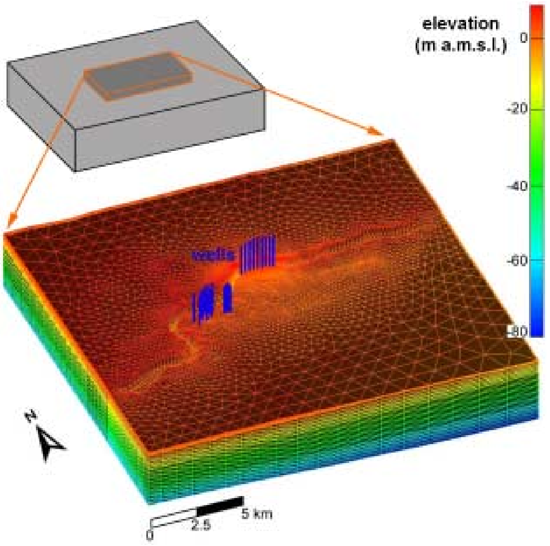

Figure 5. Perspective view of a portion of the tetrahedral FE mesh around the well-fields.

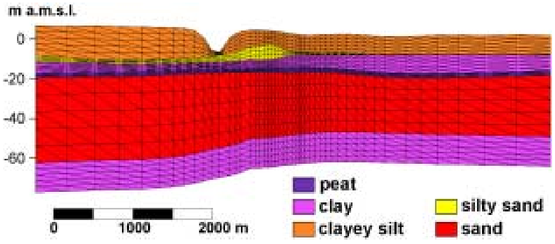

Figure 6. Vertical cross section of the tetrahedral FE mesh corresponding to the lithological section of Figure 4.

An initial plane mesh made up of Delaunay triangles has been vertically projected to get 3D tetrahedral finite elements (Figure 5). The geomechanical model has been extended down to -2000 m a.m.s.l. where the basement is fixed and quite reasonably zero displacements can be assumed. The final mesh consists of 1335996 tetrahedrons and 230510 nodes. Each single geological formation is subdivided into 5 sub-layers thus allowing for an accurate vertical propagation of the aquifer depressurization. As an example Figure 6 shows a cross section of the tetrahedral FE grid corresponding to the litho-stratigraphic section of Figure 4.

3.2. Initial and boundary conditions

The models are run in terms of incremental variables to start from a 1935 steady configuration of flow and zero displacement. Hence zero incremental piezometric head variations and zero horizontal and vertical displacements are prescribed on the model boundaries, except on the ground surface where a traction free surface is assumed (Baù *et al.* 2004). Concerning the flow model, it has been prescribed that the pumping effects do not propagate as far as the outer boundary with the overlying aquitard reducing the water exchange between the river and the pumped aquifer and precluding the vertical recharge. This is consistent with the available hydrologic measurements that show no straight correlation between the aquifer piezometric head, the water level in the Po River, and the precipitation.

Reconstructing the history of withdrawals is a quite complex task. On the whole the pumping rate from 1930 to 1964 can be reasonably supposed to increase linearly from 0 to 100 l/s, from 1965 to 1974 a winter value of 130 l/s is replaced by a summer value of 150 l/s raised to 160 l/s and 190 l/s, respectively, from 1975 to 1983. After 1983 the consumption is more variable but well documented on a monthly basis by CADF and can amount to as much as 500 l/s in particularly critical periods. Finally from 2005 to 2035 an estimated discharge of 300 l/s is partitioned 50% between the old and the new well-field with the same monthly variability as the one observed over the period 1984-2004. The cumulative withdrawal implemented into the flow model behaves from 1930 to 2035 as indicated in Figure 7. A time step of 6 months from 1930 to 1983 and 1 month thereafter is implemented into a second order Crank-Nicolson integration scheme in time.

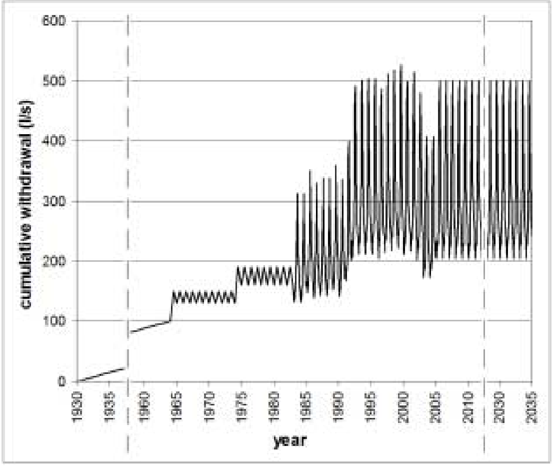

Figure 7. Cumulative withdrawal from the CADF well-fields as implemented into the FE model.

3.3. Model Calibration

The flow and land subsidence models have been calibrated against the past available records, namely the outcome from two pumping tests performed in 2003 and 2005 in a pilot borehole located in the Guarda area with the drawdown monitored in nearby wells and the settlement of a few well heads recorded from 1994 to 2004. A few alternative parameter distributions are assumed for the calibration process. The modelling results that will be shown below have been provided by the "best fit" scenario where the sand compressibility has been reduced by a factor 2 and the clay compressibility by a factor 5 relative to the values previously mentioned. With this simulation scenario the drawdown induced in four neighbouring wells by the pumping test conducted in the pilot borehole has been reproduced quite satisfactorily.

As far as land subsidence is concerned, the available measurements show a certain variability, also for close benchmarks, probably because of unauthorized private withdrawals, consolidation due to surficial loads, and local lithological heterogeneity not captured by the available geological information. The noteworthy information from the subsidence data base is that the Ro well-field has subsided by 1 cm only over the decade 1994-2004 with respect to a reference benchmark located 1 km to the north on the Po River embankment. The modelling results show a differential vertical displacement between the reference point and the well area on the order of 1 cm. Hence the "best fit" scenario is deemed to succeed in capturing satisfactorily the order of magnitude of the anthropogenic land subsidence over 1994-2004 and will be used to project the prediction in 2035.

4. MODELLING RESULTS

We focus the discussion on land subsidence, i.e. the occurrence that raises the main concerns in relation to the stability of the Po River levee. Figure 8 shows the cumulative land subsidence as obtained from the simulations over the period 1930-1983. In 1983 the groundwater consumption was significantly increased with the drilling and activation of additional wells in the old well-field of Ro. The largest settlement is predicted at the well-field site and turns out to be equal to 10 cm. From 1983 to 2005 the additional simulated settlement is given in Figure 9 with a maximum expected value of 12 cm. Based on the planned pumping rate behaviour shown in Figure 7 and equally partitioned between the old and the new well-field, the predicted land subsidence from 2005 to 2035 is provided in Figure 10. It is worth noticing that the area encompassing the old well-field does no more settle while novel subsidence is predicted at and close to the new well-field with a largest predicted value of 6 cm.

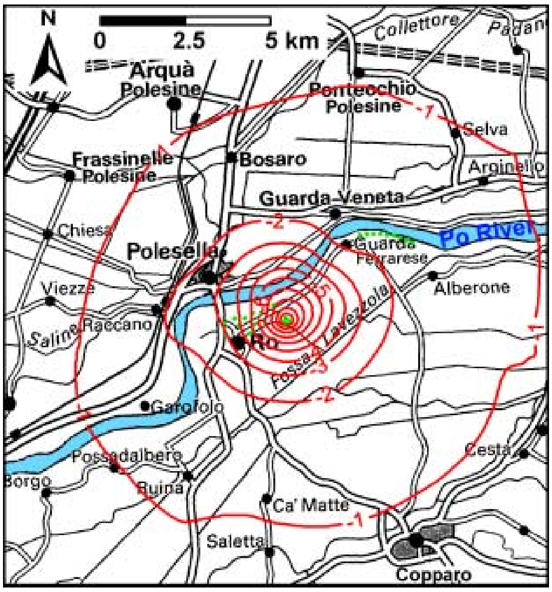

Figure 8. Land subsidence (cm) from 1930 to 1983 due to CADF groundwater withdrawals as computed by the FE model with the "best fit" scenario.

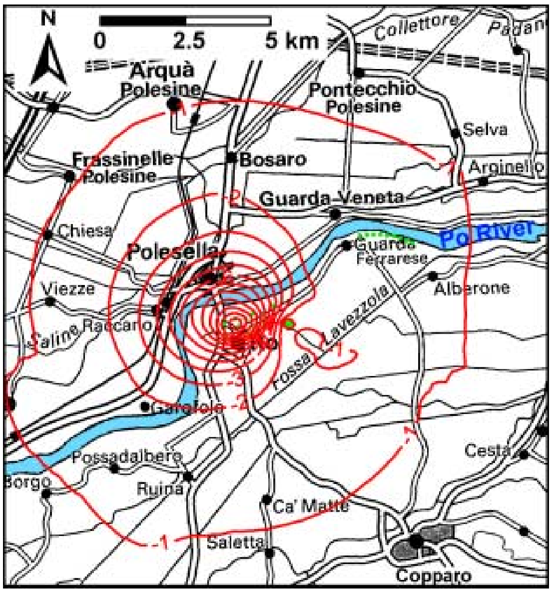

Figure 9. Land subsidence (cm) from 1983 to 2005 due to CADF groundwater withdrawals as computed by the FE model with the "best fit" scenario.

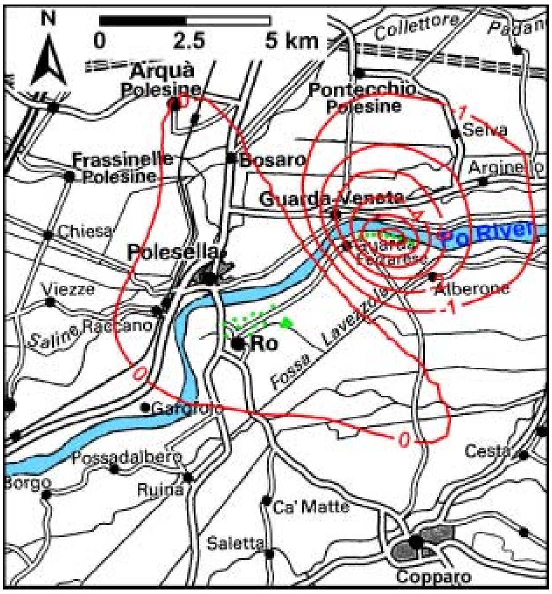

Figure 10. Land subsidence (cm) from 2005 to 2035 due to CADF groundwater withdrawals as predicted by the FE model with the "best fit" scenario.

The expected settlement behaviour as of 1983, 2005 and 2035 in important sites of the area is supplied in Table 1.

Finally, Figure 11 (middle profile) shows the land subsidence along the Po River embankment as simulated and predicted by the model from 1930 to 2005 and from 2005 to 2035. Using three other plausible scenarios for the permeability and the compressibility distribution we were able to some extent to estimate an upper and a lower land settlement profile along the river. These are represented in Figures 11a and 11b in the form of an interval bounded by two extreme profiles into which the actual occurrence should most likely fall.

Table 1. Expected land subsidence due to CADF groundwater withdrawals as simulated by the FE model with the "best fit" scenario in the sites of interest as of 1983, 2005, and 2035.

	LAND SUBSIDENCE (cm)		
	1983	2005	2035
RO WELL-FIELD	-8.5	-13.7	-13.0
GUARDA WELL-FIELD	-1.8	-3.0	-9.3
CENTER RO	-3.3	-9.5	-8.8
CENTER GUARDA	-2.0	-3.7	-6.3

5. CONCLUSIONS

A modelling study based on the geological, hydrological and geomechanical information available to date has been developed to reconstruct the anthropogenic land subsidence induced over the period 1930-2005 by groundwater pumping from the old well-field located at Ro Ferrarese and to predict the evolution of the occurrence over the next 30 years because of the opening of a new well-field at Guarda Ferrarese, 5 km east of Ro. The land surface settlement might create problems for the stability of the Po river embankment close to the withdrawal sites.

The modelling results indicate that in 2035, i.e. at the end of the prediction time, the land subsidence could affect appreciably (namely by an amount larger than 3 cm) an area with an extent between 100 and 150 km^2 and an average settlement of 5-6 cm. In this respect it is worth noting that the largest simulated subsidence (on the order of 15 cm over 105 years) is about half the natural subsidence occurred over the area during the same time. Figure 11 shows that as of today the Po River levee has settled by a maximum amount of 14±5 cm close to the Ro well-field. In the next 30 it will subside at the most by 6±2 cm near Guarda while it will slightly rise by 1±0.5 cm at the Ro field due to the partial groundwater flow recovery related to the reduced pumping from the old field. Concerning the effects of differential displacements on the stability of the Po River levee and the buildings/infrastructures of the Ro and Guarda villages, the modeling results provide a maximum gradient in the vertical displacement equal to 8×10^{-5}, i.e. 8 mm for 100 m, in the area of Ro Ferrarese and 5×10^{-5} at Guarda.

In the light of the above it may be concluded that the Po River embankment will not be damaged by the activation of the new well-field and the joint groundwater pumping from the old one, and its stability will not be jeopardized. This is also further supported by the lack of present structural weakening in correspondence to the Ro well-field where an important land subsidence has already been experienced.

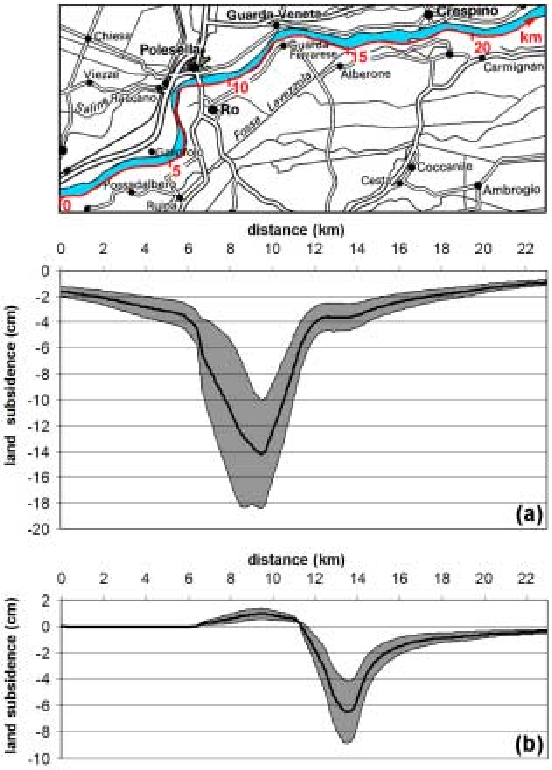

Figure 11. Expected land subsidence (cm) along the Po River embankment (a) from 1930 to 2005 and (b) from 2005 to 2035. Distance is measured along the embankment red line as is shown above in the map.

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