spatial investigation of groundwater pumping-induced land subsidence

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abstract

Acomprehensivestudyofthefactorsinfluencingmagnitudeanddistributionofgroundsettlementsobservedduring the second half of the twentieth century in the area of Bologna (Italy) is presented to derive a unifiedframework useful for interpreting the observed phenomena and for predicting future scenarios. Informationcollected over a surface of more than two hundred square kilometres includes previous geological studies,hydro-geological, geotechnical, and topographical investigations carried out with various purposes. Thegeological features of the whole region have been initially reviewed to figure out the local geological andhydro-geological setup. Then the stratigraphic sequence has been obtained by integrating the results of anextensivecampaigncarriedoutoverthewholeregionforwaterexploitation.Themechanicalcharacterizationof the soil has been based on geotechnical tests performed in the area for the construction of new transportationinfrastructures.Groundwaterlevels,periodicallyrecorded onadistributednetofwells,havebeeninterpretedwithatwodimensionalseepagemodelcapableofbackcalculatingthemodificationofthegroundwaterregimeinduced by water withdrawal. The spatial and temporal distributions of settlements have been derived bycombiningsequentialtopographicalmonitoringcampaignscoveringaperiodofaboutsixtyyearswithsatelliterecords.Tosimultaneouslyanalyseallinformationandprovideaninterpretationoftheobservedphenomena,all data have been collected in a geographical information system interpolating the measured data with ageostatistical method. In such a way the role of the different factors has been captured, finding a logicalcorrelation between land subsidence, subsoil composition and groundwater withdrawal, and a strategy hasbeentracedwhichcanbeexportedto theanalysisofothersimilarsituations.

Keywords:SubsidenceGroundwaterSeepageCompressibilitySpatial analysisMapping

Introduction

Subsidence, whether induced by natural (e.g. tectonic, self weightconsolidation of recent sedimentary deposits, oxidation and shrinkageof organic soils) or anthropogenic factors (extraction of gas, fluid orsolid), affects significant portions of territory with largely variable effectsfrom one site to another (USGS, 1999). Among all possible causes,withdrawalofgroundwaterisparticularlytroublesome,primarilybecauseitisabletoproducenoticeablesettlementswithrelativelyfastrates, but also because it is frequently carried out near densely populatedareas where exposure to risk is particularly high. Detrimental effectsrangefrommalfunctioningtocompletecollapseofbuildingsandinfrastructures,orincludeenvironmentalmodificationssuchasformationofsinkholes,changesofnaturalorartificialwatercourses,floodingandretreat ofcoastlines (Bell,1999).

Subsidenceinduced bygroundwaterwithdrawalhasbeenrecognised and cumulatively evaluated in a large number of situations, whererelatively recent alluvial, marine or lacustrine deposits include alternationof coarse grained water bearing strata with fine grained compressiblelayers.MexicoCity(Marsal andMazari, 1962; Zeevaert, 1983),SantaClaravalley(Poland,1958),Houston(Lockwood,1954),London (Wilson and Grace, 1942), Japan (Yamamoto, 1995), China (Shi et al.,2012),andGreece(Stiros,2001)representjustfewmilestoneexamples,butmanyothercasescanbefoundintheliterature(e.g.SISOLS,2000).Recordedratesofsettlementsrangefromfewmillimetrestomorethanfortycentimetresperyear,dependingonthecompositionofthesubsoilandonhowintensively groundwaterispumped.

Although the role of water extraction in increasing the overburdeneffective stresses and reducing void spaces of compressible soils hasbeenrecognisedfromlongtime(Terzaghi,1943),thereisstillasurprisingly large number of cases where nil or limited countermeasuresare taken to reduce the economical, social and environmental impactof water extraction. Reasons must be found in policies particularlyconcernedwithprotectinggroundwatersources orwithsatisfyingpopulation's demand and thus much more focused on hydrological,hydro-geological, and hydraulic issues than on the mechanical con-sequences of groundwater extraction. Land subsidence is thus con-sidered only when the ground deformation becomes evident and itseffects start to interact with human activities. Due to such a delayedawareness, measurements are often incomplete and studies rarely arrivebeyondqualitativedescriptions,whereasquantificationofmechanismstaking place in the different portions of the subsoil would be of para-mount importance to comprehensively manage groundwater exploi-tationanduseoftheterritory.

Bearinginmindthisgoal,greateffortshasbeenspentinthelasttwodecades by scientists of different disciplines to develop prompt andaccurate satellite monitoring systems DInSAR (Strozzi et al., 2001;Cascini et al., 2007; Hay-Man Ng et al., 2010) or GPS (Sato et al., 2003),to find logical relations between amount of pumping, water head dropandgroundsurfacesinkingbasedontheanalysisofdifferentcasestudies (e.g. Sato et al., 2006) or to frame this complex phenomenon intocomprehensivetheoreticalmodels(e.g.Bravoetal.,1991;Mobachand Gussinklo, 1994; Sun et al., 1999; Ferronato et al., 2003; Hung et al.,2012).

Unavoidably, when a multidisciplinary problem like subsidence isfacedonlargeterritories,acompromiseisnecessarytoconjugatecompletenessofanalyseswithinadequacyofexplorations.Harr(1999)clearlystates: "*In no field of engineering are practitioners faced with more complexand uncertain sets of conditions than those concerned with groundwatersystems…..Addtothesetheverylargesizeofprojectsandtheexpenseofundergroundsamplinganddataacquisition*".

Themostdifficulttaskrelatedwiththesestudiesistoreduceuncertaintyto acceptablelevelsbyacarefulanalysisofexistinginformation,whichisusuallyincompleteduetoaremarkableextensionand depth of the subsiding deposits and to the relatively long duration ofthe phenomenon. Additionally, the available data rarely cover all thecrucial aspects of this complex geotechnical phenomenon since theyare usually collected for other purposes. In this case the temptation tofill the puzzle, which is unavoidably incomplete, by making uncontrolledassumptions must be escaped. On the other hand, traditional and newinvestigation tools can be nowadays combined to improve the knowledgeofthesystem'spropertiesandofitsboundaryconditions.Furthermore,dataprocessingwithpowerfulandfastsoftwareandtheimplementation of relatively simple models represent a great help forthe definitions of a unified and comprehensive framework, capable ofconsistentlyrelatesubsidence causesandeffects.

Theaboveconceptsdescribethemaingoalsandtheinherentlimits of the present research which deals with the case study of Bologna, avery ancient and famous Italian city affected in the past decades bysignificant ground subsidence. This case is studied with the aim ofproviding a strategy to be exported to other similar cases. Bearing inmind this goal, information of different nature have been collectedoveranareaofabout225km^2,includingthecentreandthecountry sidepart of the city. The performed spatial analyses include geostatisticalinterpolationsofrecordeddata,aimedatrecoveringacontinuousdistribution of the studied variables, and different numerical modelsaimedatestablishinglogicalrelationsamongthedifferentvariables.Inordertosuperposeallinformationandperformacomprehensivequantitative analysis of the involved factors, each set of variables hasbeen managedon alayer ofa geographical informationsystem.

casestudyIn the second half of the past century an intensive industrialisationprocess led a significant part of Italian population to migrate fromsouthern regions and rural areas to the northern cities. Such a con-centration, together with the establishment of new industrial, agriculturaland livestock activities posed serious problems in the procurement ofwater, which was satisfied by an intensive exploitation of the ground-water sources. As a result, some cities and their surrounding areassuffered land subsidence with rates reaching in some cases dozencentimetresper year.

Oneofthemostenlighteningexamplesisthecityof Bologna,whichislocated in the southern part of the Po valley, close to the Tuscan-EmilianApennines,about70 kmtothewestoftheAdriaticsea.Thecityrepresents a very important node for the Italian economy and one ofthe most well preserved historical site of Italy, as it includes an importantheritageofmonumentsandbuildings.Itspopulationincreasedsignificantly during the last century (Figure 1), almost doubling thenumber of inhabitants during the period 1940-1970 and reaching apeak in 1970 (OsservatorioAstronomico di Bologna, 2007). Consequently with the establishment of new activities, a large number ofwells were progressively excavated all around the city to satisfy theincreased demand of water. A clear hint of such intense activity can beseen from the right axis of Fig. 1 which shows the number of wellsrecorded by the regional agency for the protection of the environmentARPA.

Thisimportantgroundwaterexploitationwaspossibleasthecityis located at the foot of the Apennines, between the occurrence in theplain of two important rivers, Reno and Savena (see the enlarged mapofthecityreportedinFigure2).Moreparticularly,thedifferentsymbols adopted in the map of Fig. 2 show that groundwater withdrawal foragriculturalandindustrialpurposesisdiffuselydistributedinthevalley, whereas most of the water extracted for civil purpose comes from fewwells, excavated during the period around 1970 in the alluvial fans ofReno and Savena to capture the most consistent part of the waterflowingfromthemountain.

Inthelateseventies,damageswerenoticedonseveralbuildingsofthehistoricalcentrewhichinducedthelocalgovernmentalinstitutionsandagencies to undertake a number of investigations aimed at discoveringthe causes of such unexpected phenomenon. Noticeable attention wasconcentrated on the buildings of Zamboni Street, a major urban arterylocated in the north-east side of the historical centre. A survey carriedout along this road between 1979 and 1983 (Alessi, 1985) gives theevolutionofsettlementprofilesreportedinFig.3.

IndeedpreviousstudieshaveshownthatthePovalleyisaffectedbyasubsidenceinducedbytheselfweighconsolidationofthe thick

the Regional Agency for the Protection of the Environment and theMunicipality of Bologna to improve the accuracy of monitoring. Thisnetincluded527 surveyspositioned at amutual distance of about250 m, homogenously distributed above the area surrounding Bologna.Systematicmeasurementwascarriedoutin1983,1987,1992and1999(http://servizigis.arpa.emr.it/Geovistaweb).

Finally, thanks to the development of differential interferometrytechniques,highaccuracydatacouldbeobtainedfromalowernumberof cornerstones. In fact, the last campaign covering the period 1999-2005hasbeencarriedoutbycombiningDInSARmeasurement(Stramondoetal.,2007)with118recordstakendirectlyontheground.By this combination, the amount of data taken from the topographicalnetwork could be significantly reduced, but the quality of informationhassignificantlyimprovedthankstothelargenumberofsatelliterecords (the authors claim a precision of ±1.5 mm in the estimate ofsettlements).

Settlements and ground levels obtained from all these campaignshavebeenhereinprocessedwithageostatisticalmethodandcombinedeachothertobackcalculatetheprogressivedeformationoftheground.

Intheadoptedmethod(ordinaryKriging)thevariationamongmeasures(γ) isconsideredstatisticallyrelatedtotherelativedistance(h)betweensamplingpointsandamathematicalfunction$\gamma(h)$(theoretical variogram)isintroducedtomodeltheobservedvariationwithdistance (experimental variogram). The mathematical function adopted in thiscaseis:

Another important aspect which needs to be evaluated from thepresent analysis is represented by the development of

whereR(range),c(sill)andp(power)areparameterstobecalibratedwiththeexperimentalvalues.Thisfunctionhasbeenselectedthanksmonitored datadidnotshowameaningfuldependencywithdirection.Interpolation of the experimental data has been finally accomplishedconsidering the spatial variation introduced by this function, by imposingminimumvarianceandunbiasednessconditions.Thedetailsofthiscalculationforthedifferentperiodsaresummarizedin Table1.Togetherwith the parameter of the model, the average standard error has beencomputedonthemonitoredpointstosyntheticallydescribethequalit

settlementswith time. With this goal, the time histories calculated in two differentpositionsofthereferencegrid(markedwithdifferentsymbolsinFigure5)arereportedinFig.6.Onepointisrepresentativeoftheregionabove the alluvial fan, which presents relatively low settlements, theother is located the middle of the plain, which is the region where thelargest settlements have been recorded. Both curves show a similar Sshape with the higher rates occurring in the period between 1970 and1980. Significant differences can be however seen on the absolutevaluesofratesandcumulatedsubsidence.Infact,themaximumsettlement rate on the alluvial fan is about 2.5 cm/year and the totalsettlement about 0.7 m, while the maximum rate in the plain area isabout 30 cm/year andthe cumulatedsettlement about 4 m. Besides, it is noted that, while the zone on the alluvial fan has reached a stableconditionattheendofthemonitoredperiod,thereisstillanonnegligiblesettlingrateofabout3cm/yearintheplainarea.

AccordingtotheplotsofFig.5,itseemsthatthecentreofthecityis notparticularlyaffectedbythe phenomenon, being the cumulatedsettlements in this area much less than for the countryside portion oftheterritory.However,thisobservationdisagreeswiththedamagesof the city centre buildings recalled in Fig. 3. To find a more clearexplanation,attentionmustbeplacedontherotationsinsteadofcumulatedsettlements.Theanalysis,restrictedtothehistoricalcentreofthe city, has been accomplished by superposing an ideal grid of points(nodes are positioned at a mutual distance $\Delta = 60$ m). and computingsettlementsateachnode(i,j)withthepreviouslydescribedgeostatistical method.Rotationineachnode$\alpha_{i,j}$ hasbeenthencomputedviathe yofestimates.Thecomparisonofalldatainthetablesshowthat,inspiteofadifferentprecision ofthe estimate,basically determinedby thenumber and spatial distribution of the monitoring data, a not particularlydifferentstructureofthespatialvariation(givenbytherangeand power) canbeinferredforthedifferentperiods.

A sample plot reporting the experimental and theoretical variogramsfortheperiod1983-1987isshown forreferenceinFig. 4.

Theevolutionofsettlementsforperiodsofdifferentlengthsstartingfrom1943isdepictedbythecontourmapsreportedinFigure5.Itis interesting to note that all plots show qualitative similar results,withanincrease of subsidence while proceeding from the mountainto the plain, and with the maximum settlements occurring in the areasurroundingthe alluvial fan ofReno River.

Subsoilcharacterisation

FromthegeologicalviewpointthePoValleyistheproductoftheforelandbasinevolutionprocess(CarminatiandMartinelli,2002)occurring at the link between the padanian-adriatic sector and theexternal portion of the thrust belt formed by the up-lifting tectonicunits of the Upper Miocene – Quaternary (Bartolini et al., 1996). InthemiddlePlio-Quaternaryage,thePoValleyformedthenorth-westextensionoftheAdriaticSea.Thereafteragradualeastwardmovementof the transition between the submarine slope and basin (TSB inFigure 8a) occurred thanks to a progressive accretion of marine sandsandcontinentalfinegrainedsediments(siltsandclays).Inthesouthernpart, this sedimentation process is tightly interconnected with theerosionoftheApennines(Amorosietal.,1996).Confiningtheanalysisto the area of Bologna, two big alluvial fans including predominantlygravelly and sandy materials are formed at the occurrence in the plainof Reno and Savena Rivers. As a result, the stratigraphicalsequencesalongthetworivers(Elmietal.,1984)showadensealternationoffineandcoarsegrainedmaterials,withthicknessesofcoarsematerialstrata progressivelysmaller(Fig.8b)whileproceedingfromthemountaintothe valley.

The hydro-geological pattern recognisedby extensive investigationscarried out over of the whole Emilia Romagna region for oil and waterexploitation(RegioneEmiliaRomagnaandENI-AGIP,1998)isalogicalconsequenceofthepreviouslydescribedgeological history.Combiningthestratigraphicalprofilesretrievedfromalargenumberofboreholesand deep wells with the resultsof extensive seismic investigation,three thick aquifer groups have been identified by this study, namelydistinguished with A (shallow), B (intermediate) and C (deep).

Eachgroupincludesadensealternationofcoarseandfinegrainedsoilstrata andisseparatedfromtheothersbythickimperviousbarriersextendinginto the plain (Farina et al., 2000). The upper aquifer group A, whichreaches a maximum depth of about 300 m, is strongly dominated bythepresenceofthetwoalluvialfansofRenoandSavenarivers,thelatterrepresenting the most important groundwater supplies of the area(Elmi et al., 1984; Fava et al., 2005). Near the foot of Apennines, thesealluvial fans form also the upper part of the aquifer group B. In thelowest investigated portion, up to a depth of about 600 m (aquiferGroupC),coarsegrainedmaterialsarebasicallyformedbyoldermarinesediments.

Thecirculationofgroundwaterinthetoplayersismostlydominated bytheunderbeddispersionofthetworivers,whileasecondarycontribution coming from remote sources is found in the lower strataof the lowland area; fossil water are eventually found in the loweraquifergroupC.

The relevant geotechnical properties of the subsoil are derived from acollectionofinsituandlaboratoryinvestigationsperformedalloverthe city (Darini, 2008; Darini et al., 2008). A typical layering of the area(Figure 9a) derived from a borehole 300 m deep (IDROSER, 1989)shows a repetitive sequence of coarse and fine grained materials withstrata of variable thickness. With regard to the fine grained soils, theanalysis of laboratory tests on undisturbed samples cored from thisboreholeandonsamplesretrievedatshallowerdepth(b30m),leadsto the following conclusion: the material is made of a predominantfractionofsilts(rangingbetween40and60%),aslightlylowercontentof clays (variable from 10 to 50%) and a small percentage of sand(between0and20%);theconsistencylimitsplottedontheCasagrandechart (Figure 9b) show a homogenous mineralogical composition ofthesediments;thecompressibilityandswellingindexes(denotedrespectively with C_c and C_s in the table of Figure 9b) obtained fromoedometer tests do not show any significant variability with depth;overconsolidation is present only in the top 20 m (Figure 9c) beingbasically determined by fluctuations of the water table. Based on theavailableresults,itisimpossibletomakeanyhypothesisonthedistribution of the physical and mechanical properties of the fine grainedmaterialsovertheconsideredarea.

Thesameconsiderationhasbeenmadeforcoarsegraineddeposits, focusingtheattentionontheirpermeabilitycoefficientsestimatedwith provides only a range of values, without any clear spatial distinction.Another possible, yet not simple, option would consist in computingthe distribution of K(x,y) by an inverse analysis, i.e. finding the field ofpermeability coefficients able to reproduce the distribution of measuredgroundwater levels under known boundary conditions. In the presentwork,thisideahasbeenpursuedinaverysimplifiedform,i.e.assumingauniquevalueofK(x,y)representativeofthecoarsegrainedmaterialatevery position (x,y). Such a value has been then found with a trial anderrorprocedure,i.e.byassigningdifferentvaluesofKinEq.(3),performing simulations with assigned (known) extracted volumes ofwater and finding the K value giving the best similarity between thesimulatedwaterheadsandthosemeasuredinthesamepoints.

Consideringtheavailabledata,thisanalysiscouldbeperformedforthe year 2002, for which the amount of water cumulatively extractedforrespectivelyzootechnical,industrialagriculturalandcivilpurposeswasknown(seeTable2fromVassena,2003)togetherwiththedistribution of water levels monitored on a number of wells uniformlydistributed over the considered area. The table reports also the subdi-vision of the water volumes extracted for civil purpose among four bigwells excavated to feed the aqueduct of the city. By looking at theirposition on the map (see the symbols in Figure 11) it is interesting tonotethatthebiggestpartofthisamountofwaterisextractedfromthealluvialfanoftheRenoriver,asaconfirmationofthegroundwaterhead distributionobserved inFig.11b.

themostimportantwellspresentinthearea,extractionfromothernotrecordedwells,althoughcannotbefullyexcluded,hasbeenneglected.

Theboundaryconditionsofthenumericalmodelhavebeenimposedby giving nil flux on the Apennines, coincidence of water head andground level at the intersection with Reno and Savena rivers, and byassigning the measured water heads at the borders of the calculationarea,takingparticularcareinfixingthesebordersfarenoughfromthemostimportantwells(Verruijt,1970).

Theabovedescribedtrialanderrorprocedurehasledtoestimateapermeabilitycoefficient$K=3*10^{-4}$m/s,whichprovidesthe comparison between simulation and measurement plotted in Fig. 12a.On the vertical axes of the two plots the water heads computed withthe numerical model on each point of the calculation grid of Fig. 2 arereported, while the horizontal axis reports the correspondent valuesobtained on the same points from the interpolation of measured dataEvenconsideringthenoticeablesimplificationintroducedbythemadeassumptions (Eq. (3) with constant K(x,y)), it is worth noting that thecomparison is satisfactory. Such a result is confirmed by comparingthemapofcalculatedgroundwaterheads(Figure12b)withthatobtainedbyinterpolatingmeasures(Figure11b).Itisfinallynottrivialto note that the Darcy's coefficient found with this procedure fallswithintheexperimentalrange(10^{-5}–10^{-3}m/s)givenforcoarsegrained soils by the Regione Emilia Romagna and ENI-AGIP (1998)study.

Oncecalibrated,theseepagemodelcanbeusedtopredicttheeffectsof different pumping scenarios. Among the various possible studiedsituations, the simulations performed by switching off the differentwellshaveshownthepredominantroleoftheextractionforcivilpurposeonthegroundwaterregime.Finally,byassigningnilextractiontoall wells,thepositionoftheundisturbedgroundwatertablecouldbeestimated, thus recovering an useful information for the analysis ofsettlements.

Interpretation

Theobservedsubsidencecanbeinterpreted,inaccordancewiththeclassicalprincipleofTerzaghi(1943),asthecumulateddeformation

Where S and S_f represent respectively the total thickness of theaquifer group and the cumulated thickness of fine grained deposits ateachsingleposition(mapped inFigure10a).$C_c$and$C_s$have beentakenequaltothemeanvaluesobtainedfromlaboratorytests(respectively 0.3 for C_c, considering the mean of the values obtainedfromshallowanddeepboreholes, and0.07forC_s).

Theaboveformulaimplicitlyassumesanilcompressibilityofcoarse grained materials, being $C^*_c(x,y)$ (and $C^*_s(x,y)$) equal tozero if $S_f(x,y) = 0$. This assumption has been made considering thedifference principally aimed at recovering a more precise reconstruction of thesubsoil profiles in order to remove, or at least to smooth, some of thesimplifying assumptions madeinthe present analysis.

Anotherimportantaspectconcernsthedevelopmentofsubsidencewithtime.Accordingtotheclassicaltheoryofconsolidation(Terzaghi,1943)somedelayshouldbeexpectedbetweenvariationsattheboundary conditions and settlements, depending on the permeabilityand deformability of the compressible layers and on the distance fromdraining surfaces. of some orders of magnitude typically existing between thecompressibilityindexesofsilty-clayeyandgravelly-sandysoils.

Infact,whiletheoedometertestsperformed onthefinegrainedmaterialof Bologna reveal compressibility indexes ranging between 0.25 and0.35, values lower by some order of magnitude are typically found ongravellysoils(e.g.Modonietal.,2011).

ThemapreportingthesettlementscomputedwithEq.(4)isshowninFig.13. Inspiteofthenoticeablesimplificationintroduced,thespatialdistribution shown by this figure is not dissimilar from that obtainedfrommeasurement (Figure5). Such asimilarityprovidesalogicalexplanation of the observed subsidence, which can be considered asthe result of the intensive pumping carried out from the alluvial fansof the Savena and, moreover, of the Reno River. Due to this activity, asignificant drop of the groundwater table has been produced on thewhole area. However, because of the relatively low compressibility ofthe coarse grained materials (gravel and sand, as shown in Figures 8band 10b) forming the alluvial fans, sinking is relatively limited nearthe area of pumping. The most evident subsidence is on the contraryproducedonthesurroundingportionofterritory,wherethereductionof water levels and the consequent variation of the effective stressregime, is associated to a relatively large thickness of fine grainedcompressiblesoils(seeFigure10a).

However,itmustbenotedthattheadoptedmodel,whileproviding an averagely good description of the phenomenon, cannot be used toderiveadetailedpredictionofsettlementsalloverthe consideredarea.Forinstance,thecomparisonofFigs.13and5showsthatthesettlements

The development of the number of wells (Figure 1)shows that large part of withdrawal has been carried out in the periodbetween1960and1975,withapeakoftheactivityintheyearsaround1970,whenthewellsadoptedforcivilpurposeswereactivated.Although the available data do not allow to establish the developmentofsettlementwithhighprecision,themaximumsubsidenceratesoccurredfewyearslater.Thisdelay,whichisconsistentwiththe

Conclusions

The land subsidence observed in the past decades on the area ofBolognahasbeenqualitativelyandquantitativelyinterpretedbyperfor-ming a large scale multi-temporal analyses of data regarding subsoilproperties, groundwater levels and settlements. Fundamental stepsfor the analysis have been the processing of data with geostatisticalmethods,the modelling oftheseepageinduced by pumping and ofthe soil deformation induced by the changes of overburden effectivestress regime, and the mapping of all variables with a geographicalinformationsystem.

Magnitude and distribution of subsidence over the studied areahave been demonstrated to be the result of the combined action ofgroundwater table lowering, which produced an increase of the over-burdeneffectivestressesandacompressionofthesubsoilstrata.Although with some uncertainty, unavoidable considering the lack ofmeasurementintheearliertimes,theanalysisoftopographicalrecords carried out for the period 1943-2005 has shown the same recurrentpattern of subsidence (Figure 5). Cumulated settlements range from aminimumof0.7mtoamaximum of4m,settlementratesin theperiod1970-1980 range from 2.5 to 40 cm/year, with highest values occurringin the area surrounding the alluvial fan of the Reno river. This coarsegrained deposit has proved to be of paramount importance for theexplanationofthephenomenon.Infact,theanalysisofthegroundwatercirculation, based on the monitoring of wells for the period after 1976and extrapolation to previous times by means of a finite differenceseepage model, has demonstrated the deep impact of the extractiveactivity carried out in this zone on the overall groundwater regime(Figures 11a and 12b). Land subsidence is concentrated around thisarea,basicallyduetothecombinationofwaterheaddropsandthicknessesoffinegrainedmaterials,beingtheselatterresponsibleforsubsoilcompression.

Apartfromthepeculiaraspectsoftheanalysedcase,themost important lesson learned from the present study is that the coupledhydro-mechanicalphenomenainducedbygroundwaterextractioncanbe nowadays studied, even on such large areas, thanks to a number oftechnological developments. For the back analysis of past phenomena,most of the difficulties lie in the limited availability of data regardingsettlements and water table position, as monitoring of these variablesgenerallytakesplaceaftertheeffectsonthesurroundingenvironment(building,infrastructures,watercoursesetc.)becomevisible.

The study of new cases, to be undertaken whenever groundwaterpumpingisplannednearpopulatedorsensitiveareas,cantakeameaningfuladvantagefromtoolsbased on satellite technologies(GPS orDInSAR).The precision of these systems, even though not(ornotyet)comparablewiththetraditionaltopographicaltechniques,iscompatible with theextent ofthe phenomenon. Abig amount ofdata covering large areas can be available in this way and used for apromptdecisionmaking,providedfastermethodologiesfortheprocessing of the satellite signals are developed. However, the timedependent nature of the process, i.e. settlements delayed with respecttothemodificationofgroundwaterconditions,mustnotbedisregardedandfutureextrapolationofmeasurementaccomplishedwithnumericalmodels may be necessary. Finally, it must be stressed once more thattheaccuracyofmodelsistightlylinkedtotheknowledgeofthegeological, hydro-geological and geotechnical conditions and to thequality(densityandaccuracy)ofinvestigations.

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