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Can Venice be raised by pumping water underground? A pilot project to help decide

N. Castelletto,[1] M. Ferronato,[1] G. Gambolati,[1] M. Putti,[1] and P. Teatini[1]

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[1] Recent field evidence suggests that injecting fluids below the ground surface can induce an anthropogenic land uplift of a few tens of centimeters over a time interval that may range from a few months to a few years. At the same time, new modeling studies using a lot of realistic hydrogeological and geomechanical information from the northern Adriatic basin indicate that pumping seawater into a 600–800 m deep brackish aquifer below the Venice Lagoon might help raise the city uniformly by 25–30 cm over 10 years (a). This could provide Venice with an important innovative defence from and a substantial mitigation to the so-called "acqua alta," i.e., the increasingly frequent floods that plague the city. To test the feasibility of an actual program of anthropogenic Venice uplift, a pilot project is designed with the aim of investigating the occurrence over a limited area selected on purpose within or in the margin of the lagoon where three boreholes down to 800 m are drilled and seawater properly treated for geochemical compatibility is pumped into the selected aquifer during 3 a. Using an improved reconstruction of the geology and lithostratigraphy from a new seismic survey to be carried out in the lagoon subsurface, the pilot project plans the instrumentation of the injection wells and other boreholes for the continuous monitoring and accurate measurement of (1) pore water overpressure; (2) expansion of the injected unit by the radioactive marker technique; (3) compaction, if any, of the upper fresh water aquifer system with the aid of an extensometer; and (4) vertical and horizontal motions of land surface via spirit leveling, GPS and interferometric synthetic aperture radar. Preliminary numerical simulations show that a constant saltwater injection rate of 12×10^{3} m^{3} s^{-1} from each well might provide a maximum 7 cm uplift at the center of the selected site over a 3-a time, namely, a limited amount that is nevertheless accurately measurable and should not raise concerns for the stability of the buildings and the preservation of the infrastructures in the area. A continuous control of the experiment is envisaged based on much refined hydrologic and geomechanical models properly updated and calibrated to the detailed lithostratigraphy resulting from the new seismic campaign, the ad hoc field analyses, and the current field observations of the event. The completion of the pilot project is expected to require 4 a including an initial year needed for the necessary authorizations and the operative implementation of the injection program. The planned cost is in the range of 5 MEuro/a. The present paper addresses the major issues concerned with the design of the pilot project and discusses the results from the experiment simulations with a glance at their prospective application to an actual project of anthropogenic uplift of Venice.

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1. Introduction

[2] Land subsidence caused by man's withdrawal of fluids from subsurface geological formations has been experienced worldwide over the past century. For a recent review of the most famed subsiding sites all over the world, see *Gambolati et al.* [2005]. Attempting the reverse, to create land uplift by the injection of fluids into the subsurface, is a much less common occurrence. This is not because the technology is unknown. Subsurface fluid injection is a widely used technique in the petroleum industry. It has been used during the last 40–50 years (a) for different purposes, with facilities discharging a variety of fluids into more than 400,000 injection wells across the United States alone [*U.S. Environmental Protection Agency*, 2002]. However, fluid injection has seldom been used for the purpose of raising subsiding areas, and therefore measurements of anthropogenic uplift are not generally planned and carried out. Two documented examples are the pumping of salt water into the

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[1] Department of Mathematical Methods and Models for Scientific Applications, University of Padua, Padua, Italy.

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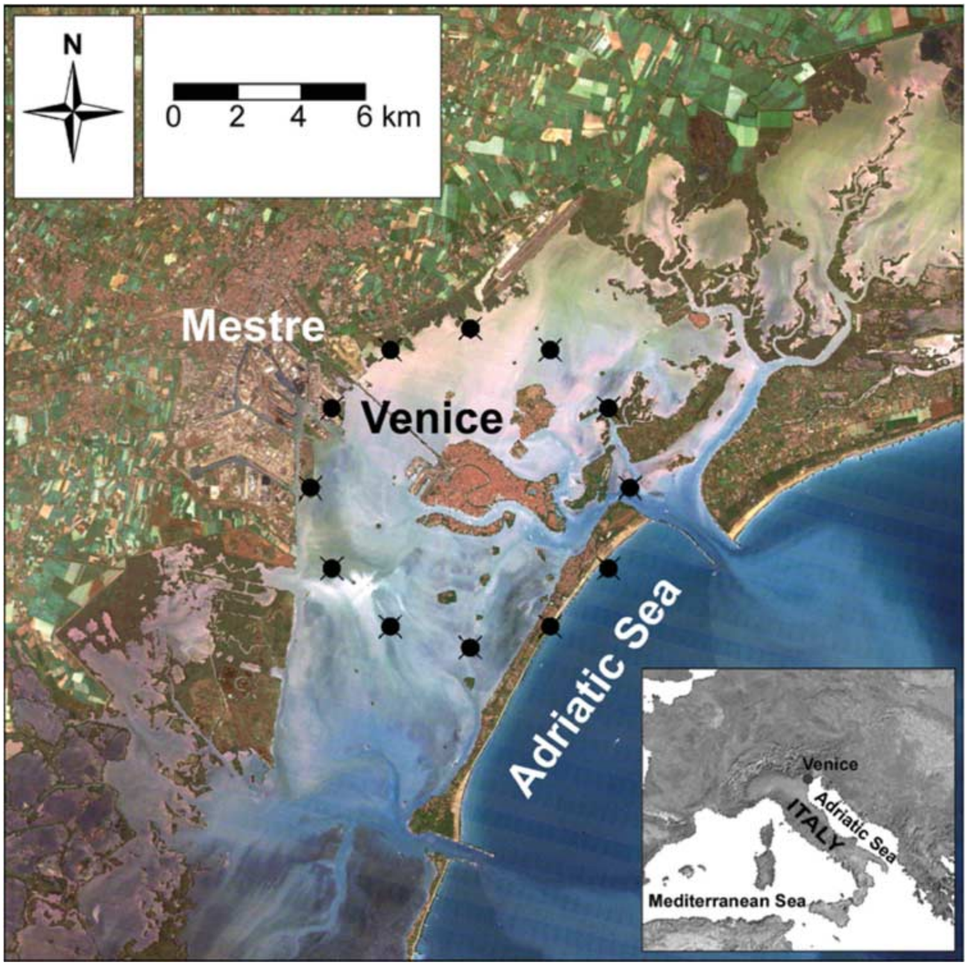

Figure 1. View of the Venice Lagoon from space with the indication of the saltwater injection wells (black dots). The two inlets of Lido (upper) and Malamocco (lower) are shown (redrafted after *Comerlati et al.* [2003]).

subsurface formations at Long Beach Harbor, California, and the artificial recharge in the Las Vegas Valley, Nevada. The maximum recorded settlement in Long Beach during the oil production period in the 1950s was equal to 8.5 m [*Poland and Davis*, 1969], and the injection program generated a modest observed rebound of 10 cm along the front pier in the San Pedro Bay [*Rintoul*, 1981], with a maximum local uplift of 33 cm from 1958 to 1975 [*Kosloff et al.*, 1980]. In Las Vegas, recent satellite maps show that the artificial replenishment, operated since the late 1980s to partially make up for the groundwater level decline due to aquifer overdraft, has succeeded in mitigating the resulting land subsidence, with a maximum seasonal uplift of more than 3 cm recorded during the 1997–1998 winter [*Hoffman et al.*, 2001]. Another reason for the paucity of uplift data is that most fluid injection projects, in particular the ones for enhanced oil recovery (EOR), occur in deserted areas where traditional geodetic leveling is not usually performed. It is only very recently that technology from space, such as Global Positioning System (GPS) and especially interferometric synthetic aperture radar (InSAR), allows for the inexpensive detection, also in nonurban land by the use of ad hoc reflectors, of small displacements (on the order of 1–2 mm a^{-1}) that can easily be related to fluid injection locations. In fact, field measurements from satellite data provide documentary evidence that pumping fluid underground has indeed produced a measurable anthropogenic uplift [*Bilak et al.*, 1991; *Wang and Kry*, 1997; *Hoffman et al.*, 2001; *Dusseault and Rothenburg*, 2002; *Collins*, 2005]. Using satellite interferograms, *Stancliffe and van der Kooij* [2001] have measured an uplift of 29 cm caused by steam injection at the Cold Lake, Alberta, Canada, over less than a 3-month period. Even larger uplifts in steam-assisted gravity drainage projects may be expected [*Davari*, 2007; T. Settari, personal communication, 2007]. In light of the above experiences, there is a distinct possibility that injecting water below the lagoon can help raise Venice by an appreciable amount.

[3] The first idea to raise Venice was advanced 4 a ago and published by *Comerlati et al.* [2003]. On the basis of hydrogeological and geomechanical modeling, Comerlati et al. predicted a Venetian uplift of 30 cm due to saltwater injection through 12 injection wells (Figure 1) in 10 a. In 2004, on the basis of more recent geological, lithostratigraphical, hydrological, and especially geomechanical data from the northern Adriatic basin that comprises the lagoon subsurface [*Baù et al.*, 2002; *Ferronato et al.*, 2003a, 2003b, 2004], the Comerlati et al. modeling study was

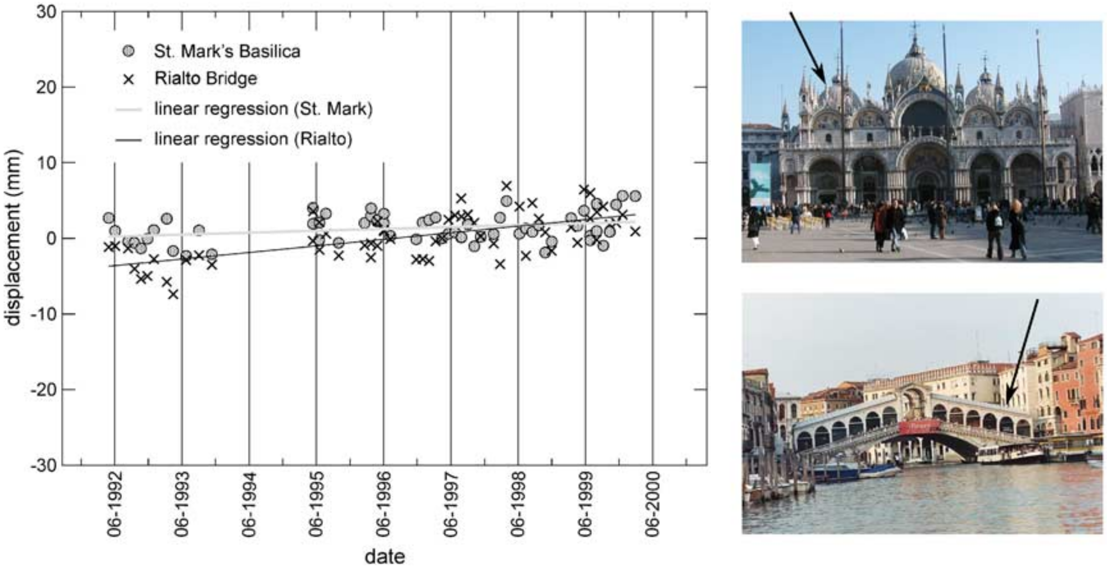

Figure 2. Vertical displacement history for two point targets (PT) as detected by interferometric point target analysis (IPTA) at the two most famous Venice monuments (St. Mark's Basilica, top, and Rialto Bridge, bottom) with respect to 23 April 1997 ERS acquisition. The approximate PT locations are indicated by the arrows in the pictures [after *Teatini et al.*, 2007].

refined, with an updated most likely uplift estimate of 25 cm, together with upper and lower bounds equal to 40 and 11 cm, respectively [*Comerlati et al.*, 2004]. It is worth noting that an uplift of 25 cm would have precluded most of the acqua alta that has occurred from 1872 to 2002 and would have limited the lagoon water level to less than 110 cm in 90% of the events [*Comerlati et al.*, 2004]. The 110 cm water level is the threshold value above which the mobile gates of Modulo Sperimentale Elettromeccanico (MOSE), the expensive (four billion dollars according to *Harleman* [2002]) and still controversial [*Ammerman and McClennen*, 2000; *Pirazzoli*, 2002; *Nosengo*, 2003; *Umgiesser and Matticchio*, 2006] structure designed to protect Venice from acqua alta and currently under construction, are planned to be activated. Furthermore, in light of the near stability in the recent vertical displacement history at Venice [*Teatini et al.*, 2005, 2007] (Figure 2), a 25–30 cm upheaval would offset the 27 cm expected northern Adriatic level rise over the 21st century as predicted in a pessimistic scenario by *Consorzio per la Gestione del Centro di Coordinamento Delle Attività di Ricerca Inerenti il Sistema Lagunare Veneziano* (*CORILA*) [1999], a consortium of universities and research institutions charged with coordinating research activity in the Venice Lagoon. Another paper by *Comerlati et al.* [2006] addresses the possibility of storing anthropogenic CO_2 underneath the Venice Lagoon, but the related uplift would be more modest than that obtained by injecting saltwater, and the success of the operation is more uncertain because of the great complexity affecting the overall CO_2 sequestration process. In summary, we believe that pumping salt water below Venice could be a viable contribution to save Venice. It would be a complementary action to MOSE, as it might prolong its operational life vis-a-vis the expected sea level rise, and at the same time reduce significantly the frequent activation that may raise concerns at an economic and environmental level.

[4] In view of the precarious lagoon environment and the great artistic heritage of the city of Venice, anthropogenic uplift by seawater injection cannot be even conceived without an extremely detailed knowledge and accurate prediction of the actual subsurface response to the planned pumping. Such an in-depth knowledge can be provided by the design and implementation of a preliminary pilot project with new geophysical investigations and an ad hoc injection experiment. The purposes of a pilot project are manifold. First, and perhaps most importantly, to ascertain whether water injection in deep geological formations below the lagoon can indeed contribute to raise Venice, as was predicted with the aid of the preliminary modeling analyses [*Comerlati et al.*, 2003, 2004]. Second, to improve the geological and lithostratigraphical representation of the lagoon subsurface down to the depth of interest. Third, to finely calibrate the hydrological and geomechanical models and improve their predictive capabilities, thus providing the fundamental tools to forecast ground deformation and keep the injection process under careful control so as to avoid any possible damage to the existing buildings and infrastructures. Also, finally, to measure the resulting land motions using the most advanced satellite technology and show how the joint use of real time measurements and numerical predictions can represent an efficient and reliable tool to monitor and control the overall occurrence in a prospective future program of anthropogenic Venice uplift.

[5] The purpose of this paper is to present and discuss the pilot project in some detail with an indication as to the four possible sites where the experiment might be performed. A campaign of ad hoc geoseismic analyses down to 1000 m across the lagoon to improve the knowledge of the Venice subsurface is also described. The plan is supplemented with a finite element (FE) modeling prediction of the injection

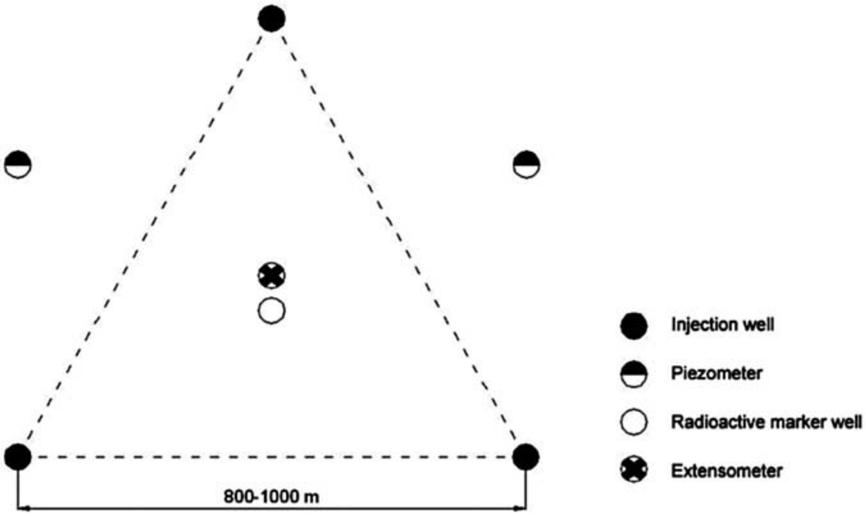

Figure 3. Layout of the injection wells and other instrumented boreholes.

rate needed to obtain a measurable uplift of a few centimeters over the planned time and the corresponding space distribution across the experimental area. Finally a rough breakdown of the cost is provided, together with a set of recommendations to close the paper.

2. Pilot Project

[6] The design of the pilot project basically consists of (1) planning both the injection wells and the monitoring and measuring network, (2) selecting the most suitable site, and (3) describing the analyses and tests required for getting a detailed knowledge of the lagoon subsurface and predicting the hydrological and geomechanical response of the injected formations and overlying land. The possible duration of the pilot project is expected to be about 3 a plus an initial year needed for the necessary authorizations, boreholes construction and plant installation. After the experiment is completed a robust evidence of the actual feasibility of anthropogenic Venice uplift should be gained including an indication of the related risks and operational difficulties.

2.1. Experiment Design

[7] The pilot project will involve a limited underground volume that is deemed to be nevertheless representative of the overall lagoon subsurface, or subordinately the Venice subsurface, without raising concerns among the people living in the experimental site or jeopardizing the activity that is normally performed there. A preliminary design of the injection wells and observation boreholes is shown in Figure 3. Three wells from where saltwater is pumped underground are located at the vertices of a regular triangle with 800–1000 m long sides and are drilled down to a depth of about 800 m, thus involving a horizontal area of 0.43 km^2. Each single well will inject the minimum pumping rate that is required to produce a measurable yet fully safe uplift at any time of practical interest within the 3-a duration of the experiment. The injection rate will be adjusted accordingly with the aid of numerical analyses to obtain a maximum uplift at the end of the experiment of about 7 cm. The final size and layout of the injection wells and observation boreholes will be based on the actual geology of the subsurface and the logistic constraints dictated by the selected site.

[8] The main variables to be measured and continuously monitored during the injection process include (1) the pore water overpressure in both the injection wells and the piezometric holes; (2) the injection rate from each individual well; (3) the deformation of the injected formation and overlying clay layer as monitored with the aid of the radioactive marker technique; (4) the compaction, if any, of the upper fresh water aquifer system as monitored with the aid of an extensometer; and (5) the land surface (horizontal and vertical) motions as monitored by the use of the remote sensing technologies (GPS and InSAR) and traditional spirit leveling. The pore water pressure in the injection wells will be directly recorded by an appropriate equipment commonly used in petroleum engineering while in the remainder of the aquifer it will be monitored by two additional boreholes instrumented with deep piezometers located outside but close to the pilot site (Figure 3). In the center of the experimental area an extensometer [*Heywood*, 1995] will be installed to measure the porous medium deformation in the upper 400–500 m and a borehole will be drilled to implement the marker technique and simultaneously measure in situ pore water pressure. Recently, creep phenomena at the extensometer foundations have been experienced, thus calling for a more in-depth investigation of the extensometer response, and perhaps partially limiting the actual use of such a monitoring tool. Recording the local in situ expansion will be very important to derive the most updated and representative estimate of rock compressibility in unloading (II cycle). This will be done using the radioactive marker technique [*Mobach and Gussinklo*, 1994; *Ferronato et al.*, 2003a, 2003b] in the central borehole where the formation expansion is expected to be largest, and hence the measurement error smallest.

2.2. Site Selection

[9] The experimental site selection is to be based on both geological and logistical considerations. From the geolog-

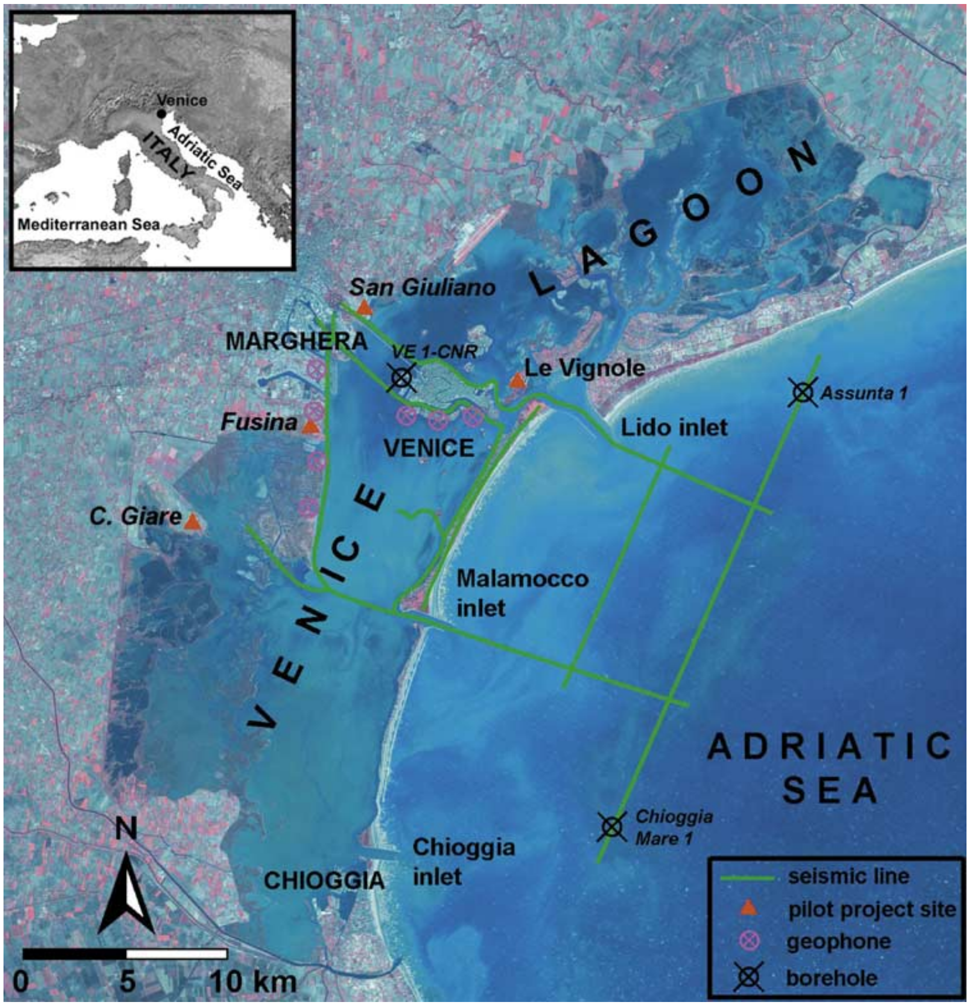

Figure 4. ASTER image of Venice Lagoon showing the possible location of the four sites where to implement the pilot project (Le Vignole, San Giuliano, Fusina, and Cascina Giare) along with the seismic profiles planned to improve the present knowledge of the geology and lithostratigraphy of the lagoon subsurface.

ical viewpoint, the aquifer where saltwater is injected should be a continuous formation underlying the entire lagoon and should coincide with the formation under consideration for the future project of Venice uplift. It is particularly important that the confining unit or caprock have adequate thickness and ideally not be affected by faulting or fractures. More detailed local geoseismic surveys may be necessary to find a location with these desirable attributes.

[10] From the logistical viewpoint, the selected area must fulfil a number of safety requirements, e.g., its ground elevation should be such as to avoid any risk of flooding due to likely events of acqua alta during the experiment, and should be distant enough from vulnerable sites (e.g., industries, villages or sensitive areas) that could be potentially damaged should the experiment evolve differently than planned. Moreover, it is important to have an easy and economic accessibility by trucks to the site in order to both install and remove the experimental equipment required by the injection plant. The availability of the injected water should also be ensured at a relatively small distance from the lagoon with easy access to an ad hoc treatment plant for geochemical compatibility. Finally, it may prove necessary to verify the availability of the selected area in relation to its ownership, either private or public, and to obtain the required authorization to operate on the site.

[11] Four possible choices are preliminarily identified that represent a reasonable trade-off between the above requirements and might fulfil the major constraints (Figure 4). For example, Le Vignole island is probably one of the most representative sites from a geological viewpoint because of its proximity to Venice, but the only access to it is by ship. By distinction, the San Giuliano site possesses several facilities that would make the access by trucks and the installation of the experimental equipment quite convenient, but its proximity to an extremely important infrastructure such as the motorway bridge might rise some concern for the safety of the injection experiment in relation to integrity of the structure itself. Alternative interesting sites could be Fusina and Cascina Giare, the latter being farther from Venice, that are easily accessible by trucks and appear to be far enough from vulnerable areas.

2.3. Geoseismic Analyses

[12] The geological model by *Comerlati et al.* [2003, 2004] is based on a 3D deep seismic survey performed by

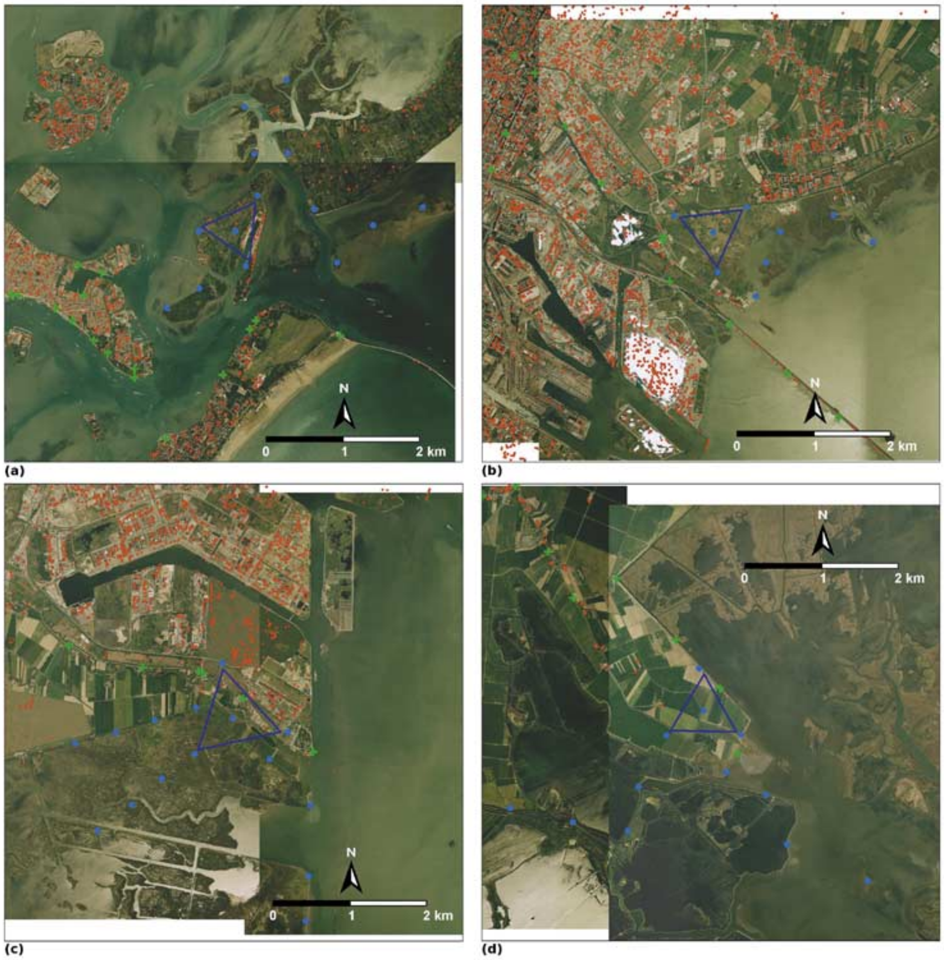

Figure 5. Aerial view of the area of (a) Le Vignole, (b) San Giuliano, (c) Fusina, and (d) Cascina Giare. The green crosses represent the leveling benchmarks of the ISES network [after *Tosi et al.*, 2000] and the red dots represent the existing point targets for land subsidence measurement detected by persistent scatterer interferometry [after *Teatini et al.*, 2005]. The blue triangle indicates the preliminary trace of the margin of the experimental site, and the blue dots indicate the position planned to establish additional artificial reflectors for measuring the land uplift produced by the pilot experiment.

ENI-E&P in the northern Adriatic, the lithology of the exploratory boreholes Venezia 1-CNR, Chioggia Mare 3 and Chioggia Mare 4, and the freshwater multiaquifer system in the upper 400 m depth as reconstructed in previous studies of anthropogenic land subsidence of Venice [*Gambolati et al.*, 1974]. More precisely, the seismic records have provided the regional maps of the top and bottom depth of the geological unit being injected with its detailed lithofacies sequence extrapolated from the borehole information along with the thickness of the clayey horizons confining the aquifer formation.

[13] Improvement of the current knowledge on the geology and lithostratigraphy underneath the Venice Lagoon is a basic requirement for both the selection of the pilot project location and the proposed full-scale project of anthropogenic Venice uplift. In this respect we need (1) to verify the continuity of the pumped aquifer and the overlying impermeable caprock across the overall lagoon area; (2) to investigate the lateral extent of the geologic sequences within the depth interval of interest and the location of faults, folds, and structural dips, if any, that could represent a hydraulic or geomechanical barrier; and (3) to accurately determine the geometry (depth, area extent and thickness) of the geologic formations involved in the injection project.

[14] In order to integrate the existing available information, an ad hoc single-channel and multichannel seismic survey is planned in the lagoon focusing on the zone between 500 and 1000 m depth. Figure 4 shows a preliminary program of the two-dimensional seismic lines to acquire new geological data. The survey is composed of about 90 km long marine acquisitions and 10 km long land acquisitions. The seismic survey will be calibrated using the Venezia 1-CNR sequence and a number of lines outside the lagoon crossing the exploratory boreholes Chioggia Mare 1 and Assunta 1 (Figure 4). Data acquisition on Lido island will focus on the definition of the velocity functions for the compressional P waves and the amplitude variation with offset (AVO) curves. Within the lagoon, the seismic survey will be carried out along the main channels with a number of geophones located on the Giudecca Island and along the Petroli channel to improve the reconstruction accuracy of the velocity functions. The length of the recording cable

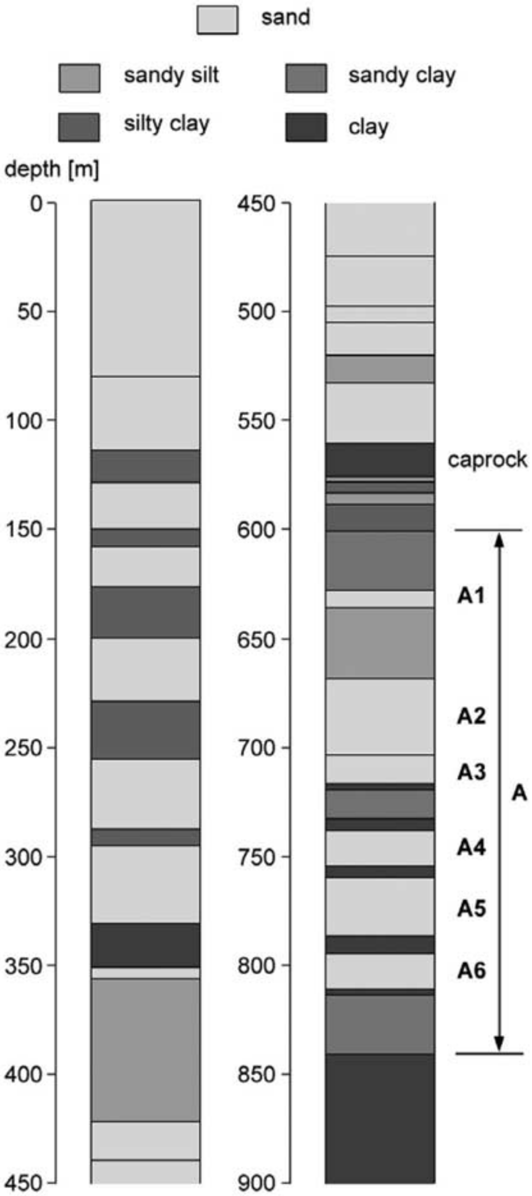

Figure 6. Representative lithostratigraphy of the brackish aquifer unit subdivided into six injected subunits and overlying layers as reconstructed below Venice by *Comerlati et al.* [2003, 2004].

should range between 150 and 600 m for the acquisitions inside and outside the lagoon, respectively. The choice between the single-channel and the multichannel acquisition system will be made on the basis of the water depth in order to maximize acquisition resolution, estimated to be a few meters, and to minimize multiple reflections, thus improving the signal to the noise ratio.

[15] In areas of particular interest, e.g., in the expected pilot experimental site, the two-dimensional seismic survey should be integrated with in situ geophysical measurements such as well logs, cross-well seismic, laboratory experiments on water and soil samples cored from ad hoc exploratory boreholes.

[16] The outcome of the new seismic investigations will be supplemented with the seismic data acquired by ENI-E&P offshore in the Adriatic Sea facing the lagoon over the 1990s and onshore, in the lagoon surroundings, over the 1950s–1980s. The data integration will allow for accurately mapping the depth and thickness of the sandy formations potentially suited for seawater injection and the clayey caprock sealing the aquifer.

2.4. Displacement Measurement

[17] The motion of the ground surface will be monitored by traditional spirit leveling, permanent GPS, and interferometric SAR analysis. Periodic leveling surveys must be performed on existing benchmarks of the Intrusione Salina E Subsidenza (ISES) network [*Tosi et al.*, 2000] to which a number of new local benchmarks will be added. Both vertical and horizontal components of the ground motion will be monitored in real time by a permanent GPS station connected to a reference international network. SAR interferometric analyses on persistent scatterers will be performed using natural point targets and artificial reflectors established ad hoc in the pilot site area and in the vicinity [*Dixon et al.*, 2006; *Teatini et al.*, 2007]. The combination of multiple independent overlapping ascending/descending tracks with a different viewing geometry will allow for mapping surface displacement in three dimensions [*Wright et al.*, 2004; *Ketelaar et al.*, 2007]. This will significantly improve measurement of the response of the pilot project in terms of ground displacements due to the high spatial and temporal coverage allowed for by the ENVISAT and RADARSAT satellites whose orbit return period is approximately equal to one month. As an example, Figure 5 shows the density of the target points detected by Interferometric Point Target Analysis over the four prospective pilot sites using the 1992–2000 ERS scenes. A sequence of tiltmeters installed in the injection wells could also help measure the horizontal displacements at the wellhead.

[18] The simulation models will be refined and calibrated using the hydrologic and geomechanical response from the experiment, i.e., pore water overpressure, in situ formation expansion and land uplift. At the same time, if needed, the models will be used to tune the individual injection rates so as to provide a distribution of anthropogenic uplift that is as uniform areally as possible. The ultimate calibration of the numerical models and tuning of the controlling parameters will result in the best possible design and execution of the full-scale project of Venice uplift by deep seawater injection as well as reliable prediction of the expected outcome.

2.5. Prediction of Uplift

[19] The experiment has been simulated numerically using the 3D nonlinear finite element (FE) models of subsurface water flow and land uplift developed by *Comerlati et al.* [2004]. Nonlinearity is accounted for by aquifer elastic storage and rock compressibility both of which vary with the in situ effective intergranular stress, hence the pore water overpressure. The lagoon subsurface is known to be normally pressurized and consolidated, at least down to 1000 m depth [*Teatini et al.*, 2000]. As was shown by *Gambolati et al.* [2000] and *Comerlati et al.* [2005], an uncoupled approach is fully justified. The volume of the

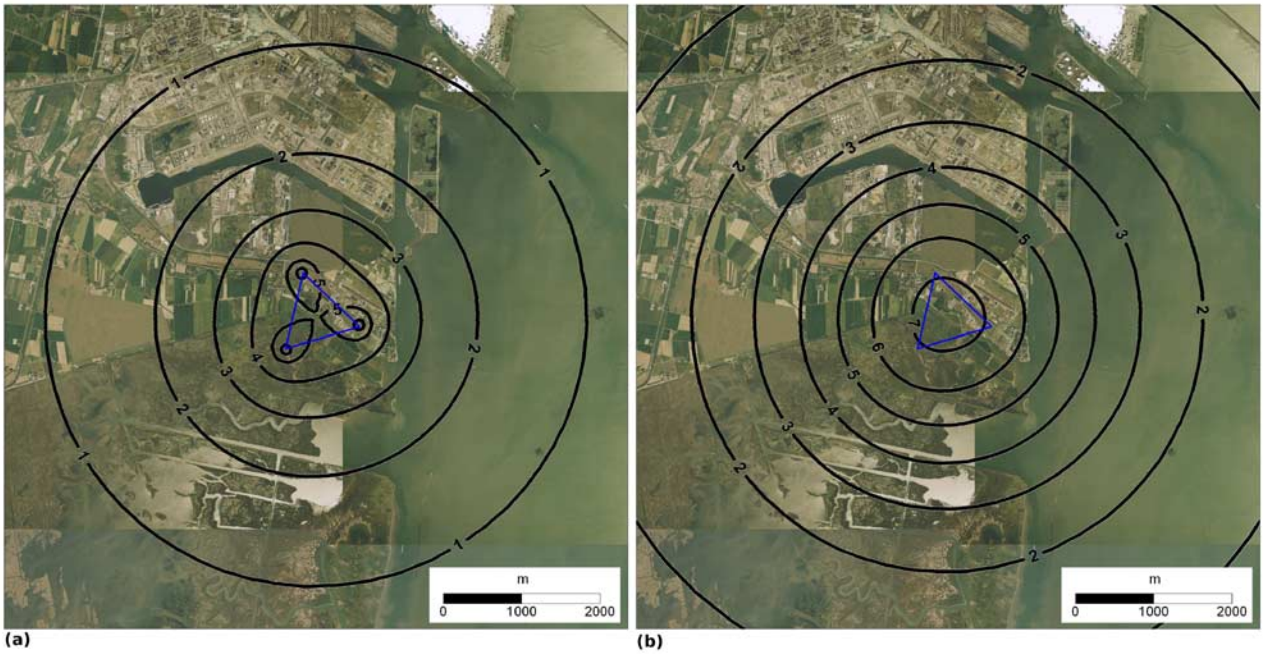

Figure 7. (a) Pore water overpressure (bar) averaged over the injected aquifer thickness, and (b) land uplift (cm) at the completion of the pilot project (Fusina site).

porous medium has been discretized into linear tetrahedral elements forming a cylinder with a 10 km radius bounded on top by the ground surface and on bottom by a rigid basement 5 km deep. Because of the limited time interval of the simulation, boundary conditions of zero overpressure and displacement are prescribed everywhere, except at the land surface where a traction free plane is assumed. A horizontally layered lithostratigraphy for the injected formation and overlying caprock based on the Tronchetto VE-1 borehole and the geological reconstruction of *Comerlati et al.* [2004] is used (Figure 6), while the upper fresh water aquifer-aquitard system is vertically similar to the one underlying Venice [*Gambolati et al.*, 1974]. To provide an order of magnitude prediction of the expected 3-a time and space distribution of uplift, the parameters of the baseline case as discussed by *Comerlati et al.* [2004] have been

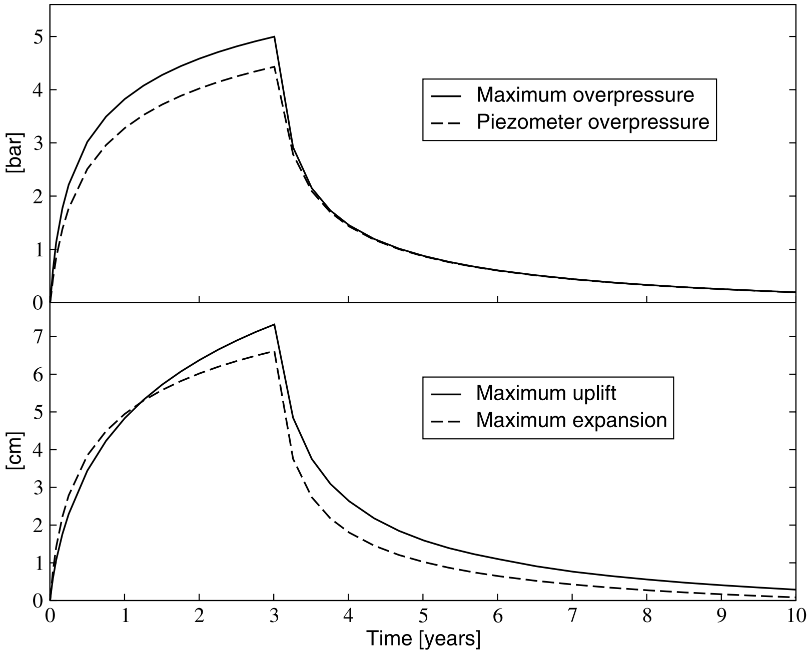

Figure 8. Time behavior of pore water overpressure (bar) averaged over the injected aquifer thickness, and land uplift and injected formation expansion (cm) at the center of the ideal injection triangle. The average pore water overpressure in one external piezometer is also shown.

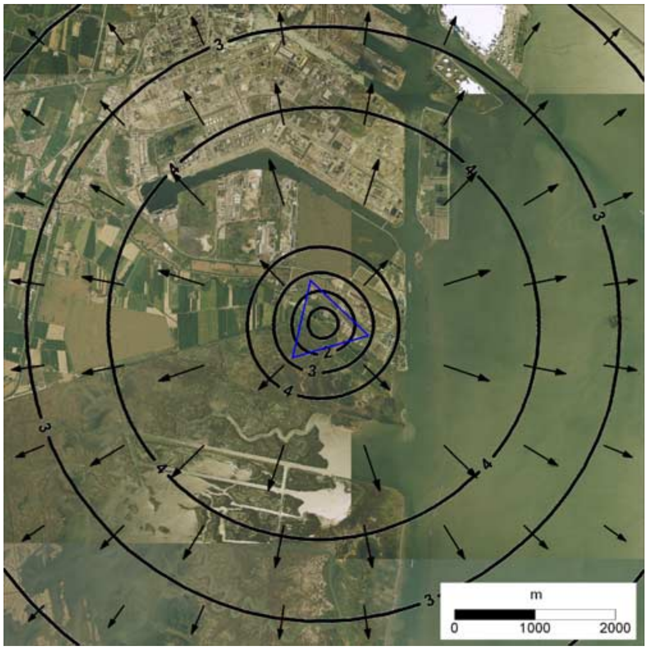

Figure 9. Horizontal land displacement (cm) at the completion of the pilot project (Fusina site).

implemented into the present models, in particular, the hydraulic conductivity listed in their Table 2 and the oedometer rock compressibility of their Figure 5. On the basis of actual field measurements from markers installed in deep northern Adriatic boreholes compressibility in expansion was assumed to be 3.5 times less than compressibility in compression [*Ferronato et al.*, 2003a; *Comerlati et al.*, 2004]. Simulations utilized a constant rate Q equal to 12×10^{-3} m^3 s^{-1} of saltwater which was continuously injected into each well and was partitioned into the six subunits displayed in Figure 6 on the basis of the respective hydraulic transmissivity.

[20] The results of the simulation were superposed on each of the four candidate sites just to provide a realistic idea of what the expected outcome of the pilot will look like. Figures 7a and 7b show the pore water overpressure and the land uplift, respectively, for the Fusina site predicted at the completion of the experiment, i.e., 3 a from the beginning of pumping. The largest overpressure and uplift are obtained at the center of the ideal triangle and are 6.7 bar and 7.3 cm, respectively. The quite limited amount of predicted pore overpressure should prevent the generation of hydraulic fractures. Note the uniform distribution in space of the uplift consistent with the quite regular overpressure distribution. Because of the relatively short pilot project duration and the small injected seawater volume, the overpressure does not migrate vertically and remains practically confined within the injected units. An overall area of about 2.5 km^2 is potentially affected by ground uplift (as a reference the entire Venice lagoon area is approximately 550 km^2). The large scale of the experiment, along with the large depth where injection takes place, is expected to smooth the effect of a possible heterogeneous distribution of hydraulic properties in the injected formations (by distinction the geomechanical properties are much less heterogeneous on the horizontal scale while vertically the geomechanical heterogeneity is realistically accounted for). Behavior in time during and after the experimentation is provided in Figure 8, including the water pressure rise and decline in one of the piezometers outside the triangle. By distinction should we continue to pump at a lower rate past the third year, ground could be kept stable forever at the elevation recorded at the end of the experiment. Similarly in a prospective project of anthropogenic Venice uplift the ground stability once the targeted raising is achieved, would require that a residual water injection be maintained indefinitely, with the related issues, such as temporary pump failures, chemical compatibility with groundwater located far from the injection point, etc., to be properly addressed. In particular using the concept of "smart soils", recently advanced and tested over large-scale applications as well by GeoDelft (Netherlands), the addition of biocement including special bacteria and nutrients could be investigated during the injection phase. This would generate calcite at the grain contact with a strengthening of the in situ sandstone over a time interval of months or few years with no important impact expected on the formation permeability. As a major result the requirement for keeping the anthropogenic overpressure forever could be relaxed and the final pumping rate significantly reduced (F. B. J. Barends, personal communication, 2007). Figure 9 shows the horizontal land displacement which is essentially radial

Table 1. Expected Costs of the Pilot Project

	Time, months	Costs, kEuro	Description
Start	2	40	existing data collection
Phase 1a	8	900	geoseismic survey
		100	model setup
Phase 1b	12	1,000	site selection and pilot project design
Phase 2a	8	6,000	3 injection wells
		2,000	radioactive marker borehole + extensometer
		4,000	2 boreholes for fluid pressure measurements
		4,000	saltwater treatment plant
		400	local geoseismic survey + lab tests
		300	monitoring network
		100	civil works to complete the installation
Phase 2b	24 ÷ 36	1,500	execution of the experiment for 36 months
		200	model calibration simulation
Phase 2c	16	360	modeling prediction of anthropogenic Venice uplift
Total	48	20,900	

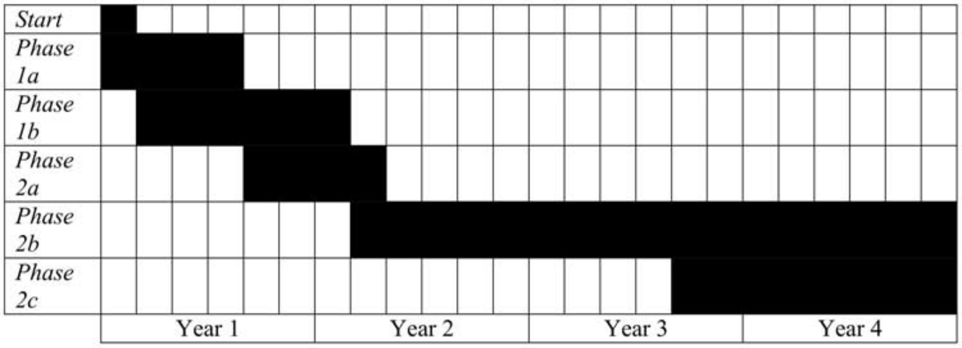

Figure 10. Time schedule of the work program for the pilot project.

beyond the circle encompassing the triangle. Again it is worth noting its regular distribution with the largest 4.5 cm value occurring at about 2.5 km from the triangle center, with no significant horizontal tensile strains. The injected formation expansion vs. time below the triangle center is given in Figure 8. The maximum expansion is of the same order as the largest uplift and should be easily detected and measured quite accurately with the aid of the radioactive marker technique.

[21] Finally the largest gradient of the vertical and horizontal ground displacement is predicted at 2×10^{-5} and 5×10^{-5}, respectively, i.e., far below the admissible bounds required for the safety of engineered structures [*Skempton and McDonald*, 1956; *Holtz*, 1991]. On the basis of the presently available knowledge of the subsurface properties, the small strains developed on the ground surface are expected to cause no adverse effects during the experiment. However, should the ground motion be such as to induce a potential risk of earth fissure generation, the real-time deformation monitoring network would help keep such a hazard under a safe control. Moreover, the prompt response of the system after pumping cessation (Figure 8) suggests that the project can be managed by the so-called hand-on-the-tap method, which allows for a quick return to a safe configuration just stopping the injection at any time.

2.6. Breakdown of Expected Costs

[22] A rough breakdown of the expected costs for implementing the overall pilot project is shown in Table 1 along with an indication of the corresponding operations. The time schedule of the work program is given in Figure 10. Total expenditure is on the order of 21 MEuro over 4 a. In our view this is the least expensive program required to obtain an adequate response from the experiment and to provide reliable and useful information for planning the full-scale anthropogenic uplift of Venice by seawater injection in deep geological formations.

3. Conclusion

[23] Recent field evidence from the oil production industry shows that underground fluid injection can generate an anthropogenic land uplift of tens of centimeters over a time interval ranging from a few months to a few years. Numerical analyses performed with the aid of advanced FE hydrologic and geomechanical models based on the best available information indicate that injecting saltwater into a 600–800 m deep brackish aquifer underlying the Venice Lagoon might induce a potential uplift of the city between 25 and 30 cm over 10 a with an ensuing substantial mitigation of acqua alta that periodically floods Venice.

[24] To test the feasibility of an actual full-scale program to raise Venice, a pilot project of anthropogenic uplift in a limited area within the lagoon or at the lagoon margin is designed and discussed. A preliminary survey of geoseismic investigations to improve the knowledge of the underground geology and lithostratigraphy down to 1000 m is planned. The designed pilot plant consists of three injection wells located on the vertices of an ideal equilateral triangle with 800–1000 m long sides and three additional boreholes instrumented with piezometers, markers and an extensometer to measure the pore water overpressure, the injected formation expansion and the upper aquifer system compaction, respectively. Land uplift is continuously monitored in time and space with the use of the most advanced satellite technology including GPS and InSAR.

[25] FE simulations of the pilot experiment based on the best presently available geological, lithostratigraphical, hydrological and geomechanical data suggest that a constant pumping rate of 12×10^{-3} m^3 s^{-1} from each single well might produce a very smooth and quite uniform uplift of land achieving a maximum value of about 7 cm over a 3-a time, i.e., the expected duration of the project. The gradient of both the horizontal and the vertical ground motion is very small and will not raise concerns for the stability of the buildings or the infrastructures located close to the experimental site. Cessation of pumping would yield a quick overpressure dissipation with the original ground elevation almost entirely restored in a couple of years or so. The execution of the pilot is expected to be carefully followed and controlled with the aid of the numerical models continuously refined and improved for comparison with the measurement of the actual pumping rate, pore water overpressure, land uplift and injected aquifer expansion. The outcome of the experiment is expected to be of paramount importance in view of a possible full-scale project of anthropogenic Venice uplift.

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N. Castelletto, M. Ferronato, G. Gambolati, M. Putti, and P. Teatini, Department of Mathematical Methods and Models for Scientific Applications, University of Padua, Via Trieste 63, Padua, 35121, Italy. (castelletto@dmsa.unipd.it; ferronat@dmsa.unipd.it; gambo@dmsa.unipd.it; putti@dmsa.unipd.it; teatini@dmsa.unipd.it)