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SALINE INTRUSION: A POTENTIAL RISK FOR COASTAL AQUIFER MANAGEMENT IN SEA LEVEL RISE SCENARIOS THE CASE STUDY OF AN ADAPTATION PLAN FOR THE MUNICIPALITY OF FANO

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EXTENDED ABSTRACT

Il modello di sviluppo sociale, economico e turistico del XX secolo lungo le fasce costiere ad elevata urbanizzazione, è in discussione in tutto il mondo, a causa dell'innalzamento del livello del mare dovuto ai cambiamenti climatici (sia su scala globale che locale). Un'importante alterazione transitoria sugli acquiferi costieri è dovuta al tasso di estrazione dai pozzi per acqua, concentrato durante la stagione estiva per soddisfare l'approvvigionamento idrico in risposta alla crescita della popolazione turistica, concomitante al massimo fabbisogno irriguo da acque sotterranee, e alla minima disponibilità di risorse di acque dolci fluenti dall'entroterra.

Prendendo spunto da queste criticità, nel contesto del Programma Interreg Italia-Croazia di cooperazione transfrontaliera dell'UE, il progetto ASTERIS (Adaptation to Saltwater inTrusion in sEa level RIse Scenarios) di durata biennale ha coinvolto un gruppo di partner italiani e croati, sotto il coordinamento dell'Università di Urbino "Carlo Bo" - Dipartimento di Scienze pure e applicate; per parte italiana, il Consiglio Nazionale delle Ricerche - Istituto di Geoscienze e Risorse della Terra, e i Comuni di Fano (Regione Marche) e Ravenna (Regione Emilia Romagna) e, da parte croata, il Centro Ricerche Metris, l'Istituto per le Colture Adriatiche e la Bonifica del Carso (IACKR) e Acque Croate.

Le fasi di lavoro WP3 "Modellizzazione presente e futura dell' intrusione salina nella costa adriatica" e WP4 "Identificazione del fabbisogno di barriere nella gestione degli acquiferi costieri" hanno portato alla definizione del WP5 "Pianificazione dell'adattamento", suddivisa in una rassegna di Buone-Pratiche, nella messa a punto di Linee Guida per gli interventi di adeguamento su scala regionale e di un prototipo di Piani di Adattamento locali, meglio sviluppati da ciascuno dei partner in ciascuna delle tre aree pilota di Fano (PU), Ravenna (RA) e della valle del fiume Neretva, nella Croazia meridionale.

Il piano di adattamento comunale organizza le azioni da realizzare in termini di uso sostenibile delle acque sotterranee, mirando a mantenere un deflusso di acqua dolce verso il mare, ridistribuendo i sistemi di pompaggio per abbassare la zona di interfaccia e creando barriere all'ingresso di acqua salata nell'acquifero costiero.

Le misure di adeguamento proposte, specificamente riferite alla città di Fano (PU), terzo comune della Regione Marche per numero di abitanti (circa 60.000 unità), sono distribuite spazialmente in base agli effetti idrogeologici attesi nelle diverse zone della falda acquifera costiera, e coinvolgono diversi gruppi di soggetti "portatori di interesse", gerarchizzati dal livello nazionale sino a quello municipale, e distinti tra pubblici ed istituzionali e privati, che svolgono ruoli-chiave nell'uso delle risorse idriche sotterranee: privati cittadini con pozzi domestici, utenze industriali e commerciali dipendenti dalle risorse idriche sotterranee, agricoltori, operatori turistici, perforatori di pozzi per acqua, associazioni di categoria, gestori del sistema idrico integrato, gestori di consorzi di irrigazione, pianificatori dello sviluppo dello spazio urbano, soggetti deputati al rilascio delle concessioni di derivazione da acque pubbliche.

Particolare cura è dedicata ai corpi idrici superficiali all'interno della città, in diretto collegamento con l'acqua di mare, esposti durante la stagione estiva alle infiltrazioni del cuneo salino verso l'entroterra, in regime idrologico di magra. In aree pilota selezionate per la loro rappresentatività sono progettati transetti di monitoraggio costituiti da allineamenti di piezometri-spia filtrati a profondità crescenti ed attrezzati per la registrazione in continuo dei livelli di falda e della conducibilità elettrica, identificando valori di soglia ai quali corrispondono opzioni gestionali specifiche. Con riferimento alla progressione dell'intrusione salina prevedibile nei prossimi decenni, l'"aggiornamento dinamico" del piano di adattamento appare il metodo più idoneo, supportato dall'osservazione sul campo.

Tramite successive ed approfondite fasi di discussione aperta in diverse sessioni tematiche e specialistiche, supportate dai risultati di due anni di monitoraggio idrogeologico e dai modelli numerici di simulazione di flusso e trasporto in falda implementati dai partner attivi durante le sessioni precedenti del progetto, si è pervenuti ad una selezione condivisa delle modalità di intervento più idonee per gli acquiferi costieri dell'alto Adriatico.

ABSTRACT

The work reported in this paper is part of a European Union project called ASTERIS and co-funded by the Interreg Italy-Croatia Cross-Border Cooperation Programme. The paper summarises the expected environmental changes resulting from North Adriatic sea level rise due to climate change, and the findings of a risk analysis of saltwater intrusion in coastal aquifers, at both regional and local scale.

Starting from this scenario, and through a review of best practices, we set up an adaption plan with a view to mitigating the environmental and socio-economic damage due to the expected increase in salinisation along the coastal aquifers in the municipality of Fano (Pesaro province, Marche region, Italy). The municipal adaptation plan identifies the actions to be taken for sustainable use of groundwater, i.e. maintaining freshwater baseflow towards the sea, relocating the pumping systems to lower the interface zone, and creating barriers to saltwater ingression. The suggested adaptation measures were spatially distributed on the basis of the hydrogeological effects expected in the different zones of the coastal aquifer. These measures involve different groups of stakeholders playing key roles in the use of groundwater resources: owners of domestic wells, industrial and commercial water users depending on groundwater resources, managers of integrated water systems, urban planners, farmers, and tourist operators. Particular emphasis was placed on surface water bodies inside the town, which are in direct connection with seawater and exposed to salt wedge seepage during summers. Monitoring transects and threshold values were established in selected test sites. With regard to the progression of the saltwater intrusion process in future decades, "dynamic updating" of the adaptation plan, supported by field observations, appeared to be the most suitable method.

Keywords*: salt intrusion, adaptation plan, best practices, monitoring transects, coastal aquifer management*

INTRODUCTION

ASTERIS (Adaptation to Saltwater inTrusion in sEa level RIse Scenarios) is a two-year project funded by the European Union (EU) Interreg Italy-Croatia Cross-Border Cooperation Programme. The project involves a group of partners from Italy and Croatia, led by the University of Urbino "Carlo Bo" - Department of Pure and Applied Sciences. The university acts as a coordinator for: on the Italian side, the National Research Council (CNR) - Institute of Geosciences and Earth Resources - and the municipalities of Fano (Marche region) and Ravenna (Emilia Romagna region); and, on the Croatian side, the Metris Research Centre, the Institute for Adriatic Crops and Karst Reclamation (IACKR), and Croatian Waters.

Completion of technical work packages WP3, "Modelling present and future salt intrusion in Adriatic coastal aquifers" and WP4, "Identifying needs and barriers in coastal aquifer management", made it possible to move to WP5, "Planning the adaptation", i.e. taking stock of best practices, defining guidelines for regional adaptation measures, and putting in place local adaptation plans, in each of the three pilot areas of Fano (Pesaro province), Ravenna (Ravenna province), and Neretva river valley (southern Croatia).

Important transient changes in freshwater distribution and availability, in response to sea ingression/regression phases (eustatic cycles), have periodically occurred over the geological timescale and, in particular, in the Quaternary. However, the rising sea levels due to global and local climate change have made it imperative to rethink the models of social, economic, and tourist development in coastal areas all over the world.

A significant stress factor for coastal aquifers is the rate of water abstraction from wells during the tourist season, to cover the increasing water demand caused by the seasonal influx of visitors. In the same period of the year, irrigation wells are used at their maximum discharge.

The paper summarises the final work package of the project – WP5, "Planning the adaptation" - the deliverables of which consist of guidelines, a review of best practices, and a local adaptation plan in a specific municipality: Fano (Pesaro province), the 3rd largest town in the Marche region (Italy) with about 60,000 inhabitants.

Based on systematic bibliographic research, we identified the most common and proven techniques of intervention at the Italian, European, and global scales. After a number of open discussions in various thematic and specialist sessions, supported by two years of hydrogeological monitoring and the application of numerical simulation models of flow and transport into the aquifer, the deliverables were shared with the Italian and Croatian institutional and academic partners involved in the project, and the most suitable intervention methods for the upper Adriatic coastal aquifers were selected.

LARGE- AND LOCAL-SCALE CLIMATE FORCING, EXPECTED EFFECTS, AND RISK ESTIMATION

The studies carried out as part of WP3 and WP4 led to the simulation of a scenario resulting from current climate change phenomena, in the absence of adaptation measures. Climate change (according to scenario RCP 8.5 of IPCC 2014) is associated with ice melting and both thermosteric and halosteric sea level variations.

In spite of the intrinsic limitations associated with the use of different statistical and deterministic physically-based models, it was estimated that, as a consequence of the above-mentioned

climate effects, there might be a sea level rise along the coasts of the North Adriatic sea of up to 80 cm in 2100, compared to 2015 levels.

WP3 developed a conceptual model for assessing the risk of saltwater intrusion (SWI) into the aquifers of the North Adriatic basin with a view to building future climate change scenarios. The assessment covered almost 2,000 km of coastline in three countries (Italy, Croatia, and the small portion of Slovenia facing the Adriatic coast) and took into account a variety of geological, morphological, and socio-economic factors. The salt ingression risk assessment required the building of a map of coastal aquifer vulnerability to salinisation at macro-regional scale (Adriatic) and another one at local scale, focused on the municipality of Fano. The maps were based on possible future scenarios of sea level rise and expected changes in the hydrological cycle: increases in temperature and potential evapotranspiration (ETP); decrease in the amount of water available for infiltration and thus in freshwater inflow towards the sea; higher frequency of dry periods; and concentration of heavy rainfall days.

Monitoring surveys carried out as part of previous activities revealed that the problem of SWI was not limited to groundwater, but extended to some important rivers. Indeed, the surface water bodies that were monitored showed higher than normal electrical conductivity (EC) values, indicating seawater ingression along riverbeds and as far as almost 4 km inland from the shoreline (Carbognin & Tosi, 2003).

The simulated scenario shows that, in the absence of adaptation and protection measures, the rise in sea level and storm surges will cause progressive shoreline erosion and retreat of the coastline.

The influence of sea level rise on SWI at local scale demonstrated to be variable, depending on a number of site factors, including hydrogeological and topographic/ morphological settings, local rates of groundwater extraction, and inland hydrological regimes.

CURRENT SALINE INTRUSION CONDITIONS THE PILOT CASE OF FANO

Different saline intrusion conditions were observed in the three pilot areas of the Neretva valley, Ravenna, and Fano.

The Ravenna area has a growing salt wedge along rivers and channels moving towards aquifers, while in the Neretva valley salt intrusion depends on its morphostructural setting and its impact on flow conditions (anisotropy in hydraulic conductivity), as well as on the reduction of freshwater discharge from submarine springs.

In the municipality of Fano, groundwater discharge was monitored on a seasonal basis in wells for multiple uses, (drinking, agricultural, domestic, and industrial water). The processing of the resulting data indicated that, at present, there are no significant criticalities in terms of SWI along the coast of Fano.

Electrolytic conductivity values proved to be variable during the year and to increase at the end of the summer season; however, they lay below alert threshold values.

Nevertheless, some "priority" risks emerged:

- uncontrolled withdrawals from multiple-use wells, especially agricultural ones;
- problems with structures and infrastructure along the coast, due to the rise of piezometric levels and corrosion by chloride-rich waters;
- lack of dedicated monitoring networks in areas close to the seafront (< 1 km from the coastline);
- high density of wells along the coast.

The plan of adaptation to Saltwater inTrusion in sEa level RIse Scenarios (ASTERIS) aims to support decision- makers in understanding, analysing, and communicating this specific risk in the municipality of Fano.

POSSIBLE SOLUTIONS FOR THE ADAPTATION PLAN IN THE FANO AREA

The proposed adaptation plan is focused on actions aiming to mitigate "priority" risks, namely:

- growth of groundwater level and soil saturation along the coastline in the coming decades, and
- degradation of groundwater quality by salts, which threatens water abstraction from wells, human settlements, and related activities (corrosion of technological networks and underground structures of buildings, soil salinisation, and potential loss of crops).

Considering the local vulnerability factors mentioned above, we designed a strategy of adaptation targeted at the municipality of Fano, but methodologically related to those built for the other "focus zones" of Ravenna and the Neretva valley (Croatia). The strategy involves both "soft" options (e.g. sustainable groundwater use on the inland, to promote sufficient recharge of freshwater towards the coast) and "hard" options (e.g. physical/hydraulic barriers, artificial progradation and redesign of the coastline, desalinisation and wastewater reuse) in areas close to the seafront.

Adopting a "precautionary principle" to take into account the uncertainty of the scenarios designed by environmental modellers, we proposed an array of complementary actions, tested in Europe and other parts of the world, which could foster opportunities and generate multiple benefits.

The adaptation plan provides a framework of actions, whose importance is related in space and time to the severity of SWI and which concern management aspects, physical structures, land reclamation or fillings (Fig. 1). The spatially distributed actions have specific relevance in terms of hydrogeological effects, and their timescale is based on progression of SWI and prevention of expected losses/damages (Fig. 2).

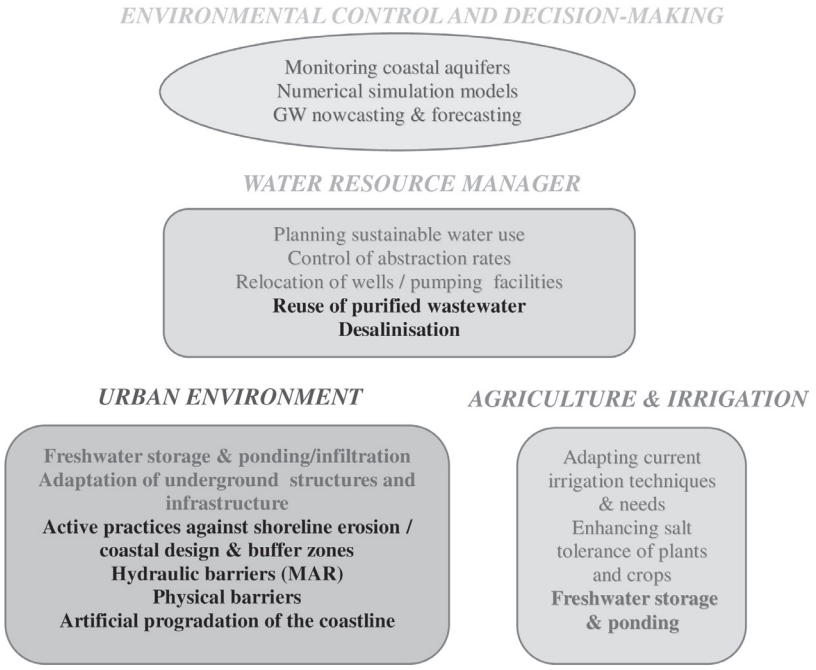

Fig. 1 - Framework of actions provided in the local adaptation plan and key-sectors

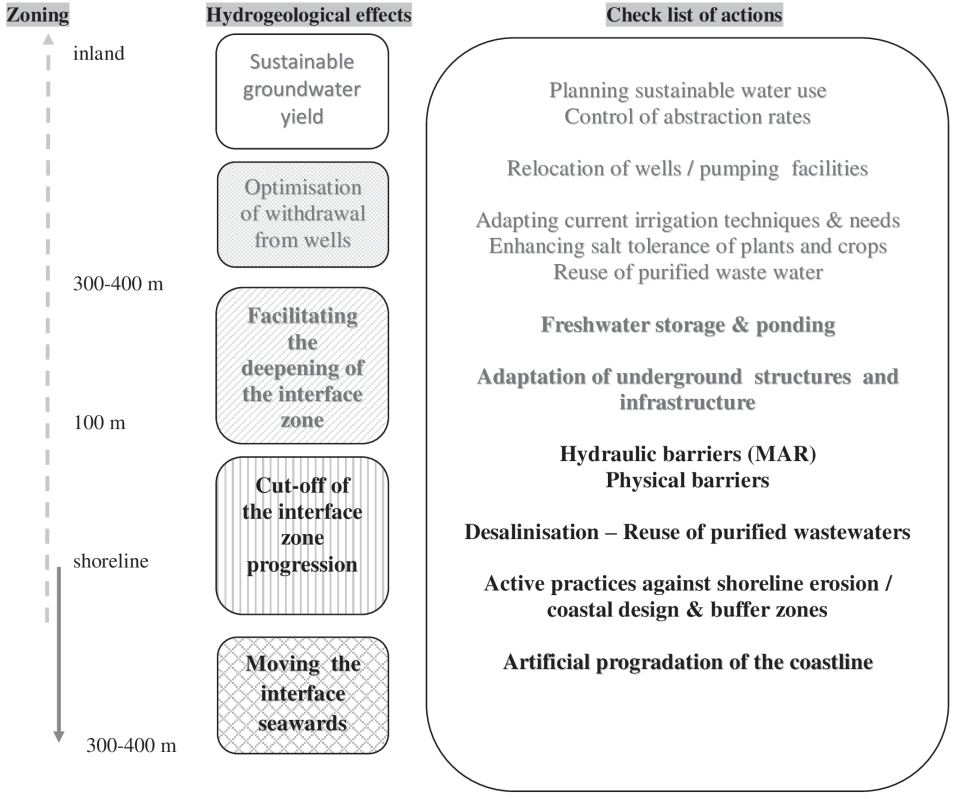

Fig. 2 - Zoning of actions and hydrological effects provided in the local adaptation plan

Test sites, environmental control and decision-making

Adequate knowledge of the local setting is crucial for optimising the planning of the required actions. Integrated systems for monitoring coastal groundwater resources (aquifer phreatimetry/pressure, salinity, hydrochemical and physical characteristics of water - isotopes, age, temperature, tidal measurements, geophysical measurements), combined with numerical simulation models of flow and transport processes, are essential for acquiring a deeper understanding of the response of aquifer systems to natural and anthropogenic influences, and for assessing and predicting SWI evolution (Mastrocicco *et alii*, 2012).

To this end, some pilot areas were selected. These areas will be equipped with continuous monitoring systems placed along significant coastal transects - a transect is an ideal line orthogonal to the coastline, along which zonation of the expected SWI risk level can be carried out (Fig. 3).

Monitoring devices will be installed along each transect, between the exposed beach and the inland area. Test sites were selected on the basis of various considerations (types of land use, solutions to be tested) in order to:

- investigate the mineralisation of aquifer levels at increasing depths, by discriminating the nature and origin of saline waters via isotope (and age) analyses;
- monitor the interface and SWI evolution after adopting "best practices" (increase or decrease of salinisation).

Continuous monitoring along the transects, coordinated by local and regional environmental control and decision-making entities, will make it possible to study the short- and long-term oscillations of the parameters to be investigated and thus to determine within a reasonable timescale whether the recorded values exceed risk thresholds (Tab.1, Tab.2).

To promptly identify the real or potential impact of saline intrusion, control thresholds were proposed for:

- specific electrical conductivity (EC), as a parameter representing mixing water salinity;
- piezometric level, as a parameter representing flow into the interface zone.

The above control thresholds should not be taken as absolute operative indications, but as warning levels to be considered alongside appropriate quantitative analyses of both flow and transport into the aquifers.

Upon reaching the thresholds, warning systems will be activated and appropriate measures will be taken, for example more detailed investigations, suspension of the use of specific groups of wells, and activation of hydraulic barriers.

POTENTIAL IMPACT	EC - Specific Electrical Conductivity µS/cm
HIGH	>5000
AVERAGE	3500-5000
LOW	2000-3500
NONE	<2000

Tab. 1 - Proposed salinity thresholds with related potential impact

POTENTIAL IMPACT	Piezometric level (m above sea level)
HIGH	<0 (static)
AVERAGE	<0 (dynamic)
NONE	>0 (dynamic)

Tab. 2 - Proposed piezometric level thresholds with related potential impact

Water resource management

Planning is an important aspect of water resource management. Priority should be assigned to the conservation of fresh groundwater bodies for key uses, by encouraging alternative forms of water supply for less significant uses. Several best practice procedures have been proposed to reduce and optimise water abstraction rates (possibly by reviewing water concessions and introducing limitations to the use of deep wells), to relocate wells and pumping facilities, or to put in place a programme of decommissioning for wells severely impacted by saltwater intrusion. Additional measures involve increasing the frequency and decreasing the duration of well pumping ("well sipping") to minimise drawdown in wells and surrounding aquifers, or shifting pumping schedules in nearby wells (Bear *et alii*, 1999).

Urban environment management

Measures of adaptation to saline intrusion in urbanised environments represent challenges that can be promoted by both public and private sectors, in cooperation, to raise awareness of the issue.

These measures (Fig. 4) will provide guidance for urban policies, in line with the strategic plan document "Fano 2030", the priority goal of which is the creation of a "green crown". The document stresses the need for furthering reforestation actions and policies, creating greenways and a higher number of rest areas made of environmentally friendly materials, and improving the urban environment by using urban gardens (Comune di Fano, 2018). These goals are in good agreement with the adaptation solutions that we proposed.

In an urban environment, it is essential to focus attention on the protection or adaptation of the existing infrastructure and therefore on the implementation of saltwater intrusion response measures.

As regards the adaptation of underground structures and infrastructure, the first actions to be taken by the managers in charge are as follows: systematic inventory and field mapping (with video inspections), preceded by archive research, in order to acquire a comprehensive knowledge of the features of networks and materials. Subsequently, based on these preliminary activities, a remediation programme should be set up, in order to replace (if

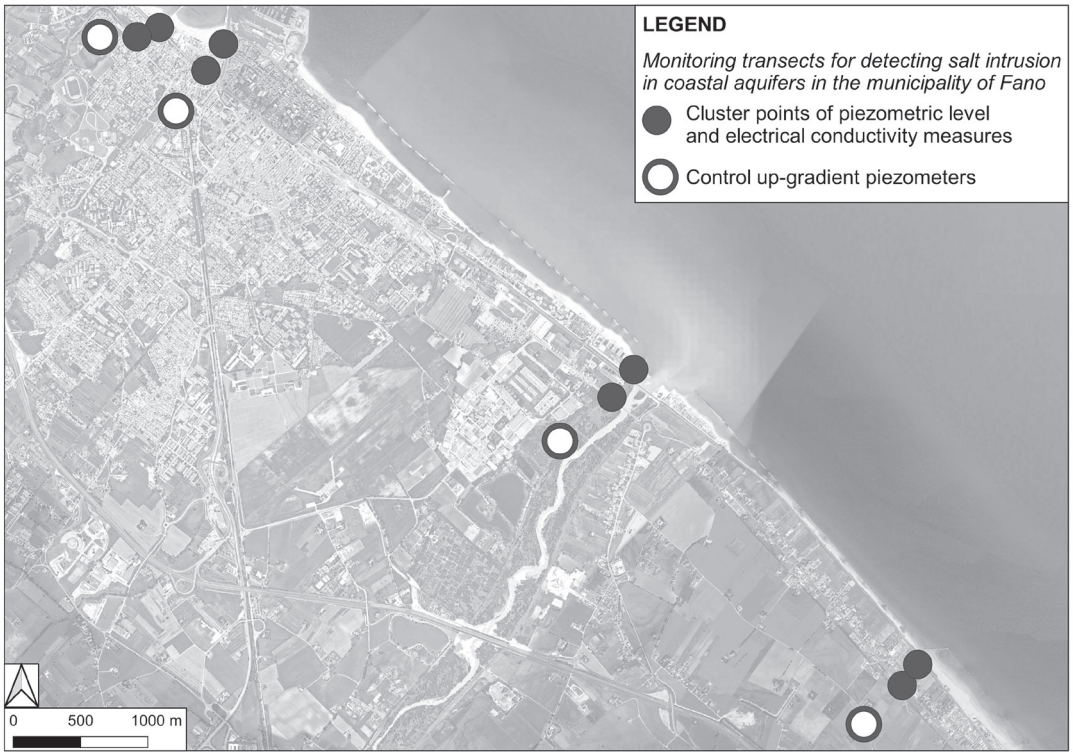

Fig. 4 - Monitoring transects for detecting salt intrusion in coastal aquifers in the municipality of Fano

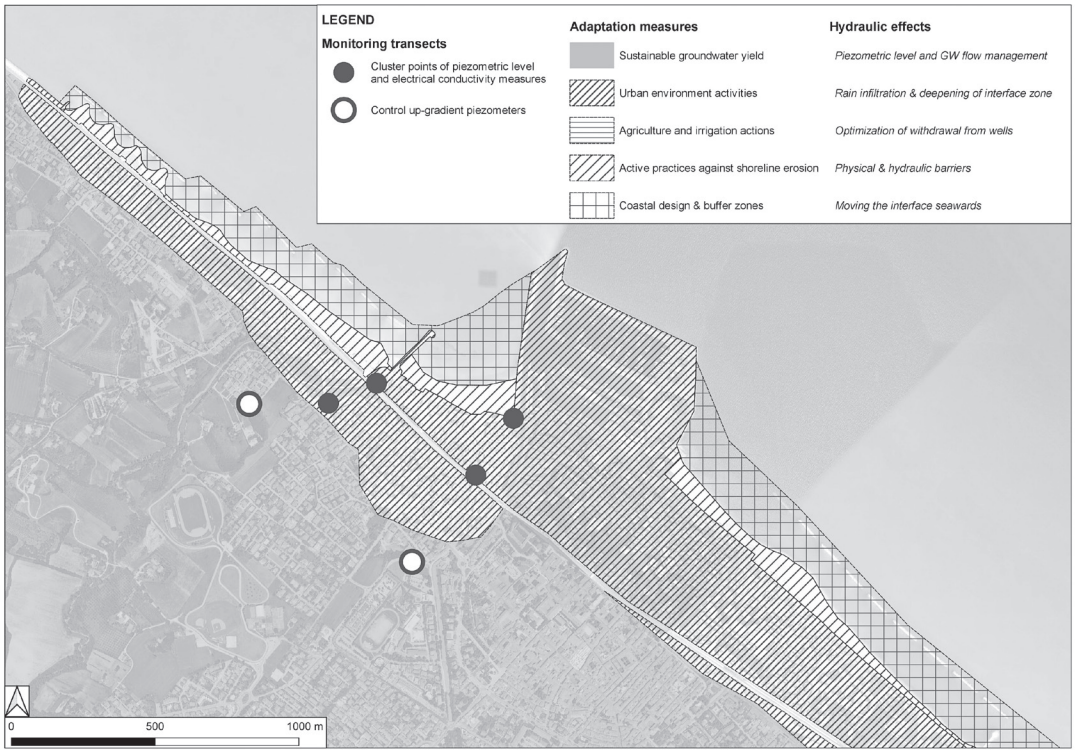

Fig. 4 - Map of proposed adaptation measures and related hydraulic effects

necessary) existing materials with other materials more resistant to saltwater corrosion.

In the coastal lowland zone, which is subject to continuous urbanisation extending as far as the waterfront, it is necessary to maximise the infiltration rate of surface (rain) water and facilitate the deepening of the interface zone, by collecting rainwater, rather than allowing it to run off, storing it by using roof-like surfaces, and redirecting it into tanks, cisterns, wells, pits or holes.

Coastal engineering structures, coupled with regeneration of on-shore ecosystems and green redevelopment of coastal areas can mitigate the impact of salt intrusion phenomena.

Hydraulic barriers, consisting of lines of recharge or extraction wells (or coupled systems) contribute to controlling saltwater intrusion (De Filippis *et alii*, 2019). Specific knowledge is already available within the municipality of Fano, although the main purpose of its Managed Aquifer Recharge (MAR) system is to dilute nitrate pollution in the Metauro aquifer system; as regards power consumption, it is desirable to adopt solutions with low-emission pumping systems (e.g. solar powered pumps).

Especially in the case of confining layers, it should be possible to inject freshwater during the wet season and then pump in the dry season; the percentage of water extracted for suitable use with respect to the injected volume defines the Coefficient of Performance (COP) of the system (Hussain *et alii*, 2019).

Physical barriers may be necessary close to the shoreline, both on the land surface – specifically to regulate river flows and sea ingression during storm surges, and to ensure protection of the most exposed and non-removable structures (Barlow, 2003; Carbognin *et alii*, 2005), and underground - to cut off the interface zone with diaphragm walls (Abdoulhalik *et alii*, 2017; Armanuos *et alii*, 2020; Hussain *et alii*, 2019).

A "harder" action of prevention of progressive sea level rise might consist of artificially prograding the coastline seawards and maintaining the newly emerged land at or near the surface or in shallow water, taking into account the related impact on the aquatic environment (Hussain *et alii*, 2019). The new coastal land would also act as an important buffer zone for storm surges and as a wetland ecosystem (U.S. EPA, 2009).

Rural and agricultural environment management

In rural areas, adaptation means putting in place new policies for water resource management and land use.

With regard to the use of water resources, it is necessary to encourage alternative forms of water supply, with the combined use of surface and groundwater and the possible relocation of wells in coastal areas. In rural areas, reliance should also be made on rainwater management systems, which could accumulate and then release freshwater into the subsoil ("rain harvesting and ponding" techniques); these systems could use "bank or dune filtration" and "infiltration galleries or ponds" to facilitate the storage of runoff water and its infiltration into aquifers (Shamrukh, 2006).

As concerns the management of irrigation networks, attention is focused on the use of innovative and technological irrigation systems and on adequate land-use planning (Kenneth *et alii*, 2002). The application of advanced crop-growing techniques can limit the use of water for irrigation to the amount necessary to sustain the soil-crop system only during peak production periods. Macro-sprinkling irrigation with new generation pivots, sprinkler irrigation, and sub-irrigation are techniques that enhance the efficiency of water use and reduce the amount of water required, by relying on dedicated pipelines and systems for reusing wastewater (Foster *et alii*, 2005).

In parallel, it is essential to develop a land use plan introducing reasonable shifts in agricultural practices and, above all, the use of plant and crop species that are tolerant to increased salt concentrations.

CONCLUSIONS

The risk of saltwater intrusion into coastal aquifers is mentioned in the Italian law on environmental protection (Legislative Decree no. 152/06). Article 96 of the decree stipulates that groundwater abstraction and recharge must be balanced with a view to avoiding the risk of intrusion of salt or polluted waters. The EU - Interreg ASTERIS project is focused on this type of risk, with its discretisation at regional scale (North Adriatic basin) and local scale (municipality of Fano) based on a scenario of expected sea level rise of 80 cm in 2100 compared to 2015 levels (IPCC AR5 RCP 8.5).

In this paper, we have proposed a wide spectrum of measures, based on "vulnerability zoning" criteria:

- prevention measures in low-vulnerability coastal areas, with the purpose of postponing the impact of groundwater salinisation;
- mitigation measures in average-vulnerability coastal areas, accepting a certain degree of salt intrusion into coastal aquifers, but trying to minimise its impact on and overall damage to the socio-economic and environmental system affected by groundwater salinisation;
- remediation and countering measures in high-vulnerability coastal areas, namely those close to the seafront, trying to restore the socio-economic and environmental system affected by groundwater salinisation.

The adaptation plan for the municipality of Fano is founded on the management of coastal aquifers through numerical modelling of flow and salt transport into them, supported by piezometric level and EC monitoring data. The plan is intended to provide support to strategic planners in implementing a number of prevention, mitigation, and remediation measures in the urban, agricultural, and natural environments.

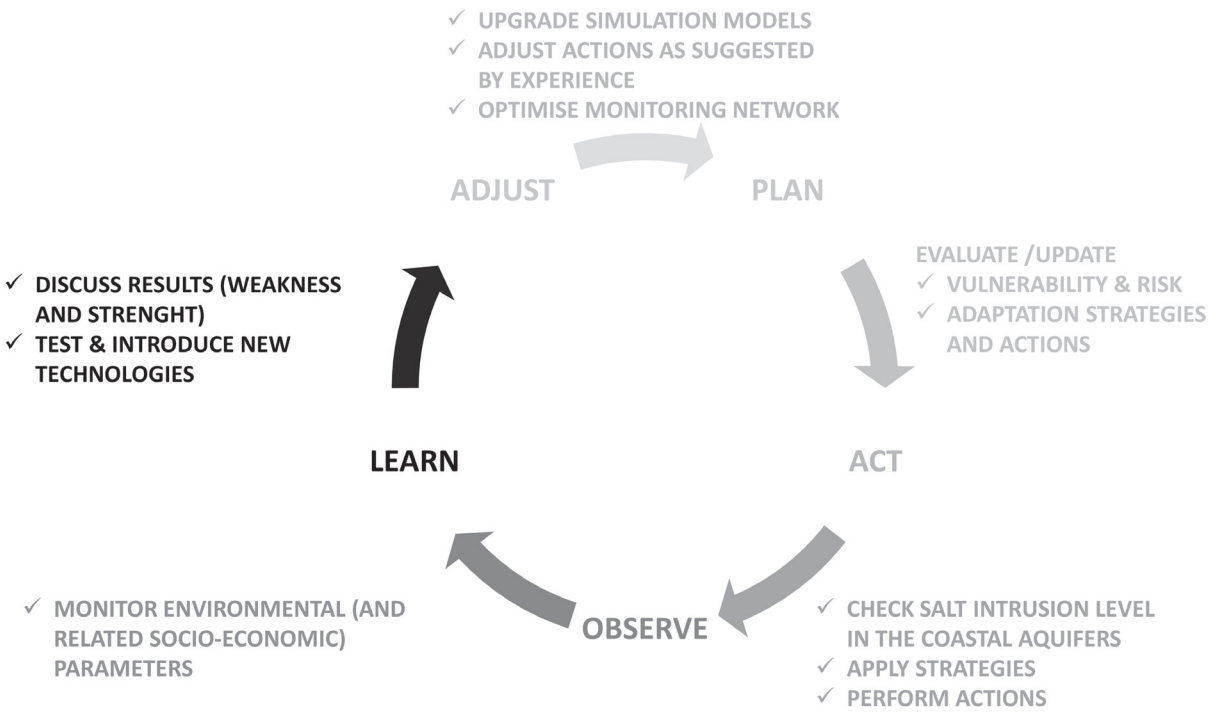

Fig. 5 - Monitoring, evaluating and optimising the adaptation plan process

Within a management horizon of some decades, the implementation of the adaptation plan should be monitored, evaluated, and optimised through a continuous adjustment process (Fig. 5); field testing of new technologies, upgrading and mesh-refining of simulation models, and implementation of best practices based on experience will be key aspects of this process.

In implementing its adaptation plan, the municipality of Fano should move from incremental to transformative and, possibly, community- and ecosystem-based changes in its local system with a view to building socio-economic and environmental capacity to mitigate the adverse effects of climate change.

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