D.5.2.1. Guidelines for adaptation measures

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INDEX

1. Introduction

This report has the purpose to provide, in the overall of hydrogeological patterns and climate change scenarios, general indications for planning the adaptation measures.

To this end, after framing the current salinization risk in the context of climate change effects, passing through a review of adaptation styles, a gradation of the measures correlated to the territorial vulnerability towards the phenomenon is proposed, applicable in a wide range of situations.
These measures refer to the best practices described in D.5.1.2 of the Asteris project.

Further considerations concern the limitations of adaptation planes and the role of heterogeneity in coastal aquifers and uncertainty estimation.

2. The geological perspective

The coastal regions are one of the most dynamic geological environments, resulting from the interaction between tectonic, erosional, depositional and geochemical phenomena on one side, and climate changes and sea level fluctuations on the other side.

The better understanding of present situation (and related risks), in terms of salt intrusion processes, may be usefully framed not only into a short-time period (or in an instant-reference year), but keeping in mind the geological scale, concerning the most recent geological time-table units (period/epoch) conditioning the evolution of the Adriatic basin; specifically, from the Neogene to Quaternary, from Miocene to Holocene.

Our knowledge of aquifer system subject to withdrawals needs to be enhanced in terms of boundary conditions and extended chronologically at least to the post-LGM (Last Glacial Maximum) period, since the actual status of groundwater resources (in terms of water availability, production potential and quality levels) „brings the memory“ of the preceeding sea transgression and recession cycles.

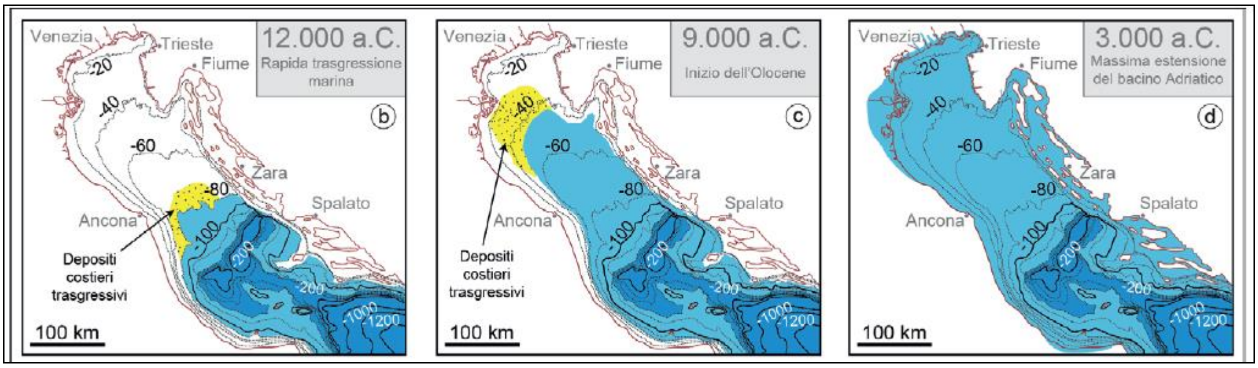

Figure 1: Adriatic basin evolution during several phases between LGM (Last Glacial Maximum) and Olocene (from: A. Fontana et al, “Paesaggi sommersi in Alto Adriatico dalla pianura glaciale al futuro innalzamento marino”; Palinsesti programmati nell’Alto Adriatico? Atti della giornata di Studi Venezia, 18 aprile 2019)

For example, the effects of transgressive marine phases recorded in North Adriatic Sea caused the occurrence of a “fossil” paleo-salt wedge into the aquifer, now isolated at a great distance from the actual coast-line, as showed in the next picture (refer to “Cona” zone). Locally, the “Channel of Cuori” actually acts on the contrary in a positive way with seepage of irrigation waters.

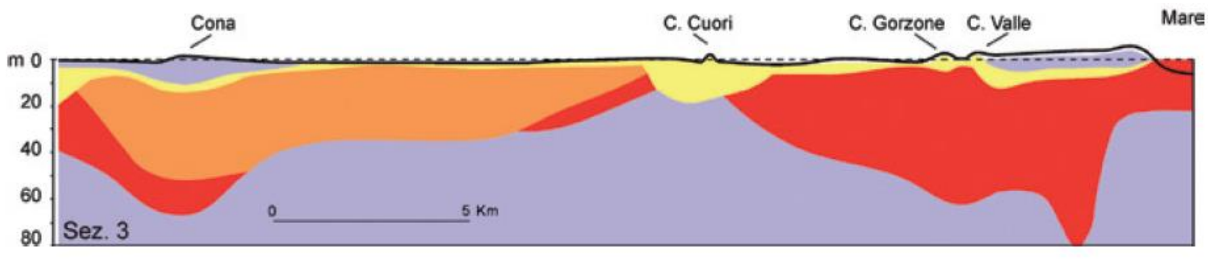

Figure 2: Distribution of groundwater facies across W-E cross section, south River Brenta estuarine zone (legend: red = salt water, orange = brackish, yellow = seasonally variable, gray = freshwaters); from: L.Tosi et alii „Atlante geologico della provincia di Venezia“ – chapter 17, ISPRA, 2011).

3. The “anthropogenic” perspective

The Adriatic coastal regions have known, in a different way on the western and eastern coasts, important (locally drastic) changes in land use and related use of (ground)water resources in the last centuries.

The regulations of surface river flows, also by dam constructions, has significantly changed the sediment transport balance along the rivers to the coast, inducing widespread erosion of the coastline.

Especially from the second world war, urbanization of the coastal area led to a strong increase of paved areas, decreasing infiltration rates, increasing groundwater abstractions for human use, industrial and irrigation purposes.

These stress factors occur in a concentrated time interval, if compared with the natural transient processes of salt intrusion phenomena in groundwater, distributed at the geological time scale.

An important stress factor on coastal aquifer is the abstraction rate from wells during the touristic season, in order to satisfy the increase of demand for water supply to the suddenly growing population. In the same period of the year, irrigation wells too are used at maximum discharge.

In this context, the WP3 projection indicate a sea-level rise to the year 2100 of almost 80 cm referred to present (2105) sea level, and, according to scenario of climate change RCP 8.5 of IPCC 2014, significant growth of dry periods and concentration of rains during a few days with short-intense precipitations.

The expected temperature growth will increase ETP too, reducing rainwater available for infiltration, thus limiting freshwater inflow toward the sea.

4. Groundwater salt intrusion: typical patterns

4.1. Fluctuations of the fresh/salt water interface

The movement of saline groundwater into aquifers is determined by the relative height of piezometric level and by the gradient of density between lighter freshwater (flowing to the sea through the seepage face) and heavier sea saline water, underlying the freshwater. The 'interface' zone is a diffuse zone of mixing between fresh and salt water.

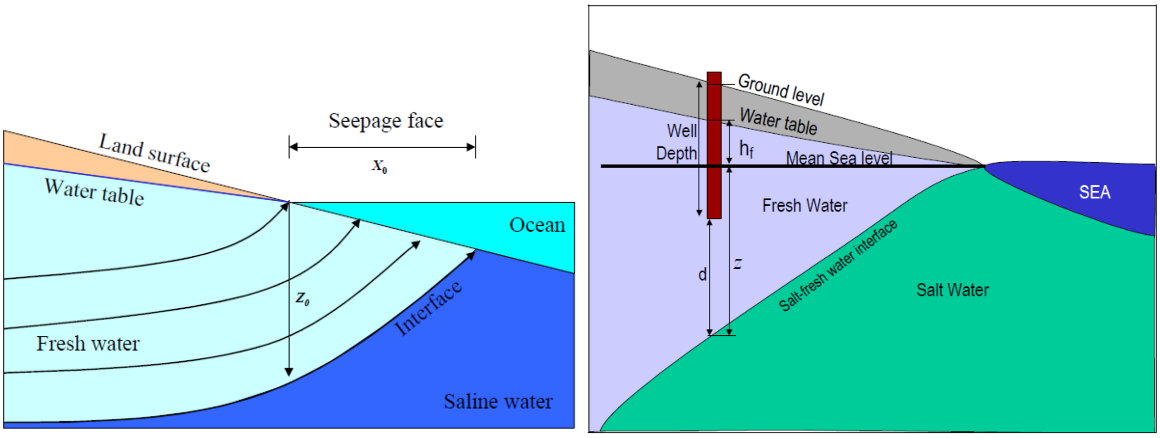

Figure 3: Lateral flow in a coastal aquifer (from "Coastal aquifer saltwater intrusion assessment guidelines". Report No. R04/18 ISBN 1-86937-543-2. Philippa Aitchison-Earl & alii, November 2003)

This movement is controlled by a number of driving forces of very different origin and time scale, varying from fluctuations of sea level due to eustatic cycles, glaciostatic rebound, subsidence (of natural and anthropogenic origin), but also tides and sea storm.

4.2. Upconing

Upconing is the conventional term used to describe the formation of a reverse-cone of salt water, as an effect of pumping in wells that causes the saltwater to move upwards towards the well.

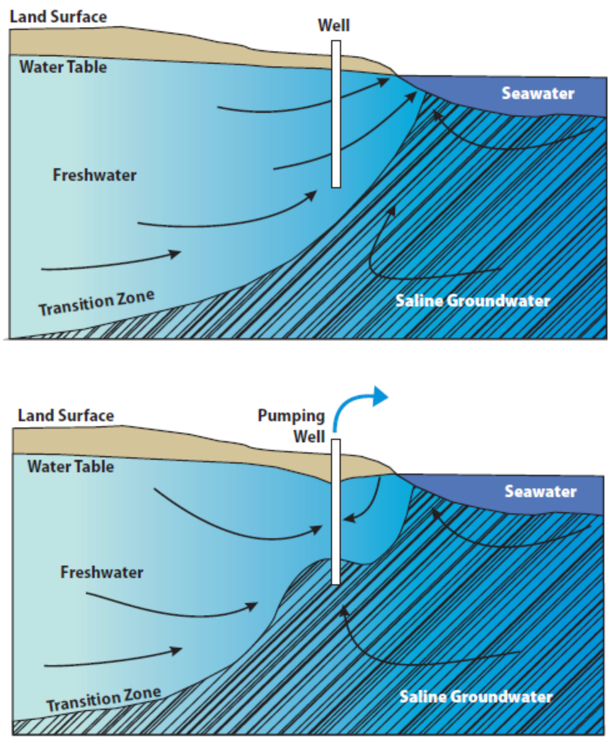

Figure 4: Upconing scheme (from Best Practices for Prevention of Saltwater Intrusion, British Columbia, March 2016)

Typical evidence for saltwater intrusion is a distinct rise in concentrations of TDS, chloride concentrations and high electrical conductivity of groundwater, coincident with pumping or low groundwater levels in proximity to the coast.

4.3. Salt wedge in rivers

The salt wedge in rivers is controlled by the discharge rate into estuaries and the coastal margin of rivers, and by tidal effects.

During dry season with long-lasting low-flow conditions (or sea storm), it could move inward for several kilometres, depending by the morphology of the inland.

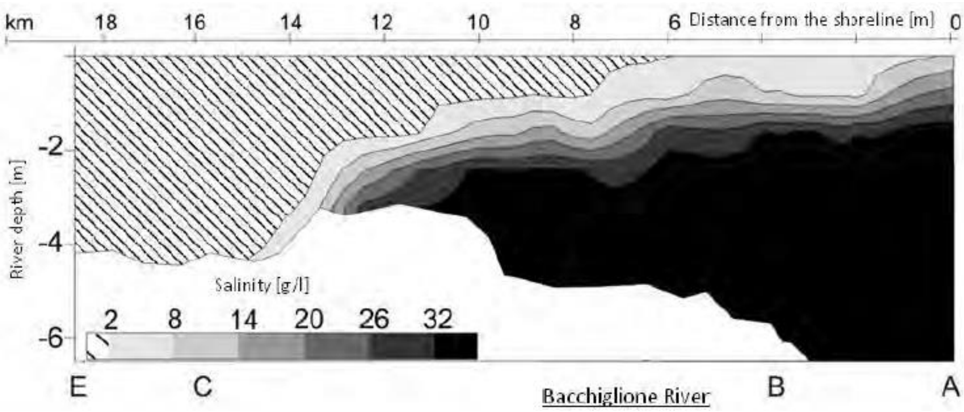

Figure 5: Example of salt wedge in Bacchiglione River, summer 2003 (from: Gasparetto Stori G. et al., 2005: L'intrusione salina nel comprensorio lagunare veneziano. Il bacino meridionale, Giornale di Geologia Applicata 2, p. 119-124, 2005).

Depending by the hydraulic conductivity of the riverbed, the salt water could migrate from the stream into the adjacent aquifer; aquifer salination in this case is due to vertically infiltrating transgression water.

5. Adaptation styles

The adaptation styles, designed as a response to aquifer stresses induced by sea level rise and salt intrusion could be very different, as result of a complex function of environmental, socio-economic and politic factors. Among them, it is possible to recognize at least the following "end-members".

- Incremental

Adaptation actions where the central aim is to *maintain the essence and integrity* of a system or process at a given scale.

- Transformational

Adaptation that *changes the fundamental attributes* of a system in response to climate and its effects.

- Autonomous

Adaptation in response to experienced climate and its effects, *without planning explicitly or consciously* focusing on addressing climate change (also referred to as spontaneous adaptation).

- Community-based

Local, community-driven adaptation that focuses on empowering and *promoting the adaptive capacity* of communities.

- Ecosystem-based

The use of *biodiversity and ecosystem services* as part of an overall adaptation strategy to help ecological, social, or economic systems adapt to the adverse effects of climate change.

- Maladaptation

Actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future.

The choice of the adaptation styles could derive from a mixing of the above descripted; in any case, it is relevant – for the decision maker at the public-administrative and strategic level - the degree of awareness of the choice.

6. Indications for planning the adaptation measures

6.1. PREVENTION MEASURES (LOW VULNERABILITY)

Prevention measures are optimal to be applied in the inner zones of coastal area, where salt intrusion is not yet detectable, but – at the same time – where the maintenance of the best quantitative and hydro-chemical good state of the aquifer is a key-strategy, in order to guarantee the highest groundwater flow and positive hydraulic gradient toward the shoreline.

Prevention measures have the purpose of obtain a DELAYED IMPACT on groundwater salination.

In these areas, the static (non-pumping) groundwater level is above sea level.

Among these measures we can recognize:

- limitations of impermeabilization - allowing maximum recharge rate to groundwater bodies;
- monitoring of piezometric trends - in order to check dynamic balance between recharge and abstraction rates, supported and integrated by numerical simulation model of aquifer flow in transient conditions (nowcasting & forecasting);
- diffuse introduction of any kind of technological solution for water saving.

6.2. MITIGATION MEASURES (MEDIUM VULNERABILITY)

Mitigation measures are needed in the intermediate zones of coastal area, where aquifer salt intrusion has already took places and/or denotes transient stages, with still reversable features.

In these areas, one or more of these features can be found:

- a low to moderate slope,
- a limited source area for groundwater recharge,
- a high density of wells
- high rates of pumping from a single well (or from multiple wells)
- the static groundwater level is at or below sea level; hydraulic gradient are very low.

Mitigation measures accept the possibility of a certain degree of salt intrusion into the coastal aquifer, trying to obtain a REDUCED IMPACT on the socio-economic and environmental system involved by groundwater salination, through limitation of overall damage.

The purposes of the measures in this zone, that could be extended inland several hectometers up to some kilometer (depending from geological history and morphological conditions) are oriented to reduce the entity and impact of the phenomena, with the objective to

- reduce global groundwater use, introducing systematic options and BAT - Best Available Technology - for water saving;
- groundwater pumping rearrangement (in terms of wells positioning, limitations of deepening and of pump depth, taking into account the expected – and monitored – position of the transition zone according to physically based formulas);
- reduce (seasonally, daily) abstraction rates from wells and shift pump-times in nearby wells;
- increase the frequency and reduce the duration of well pumping ("well sipping") to minimize drawdown in the well and the surrounding aquifer;
- setting-up a decommissioning program of the wells severely impacted by saltwater intrusion, after a trial period of discontinue using (and water supply with alternate sources), allowing level recovery;
- facilitate infiltration, ponding and storage of surface runoff; introduce rain harvesting;

Other measures are complementary to the listed above, and include:

- adaptation of underground structures and infrastructures to future saturation conditions in the soils, in contact with salt water having a high corrosive potential;

- adapting current irrigation techniques & needs; enhancing salt tolerance of plants and crops;
- active practices against shoreline erosion / coastal design & buffer zones.

6.3. OPPOSITION/REMEDIATION MEASURES (HIGH VULNERABILITY)

In the front-see zone (up to some hecto-meter), with the highest degree of vulnerability to salt intrusion because of the expected sea level rise, two opposite options can be considered:

- “zero-option” - let the salt intrusion progress into the aquifer, causing corrosion of structures and infrastructures in the aquifer under interface zone, loss of crops irrigated by wells and degradation of forests with low salt tolerance;
- “opposition measures” - trying to obtain a REMEDIATION OF IMPACT affecting the socio-economic and environmental system involved by the groundwater salination.

This second kind of measures refers to hard-engineered structures in surface waters (physical barriers such as flood gates, dikes, levees, and valves) and groundwater (physical barriers such as diaphgram walls, hydraulic barriers); physical barriers should be continuous along urban areas, without breaks.

Another measure, with important potential impact on seawater environment, consists of land reclamation, moving seaward the coast-line and designing a new landscape adapted to salt conditions; its feasibility should be considered through a systematic sedimentological approach and modelling of sediment transport along the rivers and the coasts.

7. Limitations of adaptation

The guidelines described in the above chapter represent an attempt to achieve transient and dynamic conditions of adaptation, as responses of the environmental and socio-economic context in the coastal zone to the progression of salt intrusion into the aquifers.

It should however be always kept in mind that limitations to adaptations measures are intrinsic with the methods used.

Maybe useful classify limitations between two end-members:

- a “hard” limit implies that no adaptive actions are possible – for instance, in relation to natural or physical factors that cannot be modified (e.g. – prograding deltas with high subsidence rate).

- a “soft” limit implies that adaptation options are not yet available but could be available in future through new technologies or changes in laws, institutions, or values, because it mainly depends on human factors.

The man-activities related to groundwater use, or conditioned by their availability and chemical status, will follow a constant change with respect to present conditions.

The rate of adaptation of the coastal population and economic systems to these changes will have to be foreseen, making the limits explicit.

8. The role of heterogeneity and uncertainty estimation

The understanding, planning and modelling of measures oriented to prevention, mitigation and contrast to salt intrusion into coastal aquifers needs to take in account for the heterogeneities at the local scale. The geological complexity of seaside regions is often simplified in the regional-scale approach, and only the dominant units and structures are considered, even if geological features (e.g. buried valleys due to paleo-evolution by sedimentation of Holocene deposits and variation in the river system) may provide preferential flow paths for salt water.

The correct understanding of exchange of salt water between sea and aquifers should be preliminary supported by a detailed description of the coastal geology.

The forecasting hydrogeological simulation models require one initial condition of salt (TDS), chloride concentration or electric conductivity; even if it could be detected through monitoring operations in selected wells integrated with geophysical data, experiences in literature show that the density-driven flow into the aquifers has a transient character and equilibrium conditions are very slow to be reached (also in the order of magnitude of thousands years), especially in the case of low-permeability layers interbedded to higher conductivity horizons.

Sensitivity analysis is therefore extremely important in order to have confidence interval of the results, related to hydrogeological parameters, recharge, dispersivity.

Validation of the models should be supported by determination of groundwater age (^{14}C), and, whenever significant and possible, by aerial geophysical data such as AEM surveys (time-domain Aerial ElectroMagnetic).

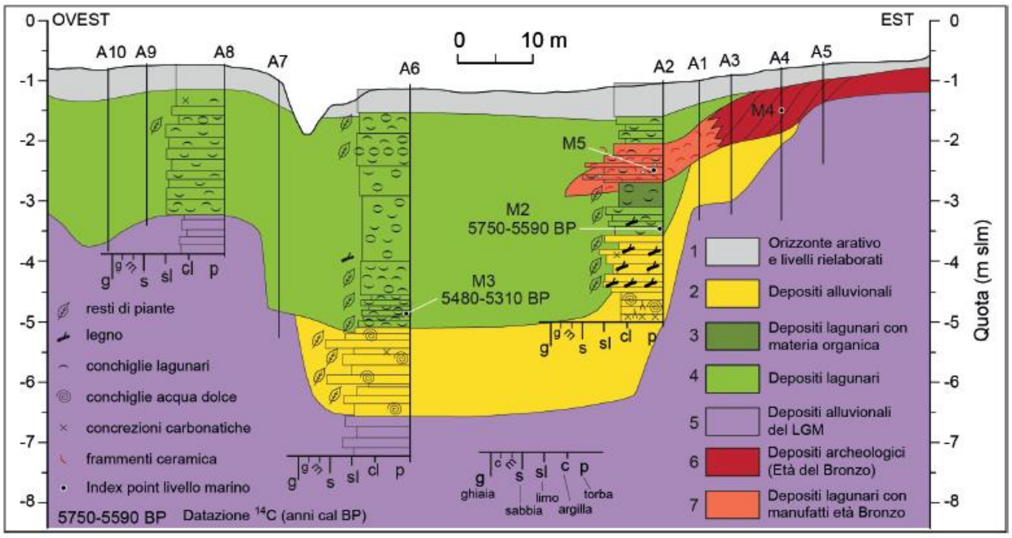

Figure 6: Example of relevance of depositional heterogeneity structures in the coastal zone (from: A. Fontana et alii, "Paesaggi sommersi in Alto Adriatico Dalla pianura glaciale al futuro innalzamento marino"; Palinsesti programmati nell'Alto Adriatico? Atti della giornata di Studi Venezia, 18 aprile 2019).