Strategies for deep aquifers protection at local and regional scale: the Piedmont region example

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Deep aquifers represent a strategic resource because of their quality, generally better than rivers and shallow aquifers. More specifically, in Piedmont Region (Italy) they represent a key source of drinking water and therefore must be protected from qualitative and quantitative degradation.
In this paper, the main strategies that can be implemented for the protection of deep aquifers are resumed. Moreover, the current application of these strategies in Piedmont Region is reported, as a virtuous example of management and protection of water resource.
Keywords: *groundwater monitoring, deep aquifers, mixing well, overexploitation, contamination, Italy.*

Strategie per la protezione degli acquiferi profondi a scala locale e regionale: l'esempio della Regione Piemonte. *Gli acquiferi profondi rappresentano una risorsa strategica a causa della loro qualità, generalmente migliore di quella di fiumi e di acquiferi superficiali. In particolare, nella Regione Piemonte (Italia) gli acquiferi profondi rappresentano una risorsa chiave per l'approvvigionamento dell'acqua potabile e pertanto devono essere protetti dalla degradazione qualitativa e quantitativa.*
In questo lavoro vengono riassunte le principali strategie che possono essere adottate per la protezione degli acquiferi profondi. Inoltre, come esempio virtuoso di gestione e protezione delle risorse idriche, vengono riportate le attuali applicazioni di queste strategie nella Regione Piemonte.
Parole chiave: *monitoraggio della falda, acquiferi profondi, pozzi miscelanti, sovrasfruttamento, contaminazione, Italia.*

1. Introduction

Directive 2006/118/EC (European Commission 2006) established that groundwater is a valuable natural resource and should be protected from deterioration and chemical pollution. This is particularly important for the use of groundwater in water supply for human consumption. This Directive was implemented in Italy with Legislative Decree 30/2009 (Gazzetta Ufficiale 2009), in which it is reported that groundwater bodies, used for the extraction of water for human consumption, are subject to protection in order to prevent their quality deterioration.

In the plains subsurface, different aquifers can be recognised, more or less communicating in relation to the geological structure. More specifically, the term "shallow aquifers" refers to aquifers closer to the soil surface, with a local and short groundwater flow system. These aquifers generally have a depth from 20 to 80 m, depending on the hydrogeological structure and the recharge from the surface. Limits are imposed by local topography, hydrographic network and lakes. The influence of climatic zones is significant.

More deeply, groundwater generally belongs to deeper flow systems (Toth 1963) and it is contained in confined or semi-confined aquifers. These systems have an intermediate or regional significance and long flow circuits, where flow conditions are imposed by regional topography (e.g. large axes of the reliefs), large hydrographic axes, great lakes, oceans and inland seas and endorheic depressions of the arid zones. The role of structural geology is, in this case, preponderant.

According to Piedmont Region law 22/1996 (B.U. n.19 del 08/05/1996) and subsequent amendments, the aquifers of Piedmont Region (NW Italy) located underneath a shallow aquifer can be called "deep aquifers". Because deep aquifers typically serve as key sources of drinking water in Piedmont, they have to be mostly protected. Indeed, deep aquifers have generally a better quality than watercourses and shallow aquifers (Lasagna *et al.* 2016) being less vulnerable to contamination. In addition, they are less subject to level fluctuations due to factors such as climate change.

In this paper, the main strategies that can be implemented for the protection of deep aquifers are resumed. Moreover, the current application of these strategies in Piedmont Region is reported, as a virtuous example of management and protection of water resource.

2. Improving the knowledge of hydrogeological systems

Any effective strategy for the deep aquifers' protection must be based on a good knowledge of the hydrogeological setting and the current state of exploitation and use of groundwater resource. Particularly, the main elements to analyse in the study area are: the lithostratigraphic structure, the hydrogeological parameters, the piezometric maps, the recharge features, the water quality, the changes in the piezometric levels over time, the number and type of wells, the withdrawals from the wells.

The water supply in the Piedmont Region plain is mainly linked to the exploitation of the following hydrogeological units (De Luca *et al*. 2004; Bove *et al*. 2005; Forno *et al*. 2018): i) shallow unconfined aquifers consisting of alluvial coarse deposits of the upper Quaternary (outwash and fluvial complex) and glacial Complex); ii) deep confined and semiconfined aquifers represented by a multi-aquifer system (Villafranchian Complex of Upper Pliocene-Lower Pleistocene) and by marine sands (Asti Sands of Middle Pliocene) (fig. 1).

These permeable deposits are followed by predominantly silty-clayey sediments in Piacenziano facies (Lugagnano Clay of Lower Pliocene) and pre-Pliocene marly-arenaceous deposits and conglomerates, mostly impermeable (Complex of marine pre-Pliocene deposits of Turin Hill) (Lasagna *et al*. 2018;)

Piedmont drinking water consumption is over 500 million m^3/year. This supply derives from aquifers (92%), mostly deep. Furthermore, 75% of the Piedmont municipalities have in the deep aquifers the only source of water supply.

3. Qualitative and quantitative monitoring of deep aquifers

An essential source of information about the quali-quantitive status of groundwater derives from an adequate groundwater monitoring network (Alley 2007). The purpose of groundwater qualitative monitoring is to evaluate the long-term changes of the water natural features and to clarify and analyse the extent of natural processes and human impacts on the groundwater system in time and space (Vrba 2003). The quantitative monitoring aims to register changes in groundwater levels, due to groundwater withdrawal or as the effects of climate change. Any monitoring programme needs to be tailored to the hydrogeological and socio-economic context (Jørgensen & Stockmarr 2009).

Groundwater quality monitoring plays an important role in the policy of groundwater protection and quality conservation and effectively supports sustainable groundwater quality management. It provides a valuable base for assessing the current state of and

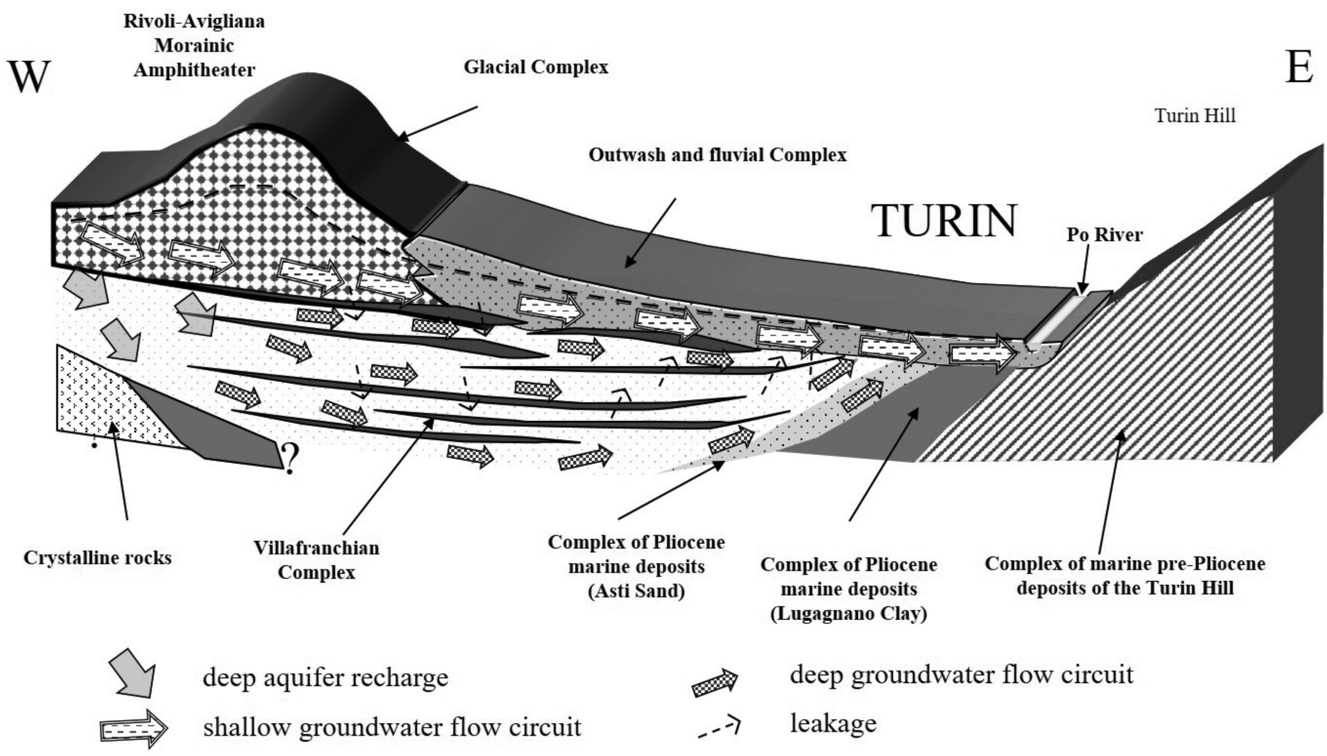

Fig. 1. Hydrogeological conceptual model of Turin plain (Piedmont, Italy) (modified from De Luca and Ossella, 2014). The dotted line represents the piezometric level of shallow aquifer.
Modello idrogeologico concettuale della pianura Torinese (Piemonte, Italia) (Modificato da De Luca e Ossella, 2014). La linea tratteggiata rappresenta il livello piezometrico dell'acquifero superficiale.

forecasting trends in groundwater quality and The Regional Monitoring Network in Piedmont was developed by the Earth Sciences Department (DST) of the University of Turin and is currently managed by Arpa Piemonte. It is composed of: 605 wells, mostly private, for qualitative monitoring and 119 piezometers (automatic network) also used for continuous detection of groundwater levels (fig. 2).

A significant difference in chemistry between shallow and deep aquifers was identified in Piedmont Region through the qualitative monitoring. Indeed, shallow aquifers are very often contaminated and the main pollutants are nitrates, pesticides, chlorinated solvents and hexavalent chromium (De Luca *et al*. 2004; Lasagna *et al*. 2015, Lasagna and De Luca, 2016, 2019; Martinelli *et al*. 2018; Fouchè *et al*. 2019). They are also characterized by a higher salinity and hardness. The deep aquifers, on the contrary, are characterised by rare contamination problems, have a lower salinity and hardness, and sometimes a natural presence of high concentrations of iron and manganese.

The quantitative monitoring network reports a situation of substantial equilibrium of the quantitative status. This means that the amount of water entering or recharging the system is approximately equal to the amount of water leaving or discharging from the system (Alley *et al*. 1999). According to Italian Legislative Decree 152/2006, a groundwater system is in equilibrium when natural recharge and discharge are sustainable for a long time (at least 10 years).

In Piedmont plain, only local problems of nonequilibrium were identified, and among these the most important situation is related to the area of Maggiore Valley (Asti). Here more than 40 wells withdraw approximately 14,000,000 m^3/year of water for drinking purposes (about 50% for the City of Asti) (Lasagna *et al*. 2014). Groundwater is extracted by wells penetrating the deep aquifer, originally artesian, consisting of Pliocene marine sands. As a result of this high withdrawal, a water table lowering of over 50 meters occurred from 1925 to 2015. The lowering trend was about 0.8 m per year.

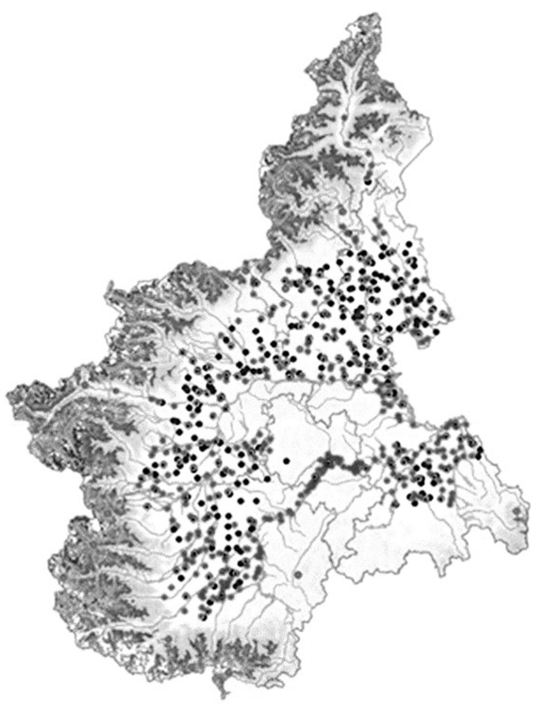

Fig. 2. Piedmont Region groundwater monitoring network (grey point : superficial aquifer monitoring well; black point : deep aquifer monitoring well)
Rete di monitoraggio della falda della Regione Piemonte (punto grigio: pozzo di monitoraggio dell'acquifero superficiale; punto nero: pozzo di monitoraggio dell'acquifero profondo).

4. Prevention of deep aquifers qualitative degradation

Shallow aquifers are particularly vulnerable to inappropriate or uncontrolled anthropic activities with spill of pollutants on the ground (heavy metals, hydrocarbons, pesticides, solvents, etc.). Deep aquifers, on the contrary, are more protected from contamination. Moreover, even deeper, semi-confined aquifers will (sooner or later) be affected by relatively persistent contaminants (such as nitrate, salinity and certain synthetic organics), if widely leached into groundwater in aquifer recharge areas (Foster & Chilton 2003). The degradation of shallow groundwater can be the cause of deep aquifers pollution. A natural reason is due to the presence of fine-grained levels, separating shallow and deep aquifers, that are always discontinuous at a regional scale, and create the conditions for a possible passage of the contamination. Anthropic works can also create the conditions of mixing between shallow and deep groundwater (fig. 3). More specifically, the presence of hundreds of mixing wells, with filters in both the shallow and deep aquifers, or defects and voids in the grout of borehole heat exchangers, that represent the main component of the so-called ground source heat pump systems (GSHPs), can lead to inter-aquifer flux (Caviglia *et al*. 2009; Bucci *et al*. 2018). Moreover, the excavation of quarries in the deep aquifers, through the overcoming of the impermeable level that separate shallow and deep aquifers, should be avoided to prevent contamination of deep groundwater (Castagna *et al*. 2015). As a consequence, it is very important to identify all the possible activities that can favour the water mixing, to monitor the si-

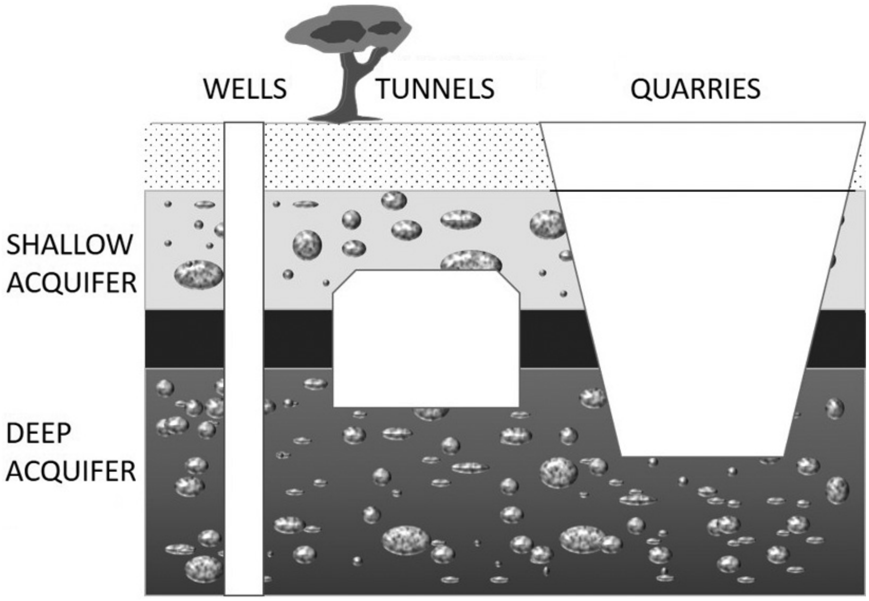

Fig. 3. *Example of anthropic works that can create the conditions of mixing between shallow and deep groundwater.*
Esempio di opere antropiche che possono creare condizioni di miscelamento tra l'acquifero superficiale e quello profondo.

tuation and to intervene with specific safety measures to safeguard the water quality and prevent the development of pollution in deep aquifers. The recharge areas of deep aquifers (RADA) represent portion of territory that must be particularly protected. Indeed, the downward movement of groundwater in RADA can more quickly transfer some pollutants in deep aquifers and thereby contaminate groundwater supplies.

4.1. Reconditioning of mixing wells

A possible direct passage of pollutants from the shallow to the deep aquifers is through the well casing and/or the filter pack, in wells that penetrate deep aquifers and with filters in both the shallow and deep aquifers and/or without impermeable sealing (mixing wells).

A qualitative and quantitative assessment of the mixing wells effects in Piedmont Region was carried out through numerical simulation (Caviglia *et al.* 2009a, 2009b). A mixing well can allow a water passage on average of 250 m^3 per day from the shallow to deep aquifers. Since about 15,000 mixing wells are located in Piedmont plain, a total flow of hundreds of thousands of m^3 per day potentially occurs. In this context the deep aquifer water resources can be seriously damaged. Adequate actions on the mixing wells are a) the ban to drill new mixing wells, b) the closure or reconditioning of existing mixing wells. Reconditioning can occur i) closing the filters in the shallow aquifer and the well casing-soil interspace; ii) closing the filters in the deep aquifers and the well casing-soil interspace.

Piedmont Region has recently published Guidelines, written in collaboration with the DST, for the implementation of reconditioning actions. Furthermore, a map of the shallow aquifer base has been realized in order to facilitate the drilling of non-mixing wells, to accurately and quickly identify the mixing wells, and to avoid contrasts between private citizens and stakeholders.

4.2. Identification and protection of deep aquifers recharge areas (RADA)

The recharge of deep aquifers occurs in the RADA, where the groundwater has a downward flow direction, from the topographical surface to the deep aquifer, passing through the shallow one. Here groundwater can more easily transfer pollutants to deep aquifers. Therefore, the identification and protection of RADA is a very important preventive action against groundwater quality degradation in deep aquifers. More specifically, the identification of the deep aquifers' recharge areas provides the local administration with a management tool to protect groundwater, through the implementation of legislative measures and restrictions for the control over the pollution sources (De Luca *et al.* 2019).

In Piedmont Region, an expeditious method for mapping RADA at a regional scale was proposed by DST, based on easily available data (De Luca *et al.* 2016). It is especially useful to have an estimate of RADA extension in areas where hydrogeological and chemical data are locally insufficient.

5. Prevention of deep aquifers quantitative degradation

Quantitative degradation of deep aquifers is generally connected to water resources overexploitation. If the withdrawal is so high that an equilibrium in the groundwater balance cannot be achieved, a water level decline can realise, also with consequences in surface water levels and ecological resources dependent on streamflow. Thus, it is necessary to prevent these phenomena with a prudent use of deep groundwater or to intervene with safety measures to re-establish equilibrium conditions.

5.1. Deep aquifers use only for human consumption

A sound strategy for deep aquifers protection could be the promotion of the use of deep aquifers for drinking water purposes only. It consists of discouraging the use of deep groundwater for industries or irrigation.

This policy was carried out in the Piedmont Region through: a) the increase of the fees on the groundwater withdrawal from deep aquifers; b) the denial of the permission to build new deep wells for uses different from human consumption.

5.2. Possible actions for mitigation of deep aquifers quantitative degradation

If the groundwater system is in nonequilibrium, it is necessary to identify the causes and to intervene rapidly, so as to avoid damages to human activities, and to the health of the population and the environment.

In case of overexploitation, a different quantitative management of groundwater resources is necessary. Actions may include: a) withdrawals reduction, b) withdrawals redistribution, c) artificial recharge. The choice must be based on a careful analysis of costs and benefits.

A study carried in the Maggiore Valley (Piedmont) by DST on behalf of ATO3 Asti identified as suitable interventions both the reduction of withdrawals (20% of total withdrawal) and the wells redistribution in the territory (De Luca *et al*. 2018). The action program started in 2014 and it is underway, but it already had important positive results with a reversal trend of the piezometric level that raised more than 10 meters.

6. Conclusions

In the subsoil different aquifers are located, in which groundwater is more or less communicating in relation to the geological structure. Among them, deep aquifers represent a strategic resource. Indeed, they generally show a better quality, being less vulnerable to contamination than shallow aquifers and watercourses. In addition, they are less subject to level fluctuations due to factors such as climate change.

However, the restoration of qualitative or quantitative status, after a degradation, can be very difficult. Thus, different strategies can be adopted to avoid the degradation, e.g. to prevent the contamination of shallow aquifers, to avoid anthropic works that can create the conditions of mixing between shallow and deep groundwater, to limit deep groundwater uses other than human consumption, to identify mixing wells, that must be subject to reconditioning, to improve the knowledge of hydrogeological systems also with a quali-quantitative monitoring.

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