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The Sustainable Groundwater Level in the Milan Area

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ABSTRACT. In order to improve the control of the hydrogeological balance, monitoring of groundwater piezometric levels, has great importance. In effect, these changes, in many Lombardy cities, can lead to a resource shrinkage in the case of groundwater overexploitation or potential damage to buildings and underground infrastructures in the case of rises in groundwater levels. The research shows that a hydrogeological equilibrium, achieved through a controlled deficit, guarantees both the water reserves and the socioeconomic needs of urban zones where the underground is used. Therefore, hydrogeological equilibrium is achieved where the piezometric level is both with reserves conservation and for urban and industrial needs supplying. This paper highlights the usefulness of the " *sustainable piezometric level*" concept, among the criteria of groundwater management in industrial and urban areas. This approach is essential for underground structures safety in the areas of potential groundwater rising and for groundwater resources protection where there is an overexploitation risk. The analysis of the causes of this phenomenon and overall the implementation of a mathematical model allowed the necessary actions to be found and quantified.

Key terms: Sustainable piezometric level, Urban areas, Hydrogeological balance

Introduction

A suitable accuracy of groundwater data management, in order to improve the control of the phenomena governing the change in groundwater piezometric levels, has great importance for any industrial cities of central Lombardy. In effect, these changes can lead to a resource shrinkage in the case of groundwater overexploitation or potential damage to buildings and underground infrastructures in the case of rises in groundwater levels. The research shows that a hydrogeological equilibrium, achieved through a controlled deficit, guarantees both the water reserves and the socioeconomic needs of urban zones where the underground is used. This paper highlights the usefulness of the " *sustainable piezometric level*" concept, among the criteria of groundwater management in industrial and urban areas. That means the most suitable piezometric level, both for natural resources and for infrastructure maintenance, in order to implement a suitable resource management. This "sustainable piezometric level" can be obtained only on the basis of an accurate knowledge and monitoring of the anthropic and natural factors governing change in groundwater mass balance. An important tool to achieve this result is mathematical modeling, because it allows us to collect and elaborate the data to foresee the consequences of an action on the basis of different scenarios.

This approach is essential for underground structures safety in the areas of potential groundwater rising and for groundwater resources protection where there is an overexploitation risk. In this context, it can be very useful to have recourse to the " sustainable piezometric level" concept, previously studied by various Authors who gave it different definitions. The present research tried to find an adequate approach to defining this level on the basis of the experience acquired working on the most common problems in the Po Valley. The methodological result of this study is that often a simple analysis of the phenomena is not enough. The monitoring of the factors that can change the mass balance, should be coupled with a modelistic approach that allows the best solutions to be found for the control of the hydrogeological equilibrium. A very important case where it was possible to implement this approach was that of Milan. In this city and in its province the rise of piezometric levels in the last ten years has had a serious impact on building foundations and underground tunnels. This rise followed a phase of general decrease of the piezometric head that had lasted for about thirty years. The analysis of the causes of this phenomenon and overall the implementation of a mathematical model allowed the necessary actions to be found and quantified.

The "sustainable piezometric level"

The study considered the possibility of setting up criteria for the management of groundwater, taking into account the most important economic aspects and the safety both of infrastructures and of groundwater reserves.

By regulating water withdrawal, the piezometric head can be controlled, keeping a suitable level (sustainable piezometric level). Owing to the importance of a correct withdrawal, since the beginning of the last century, hydrogeological research has focused on the determination of the maximum wells withdrawal consistent with water supply security (safe yield). This has been done for each hydrogeological system.

Also considering the experience of the Po Valley, it can be said that a hydrogeological system enters a crisis situation also when withdrawals do not exceed the total groundwater recharge or, because of the presence of visible symptoms of decay and of decreasing piezometric heads, that cause important supply problems. This occurs mainly where withdrawals are concentrated in inadequate areas, such as:

a) in protected aquifers with good transmissivity but located very far from the feeding areas;

b) in aquifers in the same hydrogeological condition, but that are very vulnerable to pollution;

c) in permeable and transmissive aquifers but lacking adequate recharge.

In the first case, keeping the withdrawals constant, a rapid groundwater decrease takes place followed by a stabilization of the heads after a very long time; in the second case, the same phenomena occur concerning the reserve reduction, accompanied by a quality decay; in the third case a decrease in piezometric heads takes place, not followed by a depression or stabilization, but accompanied by quality decay.

On the basis of the experience in the Po Valley, it has been concluded that for a good groundwater management, the balance study must be carried out simultaneously with the analysis of recharge and withdrawal conditions, that are strictly linked to the phenomena of reserve decrease and quality decay.

Management criteria - Going beyond the safe yield criterion: balance control

Within the hydrogeological system of the Po valley, in the first phase it was important to define areas affected by water balance disequilibrium, and rank them according to the priority of necessary interventions: actions that are essential to prevent a progressive acceleration of the deficit. In conditions of excessive exploitation, the deficit between recharge and withdrawals is also accompanied by slightly worsening factors for the qualitative state: a quick decrease of groundwater levels (one or more m/y), creating a deep piezometric depression, draws pollutants from surrounding areas and leads to quality decay.

In order to classify the seriousness of water crises and consequently to identify the most suitable counteractions, the following quantitative criteria have been considered in the Po Valley basin:

Groundwater supply conditions: feeding must originate exclusively from the effluent groundwater located upstream in the study area, or by recharge (sum of infiltration due to precipitation, natural water courses and lakes, and irrigation.

Withdrawals/Recharge ratio: limiting the definition of recharge to water flowing from precipitation and irrigation network (therefore excluding exchanges with water courses and groundwater inflow), a ratio lower than one is considered normal and would not cause a balance deficit;

Table 1 - Definition of quantitative classes

Class	Withdrawal/ Recharge	**Definition**
A	< 0.8	includes conditions of evident good water availability whose modification can only be the consequence of relevant phenomena or interventions capable of modifying the water balance.
B	0.8 – 1.2	includes areas characterized by prevailing equilibrium conditions. Also considering uncertainties in the elaboration. piezometric heads monitoring is advisable to reconstruct the evolutionary trend in the short-to-middle term. In areas with this characterization. future exploitation. even if not very relevant. may influence water availability.
C	1.2 - 1.6	includes areas with negative water balance. that can be re-equilibrated in the middle-to-long term (one to two years).
D	1.6 - 3.0	includes areas with so evident an imbalance (i.e. a marked piezometric depression) between water use and water availability that recovery measures are required to reach a new equilibrium
E	> 3.0	includes areas with so evident an imbalance (i.e. a marked piezometric depression) between water use and water availability that very urgent recovery measures are required to obtain a new equilibrium

Withdrawals/Total recharge ratio: total recharge includes also inflows coming from the upstream groundwater and exchanges with watercourses; in certain cases, these inflows are so relevant that they can rebalance the groundwater endangered by withdrawals.

Areal withdrawal: this is one of the elements that best describe the crisis areas due to overdraft. Concerning the valleys, it was observed that areas suffering serious crisis usually display areal withdrawal values of over 3 l/s per km^2.

Difference between groundwater outflow downstream and inflow from upstream groundwater: a positive value means enrichment in groundwater between the inflow and outflow points of the considered section, therefore a balance surplus. This parameter is particularly interesting to identify areas tending to increasing piezometric heads.

Qualitative crisis index: pollution – its extension and its typology – is an important element. The presence of pollutants in high concentration worsens the crisis situation, but crisis can be caused by very extensive pollution caused by not particularly concentrated pollutants that are difficult to fight due to the high cost of purification (e.g. nitrates).

On the basis of these concepts, a preliminary classification of the resources state was proposed. With regard to the imbalance between availability and use of the resource, close to what has already been proposed by Avanzini, Beretta, Francani (1999), classification introduces the following five classes (Table 1):

In order to define and update the classes, it is essential to carry out continuously an adequate monitoring of the piezometric conditions. Among the above-listed parameters, the Withdrawal/Recharge ratio has proved to be the most significant for the quantitative class attribution, as it seems to determine the water balance to a greater extent. Anyway, generally in the case of the Po Valley the same results are obtained using the ratio between withdrawal and recharge for the distinction (recharge is obtained from the sum of all factors contributing to the water resource increase, including the inflow coming from upstream through groundwater). A necessary correction of the quantitative class has been introduced in the classification for the cases when the inflow from upstream significantly influences the water balance and leads to the attribution of a different quantitative class to the study area (in our case this occurs very rarely). Concerning the area classification according to water quality, a distinction can be made between municipalities where it is difficult to identify areas suitable for new water wells, and those where problems can be easily overcome either because contamination is limited to small areas within the commune or because the aquifer is deep, productive and well protected against pollutants.

On the basis of this criterion (e.g. on the natural resource point of view) the city of Milan proves to have had, from 1960 until today, a strong negative mass balance (class D) and a poor water quality. But on the other hand (i.e. from the human point of view) since 1990 the city of Milan has been in crisis because the groundwater levels reached the underground structures. This situation shows how in an anthropicized area other criteria have to be introduced in addition to the safe yield criterion: the presence of underground structures requires the choice of a maximum piezometric level, e.g. a sustainable piezometric level. This choice can be made only through a balance control of the groundwater resource. Its implementation requires an operating structure able to provide basic information on how the hydrogeological system works and about its water balance. In these cases, it can be very useful to have recourse to a mathematical model in order to optimize the solutions. So it is possible to introduce the necessary quantitative elements in a simulation model to guarantee a correct evaluation of optimal withdrawal volumes, taking into account both the quantitative aspects of the resource and the needs arising from the productive and urban situation.

The case of Milan

The hydrogeological structure of the Milan Province consists of two main aquifers:

- Aquifer I (TR), where the water table is free, extends from zero to about 100 m from the soil surface. It consists of alluvial sediments, partly formed by streams derived from glaciers during Middle Pleistocene and partly ancient (Late Pleistocene and Holocene) and present day river depositions.
- Aquifer II (C) or the deeper aquifer is confined. It consists of alluvial sediments alternating with clayey deposits ("Villafranchiano" , Pliocene - Lower Pleistocene).

Since the 1950's, the heavy anthropic actions and in particular the withdrawal of wells for industries and public supply, have generated a very large piezometric depression, that had reached an areal distribution of about 600 km^2 in 1990. The high decrease of the piezometric levels had a double effect: on the one hand it generated a growing worry for the reduction of the groundwater resource; on the other hand it allowed an easier use of the city underground for construction of boxes and subway lines, but without any environmental planning and real understanding of the phenomenon. Since 1992, there has been an inversion of the groundwater trend and the piezometric levels have begun to rise creating several problems for underground infrastructures.

Many Authors thus started to study the new phenomenon and in 1997, the Regione Lombardia constituted a group of researchers (Avanzini M., Beretta G.P., Francani V., 1999) to monitor the increase in groundwater levels in the Milan provincial area. A number of public authorities identified a set of measures, that required high investments and management costs (several million Euros). The researchers also carried out some modeling tests in order to better understand the causes of the piezometric rising, to predict the future development of the groundwater and to assess the most suitable interventions, and to check the effects of the proposed interventions. This model was developed first by Avanzini, Beretta, Francani (1999); then it was partially modified by Alberti, Masetti, Francani, Parri (2000) and successively upgraded (2001).

The modeled area is the central section of the Province of Milan. A trapezoidal square-meshed grid measuring 400 m per side was placed over the area The grid is made up of

127 columns, 100 lines and 3 layers for a total of 16118 active cells. The length of the modeled domain varies between 27.4 and 34.6 km in a South to North direction, with an overall surface of 2579 km^2.

Vertically, a discretization in 3 layers was considered:

- Layer 1: the first aquifer presents an average depth of 40-45 m, including the unconfined aquifer;
- Layer 2: semi-pervious separation layer 5-20 m thick (aquitard).
- Layer 3: lower aquifer including the semi-confined one, a depth of 80-120 m.

Analysis of the causes of piezometric level increases and future forecasts

Thanks to the implemented model and an in-depth analysis of the hydrogeological system and of factors determining the water balance of the area, it was possible identify and quantify the causes of the groundwater level increase. Among the terms of the balance, irrigation did not change much, even though there has been a clear and constant decrease of the withdrawn quantities over the years, and therefore its equivalent contribution in groundwater recharge.

The rainfall rate in the years 1992-1998 was not higher that in the 1970s: in 1975-1979 rainfall values were 30% higher than the average observed in the last 30 years (950 mm).

With regard to the role of infiltration from losses in the drinking water distribution network and in the sewer system, no certain data are available for a correct evaluation.

The leaks in the water network are not negligible, and are estimated at about 18% of the water wells total discharge (about 40 million m^3 in 1997); this proportion can be considered constant. Taking into account the gradual withdrawal reduction during the examined period, a similar decrease of the groundwater inflow can be assumed.

Among the controlling factors of the groundwater outflow, the most relevant are the withdrawals. Public withdrawal in the city of Milan was assessed at 1 m^3/s in 1909; progressively, it reached 8.8 m^3/s in 1960 and 11.1 m^3/s in 1975; then it fell substantially to reach 8 m^3/s in 1997 due to the decrease of inhabitants by about 23.5% (from 1.7 to 1.3 millions inhabitants between 1971 and 1996).

Moreover, as the first aquifer was seriously polluted (in the years 1980-1990 a number of wells provided the withdrawal of polluted water, mostly from the first aquifer), the withdrawal of drinking water was moved from the first to the second and then to deeper aquifers, thus reducing the overall volume withdrawn from the first aquifer.

Due to the progressive abandoning of the first aquifer, a remarkable reduction of the quantities withdrawn by decontamination wells was observed, passing from estimated values of 52 million m^3 in the 1980s to 37 million m^3 during the period 1990-1997.

Another important cause of the first aquifer being overexploited is a decrease in private withdrawal for industrial use. The productive structure of the town center and of the municipalities in the hinterland has, in fact, changed because of the crisis of the industrial sector, in particular in the mechanical and chemical field, and the increase of the services. In Milan, this led to a withdrawal reduction of 73% in the years 1979-1997 (from 96 to 26 million m^3) and of 49% if we consider only the period 1990-1997 (from 51 to 26 million m^3). This diminution is even more important when considering the industrialized area north of Milan. In 22 municipalities, in the years 1990-97, the public withdrawal decreased by about 17 million m^3, to which a further decrease in industrial withdrawal must be added, equal to about 41 million m^3.

There are many examples of decreasing withdrawal form industrial sites in Milan and the hinterland, estimated at over 45 million m^3 for the years 1990-97. Sesto San Giovanni (north of Milan) can be taken as an example of a historically industrialized area: there, in the years 1980-1997, the public withdrawal fell from 13.1 to 11 million m^3/year and the private one from 41.6 to 4.9 million m^3, for a total decrease of over 88%.

From the analysis of the above-mentioned data, the total deficit of withdrawal in Milan can be estimated at about 66 million m^3/year, as the total yearly withdrawal decreased from 838 to 837 million m^3 in the years 1990-97. A further reduction of groundwater outflow of about 12 million m^3/ year, is represented by the lack of springs, as many of them have been closed.

Considering all these elements, the uncertainty of some evaluations, and comparing the decrease of withdrawal in Milan with the estimate of the stored water volume due to the increase of piezometric levels in the same period (about 135 million m^3 from 1990 to 1997, i.e. about 4 m^3/s), it can be confirmed that the main causes of the rise in piezometric level are to be found both in the withdrawal reduction in Milan and in the hinterland.

Examining the situation on a wider scale involving the whole area recharging Milan groundwater, today the rising trend seems to have stopped in the northern area. In this area, e.g. around Giussano (about 20 km north), the rising trend is limited to the years 1992-1994 with rising values of up to 14 m, linked to the years of heavy rain 1993-1994. On the contrary, in the northern area, e.g. in Desio (10 km north), the heads have remained steady after the important rising in 1992-1994, whereas close to Milan (Sesto San Giovanni), the rising continued after the period 1992-1994, due to the withdrawal decrease.

In 1998, the maximum increase in groundwater levels took place: piezometric heads reached the values observed during the years 1963-65. Still now, the Milanese area and other areas in a similar situation, e.g. Brescia, have a small deficit between inflow and withdrawal. On the basis of these considerations, the forecasting of withdrawal based on the maximum realistic decrease was inserted in the calculation. It is thought that the migratory flow from Milan to far-away municipalities has finished and that in a near future a flow towards townships in the hinterland may take place, that would not influence the groundwater level. Still, it was decided to introduce a value of withdrawal reduced by 20% into the Milan evaluations, and one at the same level as in 1952 in the municipalities to the north of the city.

Concerning the territory, Milan withdrawal represents 29% of the total (about 32.5 m^3/s) in the Adda-Ticino hydrogeological basin; the total withdrawal required is just above 5 m^3/s .

In accordance with the findings of the group of researchers, the public authorities identified a set of measures. The interventions must be mainly synergic, but in some cases, e.g. urban withdrawal increase in the town and water discharge in the sewage system, several solutions may be carried out in the middle-to-long term, and can be implemented in the short term, either singly or jointly:

- interventions on the superficial irrigation network (impermeabilization of the Villoresi canal);
- interventions to increase the outflow (e.g. water withdrawal from quarries by natural or induced outflow, activation of pumping wells for buildings that have to be protected).

The Comune di Milano has already started the implementation of some draining wells (Vettabbia Plant) and others are in the advanced planning phase. Among these solutions, the reduction of irrigation is the most suitable; the calculations demonstrate that a good use of irrigation can guarantee the control both of excessive groundwater increase and decrease .

Conclusions

The research has shown the importance and the advantages of an adequate groundwater management. The principal step to obtain this result is to set up an accurate monitoring network that allows an efficient control to be had of the factors ruling the change in piezometric levels: the knowledge of precipitation, piezometric levels, volumes withdrawn for every well, make it possible to know the quantitative conditions of the reserve. This is the case of Milan, where the lack of an adequate management in the last ten years, after a phase of general decrease, led to a rise of piezometric level in the city and in its province. The groundwater reached the foundations of many buildings, threatening their stability, and leakage of groundwater in several sub-way tunnels has been noticed, damaging many constructions. To quantify the “sustainable piezometric level”, an analysis of the mass balance factors is often not enough, but it can be very useful to implement a mathematical model. In this way we can find the best solutions to re-equilibrate the groundwater levels controlling the deficit of the water reserves and to guarantee the socio-economic needs of the area.

References

Airoldi R., Casati P.(1989) – Le falde idriche del sottosuolo di Milano.Comune di Milano, 29.

Alberti L., Francani V. , Masetti M., Parri A. (2000) – Valutazione del livello massimo raggiungibile dalla falda nel comune di Milano. In : Quaderni di Geologia Applicata, suppl.2, n°4, 13 – 28.

Avanzini M.,Beretta G.P., Francani V. (1999) – Il controllo della falda. *Costruzioni*, **516**, may 136-150.

Avanzini M.,Beretta G.P., Francani V.,Nespoli M.(1996) – Recharge and groundwater availability of deep aquifers in Milano Province (Italy). Proc. 1st International Conference “The impact of industry on groundwater resources”, Cernobbio (Como),sect.I, 55-67.

Avanzini M.,Beretta G.P.,Francani V., Nespoli M. (1995) – Indagine preliminare sull'uso sostenibile delle falde profonde nella Provincia di Milano. C.A.P, 85 .

Gruppo di intervento per l'innalzamento della falda nel Milanese (1997) – Progettazione di massima degli interventi. Provincia di Milano, 208.

Provincia di Milano-Politecnico di Milano (1995) – Le risorse idriche sotterranee della Provincia di Milano, vol.1 : Lineamenti idrogeologici, Provincia di Milano, 60 .

Pozzi R., Francani V. (1981) – Modalità di alimentazione dell'acquifero milanese, *Le Strade*, n° 303, 1-25.