Experimental study of an artificial groundwater recharging process

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Abstract

Groundwater recharge is gaining ever greater importance in the context of the management of water resources. This practice can improve the quality of aquifers, or at any rate temporarily store resources that would otherwise be lost. The recent stipulation of the “Piano Direttore”, an extract from the Plan for Safeguarding Water Resources (“Piano di Tutela delle Acque”) by the Commissary appointed to deal with the environmental emergency situation in Apulia, has removed the prejudicial clause of illegality introduced by the Law Decree (D. Lgs. 152/99) of allowing rainwater runoff underground. Nevertheless, this type of plant is still rare in the territory, perhaps due to the lack of experimental data supporting the efficacy of the procedure. In the present work the experimental results obtained in an investigation campaign carried out at a recharge site are illustrated and discussed. The recharge site is equipped with suitable devices for continuous monitoring of the rainwater levels, the volume influx to the network, and the variations in the levels of the perched water. Finally, the experimental data are used as the preliminary settings for a mathematical model drawn up to represent the phenomenon.

Keywords: aquifer recharge, experimental investigation, mathematical model.

1 Introduction

The recent national and regional norms regulating the dispersion of rainwater (D.Lgs. 152/99, D. L.vo 258/00 Piano Direttore, an extract of the “Piano di Tutela delle Acque”) pose fairly strict limits on rainwater runoff intercepted by the drainage/sewage system.

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In a region like Apulia, that is practically devoid of superficial bodies of water, the only catchment system responding to these norms is the soil, or the superficial layers of the subsoil.

Besides, the endemic lack of water resources in the Apulian territory means that alternative solutions for the storage of these water volumes, purged of the first rainfall, need to be found to make them suitable for irrigation and, if possible, for production purposes.

Because of the extent of the volumes involved, together with the limited availability of ground, the idea of storing rainwater in storage tanks has had to be excluded.

A possible alternative would be that of using the rainfall as a means of artificially recharging the superficial groundwater, by allowing it to filter through the superficial layers of the subsoil.

This solution has the dual advantage of storing the resource, making it available for future use, and of raising the piezometric level of the aquifer, contributing to combat the saltwater intrusion phenomena due to the widespread, uncontrolled water pumping for irrigation that occurs near the coastline.

Despite the fact that the works necessary to per-form artificial recharge are relatively simple, few experimental data validating such procedures are currently available.

In the present work, the data collected at an experimental recharge plant set up in the countryside of Avetrana, thanks to an agreement between the Polytechnic of Bari and the municipal administration, are analyzed and discussed.

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Figure 1: Geographic setting.

2 The experimental apparatus

The built-up centre of Avetrana (figure 1), is located south-west of the city of Taranto, 5.5 km from the Ionian coast, at an altitude of approximately 60 m above sea level. Geologically, it stands on the permeable formation of quaternary calcarenite, as demonstrated by the high number of tufa extraction quarries present on the edges of the town, now al-most all abandoned.

The final storage area of the urban drainage network is a basin inside an abandoned quarry, lying beside the roadside, and adjacent to the terminal tract of the drainage system [3].

The basin (figure 2) is trapeze-shaped and has suitably shaped banks on three sides, while the fourth side corresponds to the vertical wall of the quarry adjacent to the road. The bottom of the basin is that of the quarry and, being made of permeable calcarenite, promotes natural dispersion. The runoff is irregular but generally downhill in a direction away from the road, so that depending on the volumes that flow into the drainage pipes, well de-fined areas with a growing extension are involved.

Figure 2: Area of the recharge plant.

The outflow of the rainwater collector lies in the vertical wall at a level of 51.78 m above sea level, approximately 4 m above the bottom of the basin, so that apart from infiltration losses, a volume of approximately 18.600 m^3 can accumulate before the collector is swallowed up.

At the outflow of the drainage pipe there is a basket-shaped grating, supported by a reinforced concrete structure, that receives the waste water and al-lows it to settle. This bowl has a planimetric area of 10 x 9 m^2 delimited by reinforced concrete sides built up to approximately 4 m above the bottom of the ba-sin. The water passes from the bowl into the basin through a right-angled triangular weir 2.40 m wide at the top, which is situated 50.67 m above sea level. Issue from the bowl is assured by small lateral openings protected by interception devices.

Drainage of the water stored in the bowl occurs not only by infiltration through the bottom but also through a well, which allows water to sink only through the calcarenite fissures in the base, while the water entry is protected by another grating, situated approximately 0.50 m from the bottom of the well.

Inside the quarry a sentry well has been created to measure entry into the perched water, while a pluviograph, placed at a sufficient distance from the flooding area, records the rainwater falling directly into the plant area.

A hydrometrograph measures the water volume entry, placed in the bowl above the weir; another hydrometrograph is placed on the outside, beside one of the walls of the basin, to record the water levels inside the basin.

Finally, there is a ball cock inside the sentry well at the upper end of the aquifer, serving to measure fluctuations in the levels over time.

3 The hydrogeological situation

The final receiver site has all the typical geological characteristics of the Apulian territory.

In general, the mesozoic calcareous crust at the base is covered by a layer of calcarenite rock ("calcareous tufa") of the quaternary age, having an over-all mean thickness of 20 m. This is a massive structure, with rare, irregular subdivisions into great masses.

From the lithological standpoint, the rock is composed of whitish-yellow calcareous granules, tender and porous, with abundant fossils clustered together at irregularly distributed levels inside the body of the rock. The granules vary in size and have variable degrees of hardness and compactness at the different levels.

The absorption trial carried out at the end of perforation of the first sentry well allowed the hydraulic conductivity of the aquifer to be estimated in the order of 10^{-5} m/s.

More details on this topic and on the geological issue are available in [3].

4 Data analysis

The instruments installed at the plant in Avetrana have enabled a high quantity of data to be collected, over several seasons with few interruptions. As in most other experimental plants set up in Mediterranean climatic conditions, the time of year when the most significant events occurred as regards inflow from the urban drainage system was the summer sea-son, when the heaviest rain normally falls in our climes.

Figure 3 shows the water levels trend over time, recorded by the hydrometrograph positioned in the sentry well to control the upper aquifer area, and the volumes passing through the triangular weir de-scribed above. At the representation scale, these volumes are variable and sometimes impetuous.

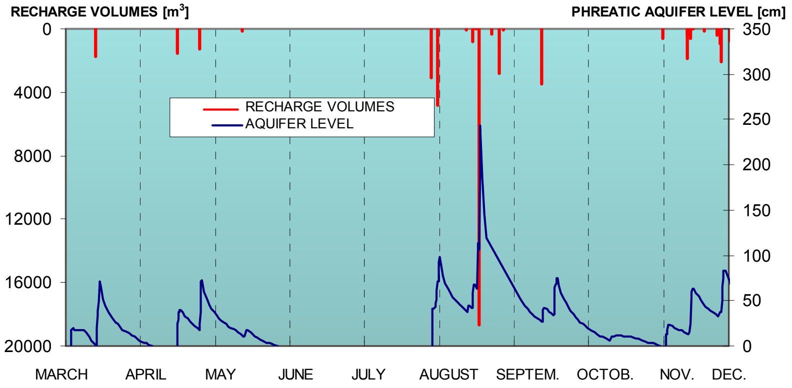

Figure 3: Experimental trend of the overflow volumes and the level of the superficial groundwater.

It can be seen in the figure that at some time intervals, the groundwater level has a value of zero; in fact, this corresponds to the recording of the hydrometrograph ball cock, stuck in the lowest position due to the fall of the water level in the phreatic nappe. According to the controls carried out at the time when the plant was set up, this lowest position can be estimated at approximately 1 m from the bed of the groundwater.

Combined analysis of the trend of the two variables shown in figure 4 shows the close correlation between the volumes overflowing in the bowl and rises in the water levels of the phreatic groundwater.

Figure 4 refers to the event that occurred on the 13th May: the overflow of the bowl was fairly modest, little more than 100 m^3, and did not give rise to a significant filling of the infiltration basin; in fact, the hydrometrograph recording the levels inside the tank indicated a zero value throughout the duration of the event. However, this does not exclude the possibility that some flooding may occur, because this zero value of the instrument corresponds to a geodetic level approximately 15 higher than the minimum level in the tank. It should be noted that the effect of this overflow is felt about 24 hours later: the maximum rise, approximately 6 cm, was reached about 48 hrs after the overflow.

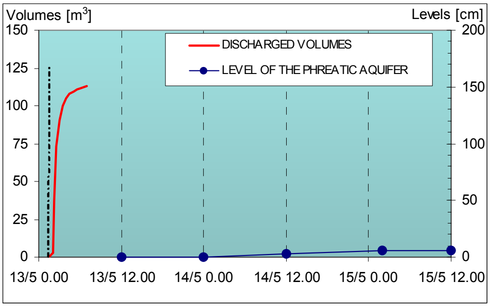

Figure 4: Event on the 12th May.

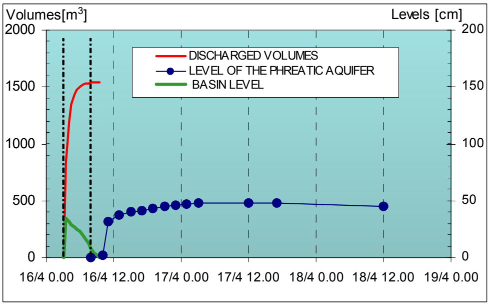

Figure 5: Event on the 16th April.

On the 16th April, the event shown in figure 5 began. The overflow of the bowl, which was greater than in the previous case, caused high filling of the infiltration basin with a permeable bottom, as demonstrated by the recording of the hydrometrograph, that showed a maximum value of 34 cm (as com-pared to the previous zero), that was certainly less than the quantity flowing into the emergency well.

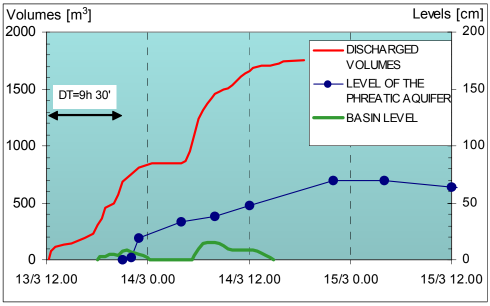

Figure 6: Event on the 13th and 14th March.

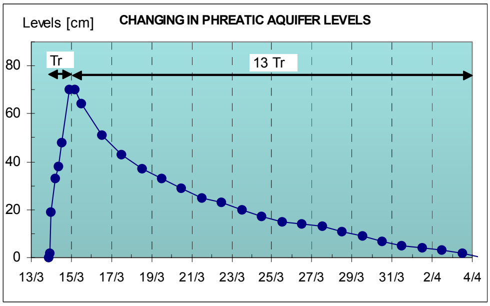

Figure 7: Event on the 13th and 14th March. Complete trend of the variations in the superficial groundwater levels.

The effect of transfer into the groundwater of the overflow volumes started about 7 hours after the beginning of the event, and after a fairly rapid initial rise, the levels reached a maximum increase of 48 cm after about 24 hours.

Comparing the two cases analysed up to now, we can see that the recharge phenomenon depends not only, obviously, on the entry volume but also, bearing in mind the delay before it occurs, on the initial humidity value characterizing the unsaturated state and intensity of the recharge, illustrated to some ex-tent in the diagram showing the steepness of the curve value representing the overflow volume.

Figure 6 shows the event that occurred on the 13th and 14th March, that differed from the previous events because the overflow occurred in two successive time phases. The first phase began on the 13th March at about 12 o'clock and lasted less than 12 hours; it was followed after an interruption of about 6 hours, by a second overflow that reached volumes of 1500 m^3, as compared to the previous volumes of about 700 m^3.

In the infiltration basin, too, the filling occurred in two phases, the first at a maximum height of 9 cm and the second, of 15 cm. It should be noted that the second filling started at virtually the same time as the second overflow of the bowl, as the previous phenomenon had evidently not completely ended during the intermediate phase.

A very similar situation is present as regards the trend of the levels measured in the upper aquifer. In fact, the aquifer began to be affected by the recharge about 10 hours after the beginning of the phenomenon (12 o'clock on the 13th March), while the second delay was only by about three hours. This substantially confirms the fact that the initial conditions (the state of water saturation of the soil) and the hourly intensity of the recharge have a significant effect on the whole phenomenon.

Figure 7 illustrates in detail the trend of the superficial level of the groundwater after the event: the maximum rise, equal to 70 cm, occurred after about 38 hours from the beginning of the overflow of the infiltration basin. The latter time interval is comparable to the duration of the recharge phase. The discharge phase, in the sense of the return to the initial level in the groundwater, lasted about 21 days. The ratio between these two durations is more than 13.

Finally, figure 8 shows the event that caused the greatest rise of the superficial groundwater during the period of observation (178 cm). This is very interesting, as it fully confirms the previous analyses and especially the link between the steepness of the curve representing the overflow volume and the delay before recharge occurs.

It can be seen that the curve indicating the water level inside the infiltration basin shows a horizontal line between the hours of 10 o'clock and 11.30 of the 19th August, at the level of 0.58 m above zero of the measurement tool. This trend can be imputed to the effect of the emergency well, the crown of which is 0.50 higher than the bottom of the infiltration basin.

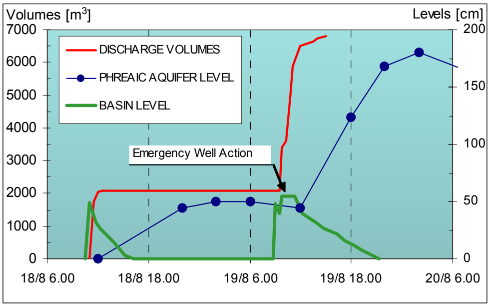

Figure 8: Event on the 18th and 19th August.

5 Modelling the phenomenon

Mathematical modelling of the phenomenon under study must be done by adopting a saturated-unsaturated approach, thus using equations that can describe the filtration process of a water-air blend.

It is possible to simplify this by refraining from making a direct description of the air phase, taking into account its interaction with the liquid phase purely in the retention curve. Empirically built, this shows the correlation between the water charge and the liquid fraction present in the blend, and between these parameters and the real permeability of the aquifer [6].

Taking an ideal vertical two-dimensional domain, the infiltration process can be described by the equation [1]:

$$\left(\Gamma S_S + (1-\Gamma)\frac{\partial \theta_W}{\partial \psi}\right)\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x}\left(K(\psi)\ \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial z}\left(K(\psi)\ \left(\frac{\partial \psi}{\partial z}+1\right)\right) + Q$$

where

$$\Gamma = \begin{cases} 1 \ \ \textit{Saturated zone} \\ \\ 0 \ \ \textit{Unsaturated zone} \end{cases} \qquad \Psi = \text{hydraulichead} = \begin{cases} \dfrac{\mathrm{p}}{\rho \mathrm{g}} \ \ \textit{Saturated zone} \\ \\ \dfrac{\mathrm{p_c}}{\rho \mathrm{g}} \ \ \textit{Unsaurated zone} \end{cases}$$

K(ψ) = Water conductivity, charge function and hence degree of saturation

θ_W = Water content

S_s = Storage coefficient

The functions:

$$\theta_W = \theta_W(\psi); \ \ K = K(\psi)$$

must be taken as given. The present work adopts the ratios proposed by van Genutchen [7]:

$$\frac{K(\psi)}{K_S} = \frac{\left\{1-(\alpha\psi)^{\beta-1}\left[1+(\alpha\psi)^{\beta}\right]^{\frac{1}{\beta}-1}\right\}^2}{\left[1+(\alpha\psi)^{\beta}\right]^{\frac{\beta-1}{2\beta}}} \tag{1}$$

$$\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right) = \left[\frac{1}{1+(\alpha\psi)^{\beta}}\right]^{1-\frac{1}{\beta}} \tag{2}$$

K(ψ)= Water conductivity, charge function and hence degree of saturation

θ_W = Water content

S_s = Storage coefficient

where K_S is the water conductivity in saturated conditions, θ_s is the water content when saturated conditions are reached, θ_r is the irreducible water content, α and β are empirical parameters linked to the characteristics of the soil.

The processes described below were carried out using the calculation code SATINSAT [2,5], operating at finite differences. The domain scheme was drawn by a Eulerian grid with variable sized cells. The flow values were calculated on the basis of the elements defined by the cells, while the water charge, degree of saturation, water conductivity and other scale dimensions were calculated on the basis of the single nodes.

The domain scheme is shown in figure 9. It was drawn with reference to a vertical section of the aquifer, with a homogeneous width, and a depth equal to 9.70 m (the depth of the bed of the phreatic groundwater) passing through the sentry well, the zone behind the grating and so directly involved in the overflow of the latter, and through the hydrometrograph positioned in the bowl.

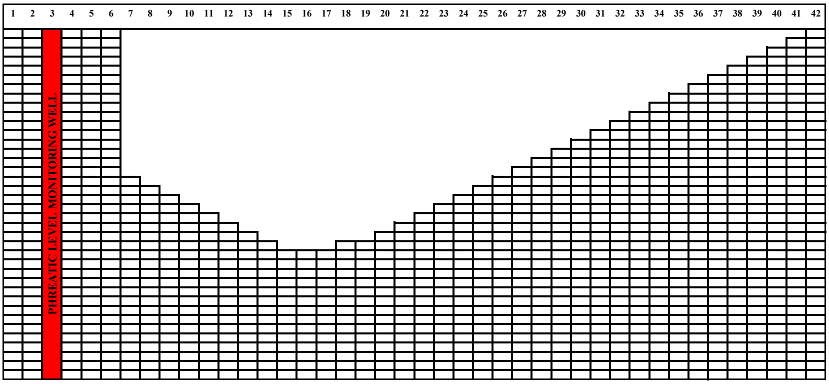

Figure 9: Scheme of the integration domain.

Unlike what is depicted in the figure to make it easier to read, different sized cells were actually used to reduce the number of calculation processes, adopting a much finer grain in the superficial soil zones, where the cells have a much lower height (in the order of cm) than those representing the lower levels. An even rougher grain was used for the saturated soil zone occupied by the phreatic groundwater, represented by the last two rows of cells, each having a height of 1 m. In the same way, the width of the cells was varied according to their site: those involved in the overflow of the bowl (on the right in figure 9) were assigned widths in the order of centimetres, while the other widths are in the order of metres.

6 Settings of the model

The selection of the experimental event to use for the setting of the model was made taking into account the need to reduce as far as possible the uncertainties connected with the initial conditions, especially those having to do with the soil humidity content.

For this reason, among the significant events recorded, the one that occurred on the 30th July was chosen. As can be seen from the graph in figure 3, it was preceded by more than two months without rainfall. This circumstance made it possible, during the flow modelling phase, to consider the initial condition in the zone uninvolved by the groundwater as that of dry soil ($\theta_w = 0$).

The event consisted (figure 10) of a rainfall of 21.2 mm (measured by the pluviograph positioned inside the quarry) lasting about one hour. The volume overflowing from the tank, that did not give rise to any water head in the infiltration basin, was equal to 310 m^3; the groundwater level rose by about 49 cm.

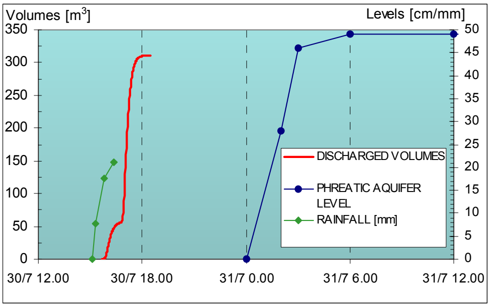

Figure 10: Event on the 18th and 19th August.

The main elements of the physical phenomenon that needs to be reproduced are:

1. time 15.15-16.35 hrs on the 30th July: the recharge basin receives an overall rainfall of 21.20 mm
2. time 16.35 hrs on the 30th July: the overflow from the bowl begins, and ends at time 18.30 hrs (the overall overflow volume is equal to 310 m^3, and involved an area of approximately 1200 m^2)
3. time 17.00 hrs of the 30th July: the ball cock in the infiltration basin records the presence of a water level of 20 cm
4. time 00.00 hrs of the 31st July: the groundwater begins to be affected by the recharge.

When applying and setting the model, the events at points 1, 2 and 3 were used as inputs, and the information at point 4 was used to assess the robustness of the response indicated by the model.

In accordance with the dynamics of the real phenomenon, the simulation was carried out in various steps in order to take account of the variations over time of the border conditions in the integration domain. The condition at the eastern border was an imposed fixed recharge value, at the western border, the free flow of the groundwater, and finally at the bottom, the presence of the impermeable clay limestone layer.

The initial condition was the position of the phreatic line, considered to be 7.70 m below the plane of the countryside.

As mentioned above, the water conductivity of the unsaturated domain was calculated on the basis of the knowledge of its value in saturated conditions, applying the ratios (1) and (2). It was therefore necessary to ascertain the most suitable values for the coefficients α and β.

Indications for the first attempt were taken from the experimental trials carried out by Lakshman and Prasad [4] working with foxhill sandstone, that has a fairly similar behaviour to that of calcarenite.

The next phase of refinement is extremely laborious and, as described below, not entirely satisfactory. The values assigned to α and β were iteratively changed, using a heuristic procedure, within a previously determined physically consistent range, in the attempt to reproduce the behaviour of the system.

Figure 11 shows the final result of simulations, compared with the experimental data. It can be seen that the laborious sensitivity analysis has only yielded a correct reproduction of the shape of the rise of the phreatic groundwater curve, but not the arrival time, which is approximately 5 hours earlier than the experimental time. Similar results were obtained when applying the model with the above settings to other experimental events. The correct reproduction of the shape of the level rise curve continues to be associated with a time lag of the same order as the one described above.

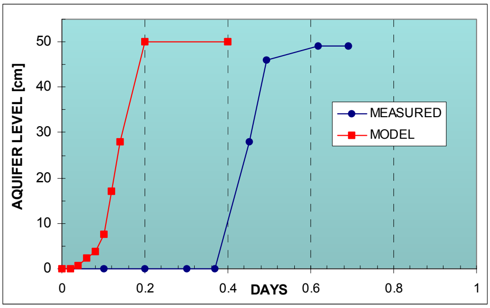

Figure 11: Comparison between the calculated and the measured levels in the groundwater sentry well.

As this difference does not vary according to the event, the proposed calculation model can be considered acceptable, despite the difficulty in transferring the perturbations in the pre-existing movements of the groundwater.

7 Conclusions

This experience of setting up and monitoring an artificial recharge plant of the phreatic groundwater has supplied a large quantity of data. They may be of important interest for the purposes of understanding and carrying out mathematical modelling of processes of infiltration through unsaturated zones.

Comparison of the dynamics of different events has demonstrated that the recharge phenomenon does not only depend on the entry volume but is also conditioned, in view of the delay before it occurs, by the initial value of humidity of the soil characterizing the unsaturated state and by the speed of infiltration.

Analysis of the experimental data collected up to now seems to show that the recharge effects, monitored on the basis of the rise in the free surface of the phreatic groundwater, is exhausted fairly rapidly, in a period in the order of days not weeks.

On the basis of this evidence, it therefore seems that adoption of this practice, at least for relatively small areas of groundwater like the one under study, is not feasible as an alternative method of storage of water resources, at least on a long term basis. The difficulties encountered in mathematical modelling of the phenomenon, due largely to the lack of published data on the values to be assigned to the van Genutchen parameters, demonstrate the need to carry out further experimental surveys of this kind.

In any case, the laborious sensitivity analysis conducted has made it possible to reproduce correctly in the model, the rise in the curve, experimentally recorded by the sentry well. The considerable delay observed before the water arrives in the groundwater could be attributed not only to incorrect individuation of some hydrogeological parameters, due to the lack of specific experimental analyses carried out on site, but also to the formation of a superficial layer of solid material, carried by the urban drainage system used for the recharge. This material, having different characteristics from the underlying calcarenite mass, could have deposited on the bottom of the basin.

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