With funding from the LIFE+ financial instrument of the European Union (LIFE 2010 ENV/IT/380)

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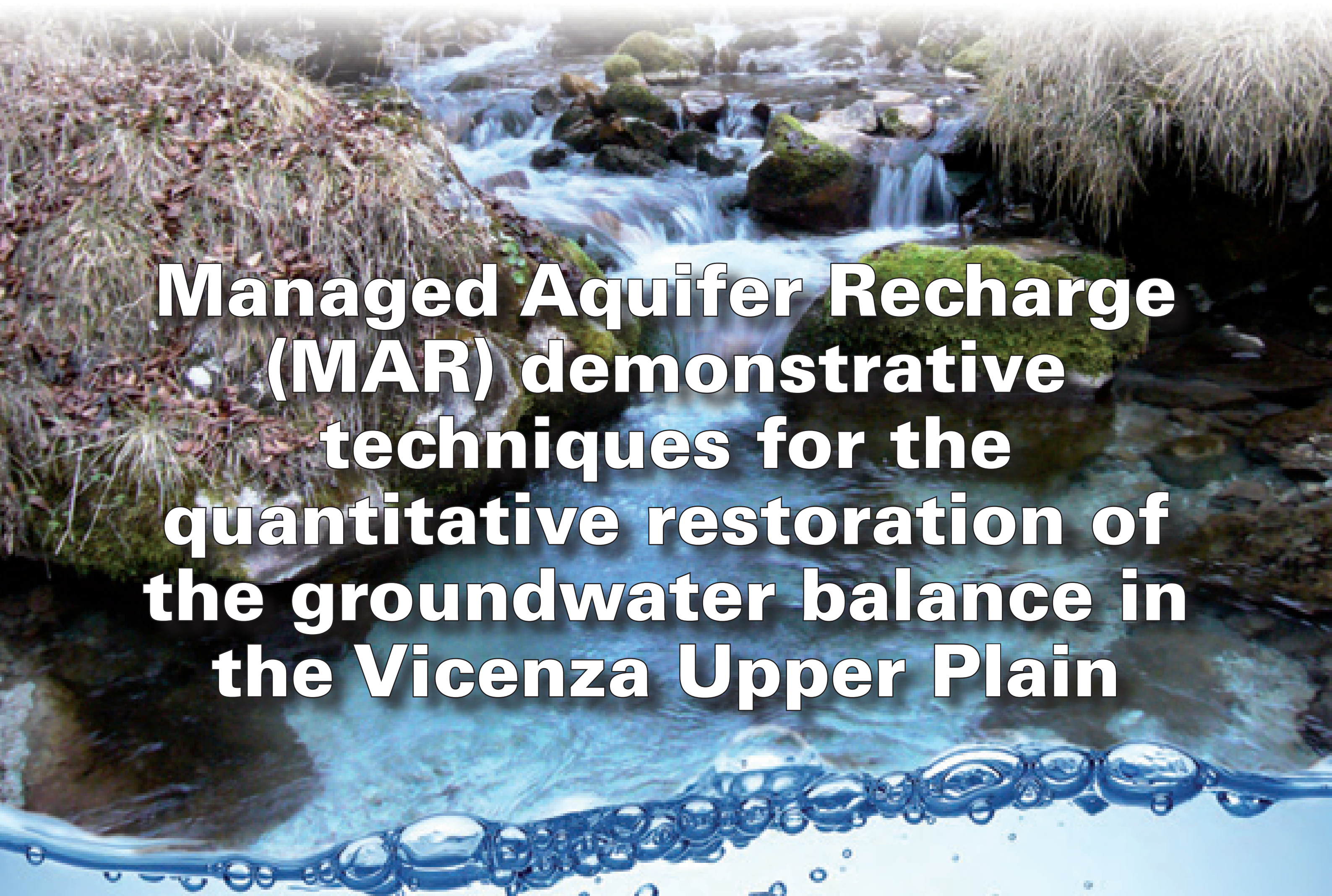

Managed Aquifer Recharge (MAR) demonstrative techniques for the quantitative restoration of the groundwater balance in the Vicenza Upper Plain

AQUOR

ABBIAMO A CUORE L'ACQUA

Implementation of a participatory strategy for water conservation and artificial groundwater recharge to quantitatively restore the groundwater balance in the Vicenza Upper Plain

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INTRODUCTION

The objective of the AQUOR Project is to "implement a participatory strategy for water conservation and artificial groundwater recharge to quantitatively restore the groundwater balance in the Vicenza Upper Plain". The project is co-financed by the European Commission LIFE+ Programme. The partners involved in the project are: Province of Vicenza (coordinator), Acque Vicentine, Alto Vicentino Servizi, Consorzio di Bonifica Alta Pianura Veneta (Veneto Upper Plain Drainage Authority), Consorzio di bonifica Brenta (Brenta Drainage Authority), Centro Idrico Novoledo Water Analysis laboratory and Veneto Agricoltura. The total cost of the project is € 1,814,548 of which € 693,348 is being financed by the European Commission and € 1,121,200 is the responsibility of the Province and associated beneficiaries. Initiated in September 2011 with a planned duration of three years, the project was conceived as a demonstration activity to foster a reversal of the current trend of overexploitation of groundwater resources and to increase the hydrogeological recharge rate of aquifers. The goal is to restore the groundwater balance in the Vicenza Upper Plain and ensure the sustainable use of this resource by current and future generations.
The objectives of the project are as follows:

- Create and share an integrated knowledge structure on the hydrogeologic system and its primary weaknesses;
- Make users of these water resources aware of the problem and actively involve them in efforts to conserve water and restore the groundwater balance;
- Demonstrate the technical feasibility, economic advantages and environmental sustainability of aquifer recharge;
- Develop an integrated and participatory model for the governance of groundwater resources on a local level.

The principal activities involve: increasing awareness among the various regional players regarding the importance of water conservation, creating groundwater recharge pilot systems, monitoring the efficacy of recharge, drafting and adopting a multi-user agreement for groundwater governance (Groundwater Contract) and promoting activities to disseminate information on the project and its results.

GENERAL INFORMATION ON GROUNDWATER RECHARGE

The Vicenza Upper Plain is part of a region that is very important from a hydrogeological perspective, since it is the recharge area for the underground aquifers that constitute the primary potable water resource for large portions of the Veneto Plain.
This area is characterized by a high-permeability, undifferentiated sandy-gravelly alluvial bed (whose depth ranges from approximately 200 metres to the North of Vicenza to more than 400 metres to the East, in the direction of the Province of Padua). It contains a single unconfined aquifer that stretches from the upper plain to the springs line.
From a hydraulic perspective, this aquifer regulates changes in the deep groundwater reserves to the South, which are subject to significant extraction for human use.
Since the 1960s, the water reserves in the hydrogeological system of the alluvial plain have been progressively diminishing.
The lowering of the water table has had serious effects, including a notable depressurization of the artesian aquifers in the middle plain, which threatens the supply of drinking water resources and compromises the spring system. In particular, the compromised spring system is one of the most apparent results of the change in the aquifer level, as it has led to the loss of many resurgent springs and a drastic decrease in the total discharge of spring-fed rivers, with a consequent reduction in the habitat of plant and animal species. The primary factors that have contributed to the decrease in groundwater level are outlined below (see Table 1).

Table 1 - Primary factors that have contributed to the decrease in groundwater level

FACTOR	DESCRIPTION
Increase in water withdrawals	The increase in civil, agricultural and industrial water withdrawals is due to the socio-economic growth of the region and water resource usage that is at times irrational and inefficient
Alteration of the course and hydromorphological dynamics of rivers	Impacts from artificial alterations to watercourses and river bed lowering due to excavation
Increase in impermeable surfaces (soil sealing)	The significant development of residential, industrial, handcraft and commercial areas has significantly reduced the recharge surface area and modified the manner in which meteoric water drains toward the aquifer. In fact, precipitation water is quickly transferred downstream due to the large areas of impermeable surfaces, resulting in a dramatic decrease in the time of concentration and an alteration in the infiltration rate
Shift from gravity surface irrigation to sprinkler irrigation	While the shift from gravity surface and flood irrigation systems to sprinkler systems optimizes water resource usage by reducing withdrawals, it also decreases the volume of groundwater infiltration that originates from the water supply and distribution network
Use of pressurized pipes to divert water in the minor hydrographical network to supply hydroelectric plants (including during non-irrigation months)	This leads to a reduction in runoff along the infiltration network and, in several cases, the water is discharged downstream of the deep aquifer recharge zone (therefore only benefitting the more superficial aquifers and, if the release point is near a natural hydrological regime, the springs)
Climate change	Changes in the rain regime, with shorter and heavier showers than in the past

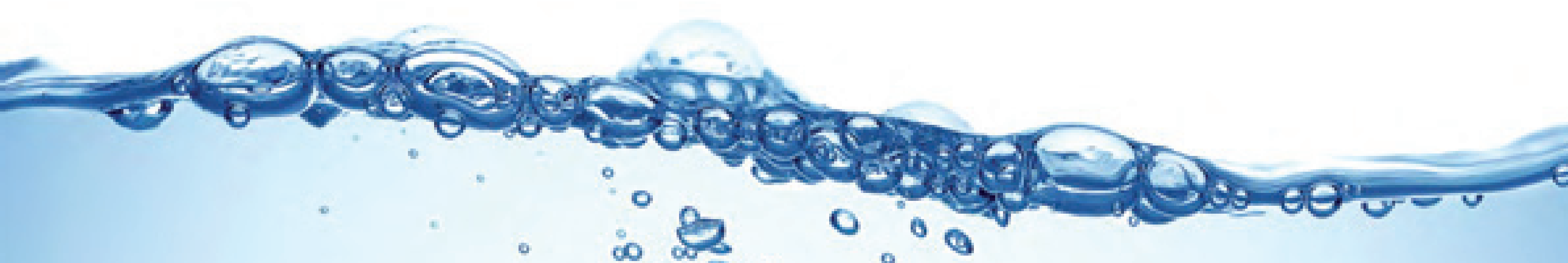


Figure 1 - Permeable surfaces

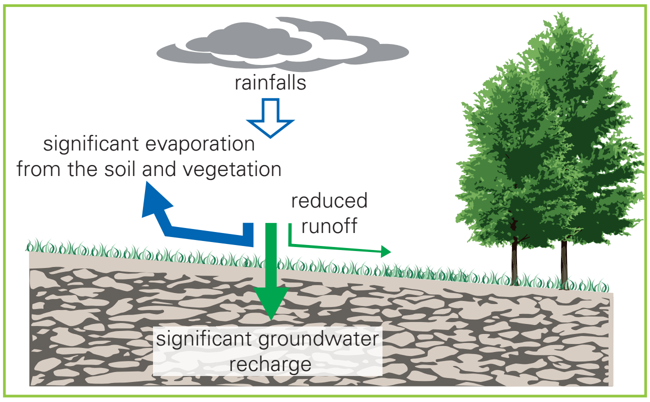


Figure 2 - Impermeable surfaces

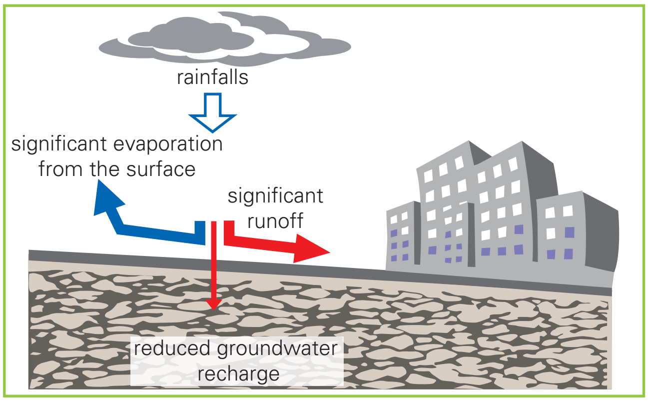


Photo 1 - Permeable surfaces

Photo 2 - Impermeable surfaces

THE NATURAL PROCESSES OF WATER INFILTRATION INTO AQUIFERS

The primary natural water sources that feed the underground hydrogeological system and therefore contribute to groundwater recharge are:

a. infiltration of meteoric water;
b. infiltration of water through the beds of natural waterways;
c. percolation through areas irrigated with gravity surface systems;
d. underground flows from fractured aquifers located in the foothills of the Alps.

a. Infiltration of meteoric water from precipitation (rain, hail, snow, etc.) is an effective contribution to groundwater recharge.
It provides a particularly significant contribution in the undifferentiated aquifer area, in the zone between the hills and the area where the first low permeability lenses appear (spring zone).
The relatively modest slopes and the high vertical permeability that characterize this area favour vertical percolation of rainwater. In the area between where the first clay lenses appear and the lower spring line, the rainwater infiltration conditions and therefore the aquifer recharge conditions are quite limited. In the area South of the springs, on the other hand, only a small part of the precipitation feeds the phreatic aquifer (very thin), while the majority is lost through evapotranspiration or is drained by the surface network.

b. The most significant contribution to groundwater recharge is provided by infiltration from the beds and sub-beds of the main watercourses (rivers and streams), which is fostered by the gravelly subsoil and the undisturbed geomorphology.

c. Another important factor that affects the aquifer recharge process is the water distributed on the ground by irrigation systems, or rather the percolation of water that occurs in areas using surface gravity irrigation. The distribution and supply of water resources for agricultural purposes is managed by the drainage authorities. The quantity of water used and its contribution to groundwater recharge varies dramatically depending on the irrigation method utilized by the different drainage authorities. In gravity surface irrigation systems, water is distributed by means of open, unlined chan-

nels (irrigation ditches) that have highly permeable beds. This allows a significant portion of the water to infiltrate into the soil and feed the aquifer.
With the replacement of traditional gravity surface and flood irrigation systems with sprinkler systems, irrigation water is now distributed by means of impermeable artificial channels and pipes. While this has allowed for significant savings in water resources, it has reduced an important source of groundwater recharge.

d. Aquifers contain water bodies whose characteristics vary depending on the type of materials from which they are formed. When contained by crystalline or sedimentary rock, water predominately circulates along fractures and discontinuities (fractured aquifers). In the case of carbonate rocks, water circulates along karst cavities and conduits (karst aquifers), while in the case of loose soils, water fills the spaces between the granules (porous aquifers). Regardless of the type, aquifers store water that contributes to the groundwater supply.

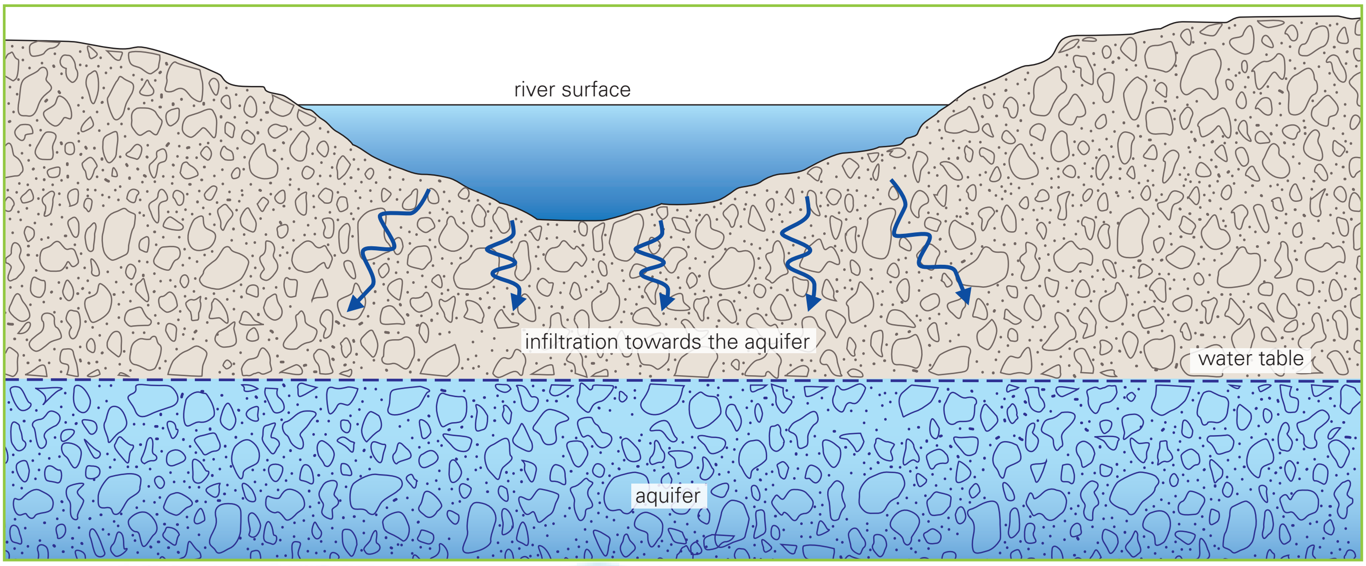
THE ARTIFICIAL PROCESSES OF WATER INFILTRATION INTO AQUIFERS

Various artificial aquifer recharge activities can be utilized to attempt to restore the groundwater balance in the upper plain. These solutions encourage controlled infiltration in particularly suitable sites and are used during periods when excess water is available. As part of the AQUOR Project, various groundwater recharge methods were evaluated, including part of those that have been reported in the literature and that have already been tested to some extent in the Vicenza region. A few of these techniques are described briefly below, while the second part of this document provides case studies.

Forested Infiltration Areas: A recharge system that involves distributing water during non-irrigation months in areas that have been equipped with a network of channels and various species of trees and shrubs, planted based on the type of forest system being created. In addition to recharging the aquifer, this system purifies the water as it passes through the 'filter' of plant roots and microorganisms that live in symbiosis with the vegetation.

Photo 3 - Forested Infiltration Area that produces wood biomass for energy purposes

Figure 3 - Riverbed cross section showing groundwater infiltration



Infiltration wells: This technique is particularly suitable when only a limited amount of space is available and the previous technique, which requires an extensive area, is not possible. In this case, the infiltration system features vertical structures made of perforated rings that are two meters in diameter and reach a depth of between four and six meters[1].

Infiltration trenches: This technique involves the use of artificial excavated depressions that are filled with inert, high-permeability materials. One or more perforated pipes known as infiltration pipes are placed at the centre of the trench, immersed in the drainage material, to ensure regular distribution of water along the length of the trench. It is a good idea to cover the sides and the top of the trench with a geotextile to prevent obstruction of water flow by small particles washed from the surrounding soil.

Infiltration trenches and **wells** are often built to accept excess meteoric water from impermeable surfaces (buildings, roads, paved areas, etc.). In addition, they are used to aid infiltration by bridging superficial layers of low-permeability soil in order to reach a more permeable layer. These systems have the advantage of needing little surface area, having good holding capacity and not having any particular restrictions regarding the use of the area above the structure.

Photo 4 and Figure 4 - Photo and diagram of infiltration well

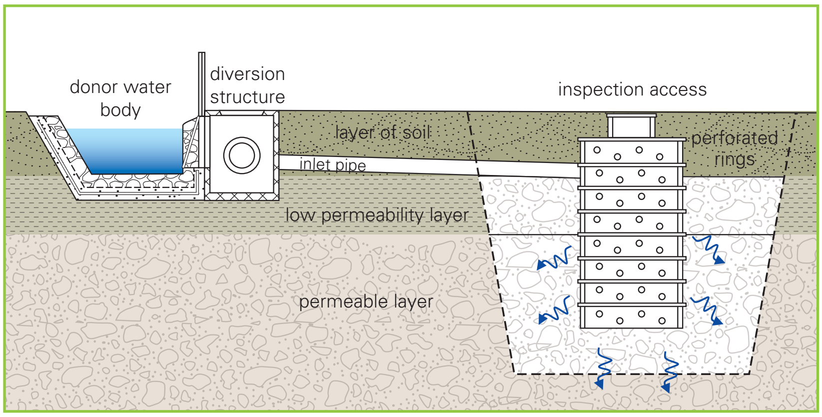
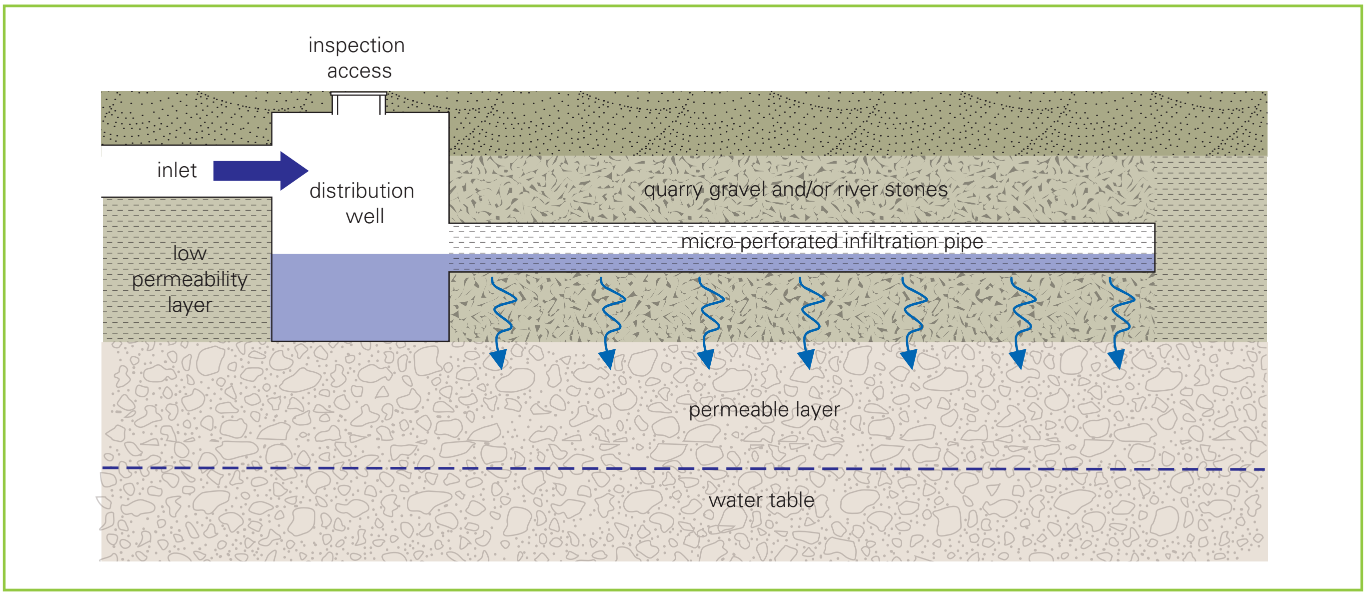


Figure 5 - Diagram of infiltration trench



[1] These dimensions are indicative and refer to specific applications in the AQUOR Projects. In general, the size and shape of the structures must be designed to meet the project requirements.

Sub-surface infiltration field: Sub-surface infiltration field involve a network of perforated pipes placed under agricultural fields. The pipes are placed in small trenches filled with inert, permeable material to facilitate water percolation. This technique enables the use of agricultural land situated in suitable recharge areas that would otherwise not be made available by the owner, due to the agricultural value of the land. If the owner wishes to continue farming the land, the only requirement is to follow proper agricultural practices with respect to applying fertilizers and weed-killers.

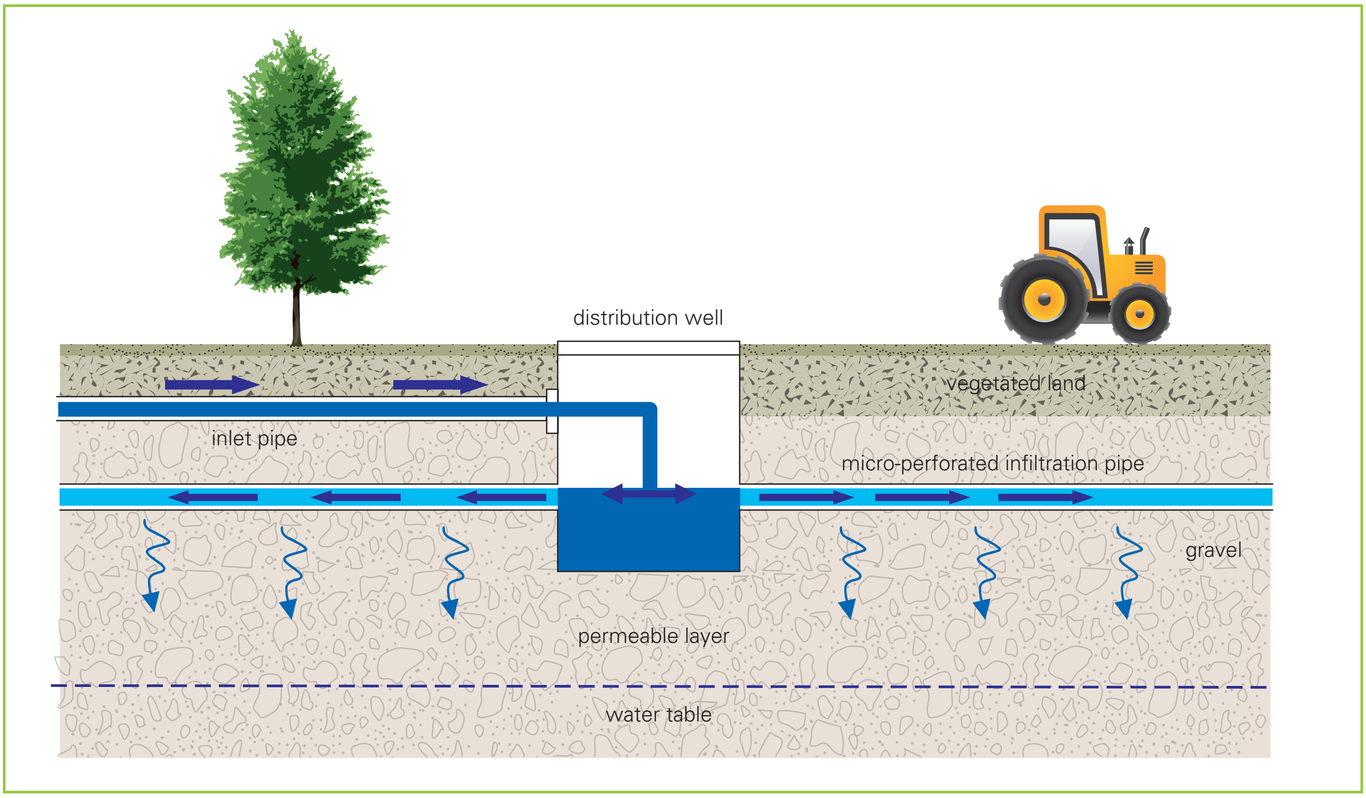
The water for all of the techniques described is supplied via a regulated inlet system (typically small channels or pipes equipped with gates) connected to a donor water body (typically the irrigation network).

DETERMINING THE SUITABILITY OF AN AREA FOR GROUNDWATER RECHARGE PROJECTS

The potential for constructing an artificial groundwater recharge system on a specific site depends on the suitability and availability of the land. In some cases, a site may already be available for use for this purpose, but it must be tested for suitability before proceeding. In other cases, it may be necessary to find a suitable site (or sites) within a certain geographic area.
The suitability of a particular site (or area) for groundwater recharge projects therefore depends both on its intrinsic infiltration characteristics, as well as its availability for use. Such suitability can be established by verifying a few key factors, which are described and analyzed below. First and foremost, five fundamental aspects of the potential site (or area) must be considered:

A. The characteristics of the subsoil and soil – pedological and hydrogeological aspects;
B. Land use – what stands on top of the soil;
C. The availability of the land for the installation of recharge systems;
D. Potential water supply – proximity to natural or man-made watercourses and water quality;
E. Proximity to draining watercourses – natural watercourses that have beds below the water table.

Figure 6 - Diagram of sub-surface infiltration field



A. The characteristics of the subsoil and soil – pedological and hydrogeological aspects

As is apparent in the hydrogeological diagram (see Fig. 7), the unconfined aquifer has a water table that slopes from the uphill area to the downhill area. The piezometric level of the phreatic aquifer is not constant, but rather varies throughout the year. In fact, since it is directly connected to the precipitation and surface runoff regime, the aquifer has two low periods and two high periods per year. The groundwater moves downhill at a velocity that varies depending on such factors as the granulometry of the alluvial bed, the quantity of meteoric water that infiltrates, etc.

From the northern mountain slopes to the first clay lenses, the permeability of the alluvial bed is continuous and uninterrupted both vertically and horizontally (but for the colluvial belt of the piedmont).

The bed is composed of pebbles and gravel that gradually turn to finer yet still permeable materials downhill.

Continuing downhill, at a certain point the first clay lenses appear, disrupting the vertical permeability of the alluvial bed. This occurs along a line known as the "deep aquifer recharge zone boundary".

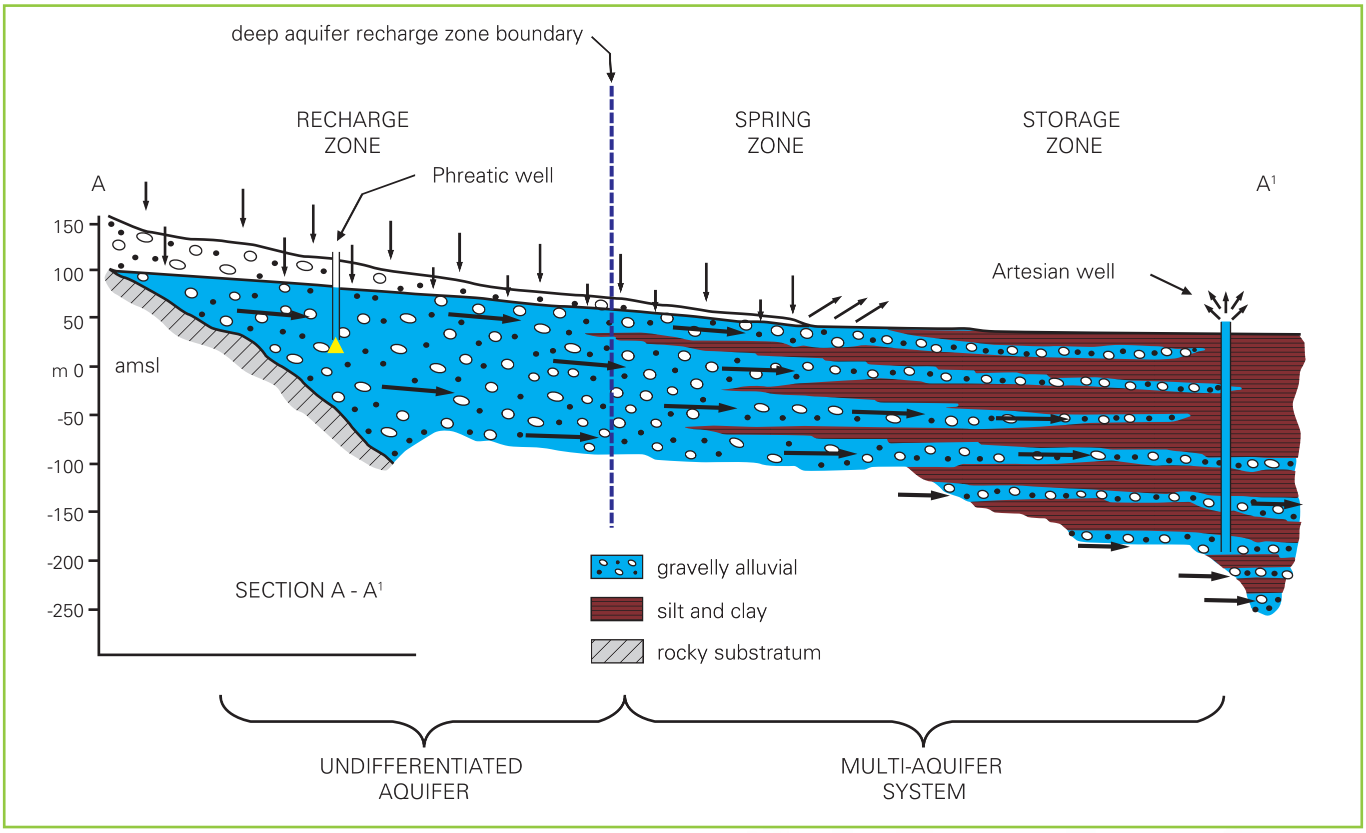
The deep aquifer recharge zone boundary is very important in determining a site's suitability for recharge systems.

Uphill of this area, solely from a hydrogeological and pedological perspective, all types of recharge systems are appropriate. In fact, there are no obstacles between ground level and the water table; the water that infiltrates into the ground has no obstructions and travels directly to the deep aquifer.

Downhill of the boundary, there is an initial area where it is still possible to install certain types of groundwater recharge systems.

In this area, again solely from a hydrogeological and pedological perspective, recharge systems that can perforate the clay lenses that block the vertical flow of water are appropriate; such systems include infiltration wells of various depths. Perforation of the impermeable lenses allows the recharge water to reach the deep aquifer. This would not happen with forested infiltration areas or surface recharge systems.

Figure 7 - Hydrogeological diagram of the upper and middle Veneto Plain (A. Dal Prà)



Beyond this initial zone, water infiltration by gravity alone (without mechanical aid and associated energy consumption) is not possible due to the presence of several layers of clay, which bound the pressurized aquifers.

Stratigraphic study of the ground

Once a potential site has been identified, it is necessary to conduct a pedological and geognostic study of the ground. This is essential because it identifies the underlying structure of the ground and allows the evaluations described in the previous section to be made. Even within small areas, soil and subsoil can vary dramatically. It is necessary to verify that there are no vertical obstacles between the ground level and the deep aquifer at the site. These obstacles could be formations of various types, including small clay lenses, rocks and other types of impermeable material. The depth and thickness of these formations must also be measured to evaluate the possibility/feasibility of perforating them in order to install, for example, an infiltration well. The pedological study, on the other hand, enables characterization of the soil permeability, making it possible to determine whether surface recharge methods (e.g. forested infiltration areas) or deep recharge methods (e.g. wells) are appropriate.

The scope of groundwater recharge

Aquifer recharge enables restoration of the quantitative groundwater balance when the aquifer has been depleted due to an infiltration deficit (e.g. impermeable surfaces or changes in river discharge regimes) or excess water withdrawals (e.g. intensive or irregular use of water resources). The hydrogeological condition of the aquifers is also related to the state of health of various surface ecosystems, specifically the spring-fed watercourses and the land-based ecosystems that come into contact with groundwater (e.g. wooded areas or wetland plains that are in contact with groundwater).
The efficacy of the recharge activity must therefore be measured based on the specific objectives and recharge methods must be chosen accordingly. Specifically, deep recharge can be achieved by bridging layers of low-permeability subsoil by means of vertical structures (infiltration wells) that are deep enough to reach the target aquifer. Shallow recharge (e.g. intended to revitalize springs or shallower aquifers) can be achieved without bridging impermeable layers of subsoil, once the details of the specific site have been ascertained to ensure the hydrogeological correlation between the proposed recharge site and the desired spring zone.

B. Land use – what stands on top of the soil

Once the area has been analyzed from a hydrogeological and pedological perspective and it has been determined to be suitable for the installation of a groundwater recharge system, the land use must also be analyzed to determine the feasibility of the project. Examples of land use include the following:

- Woodlands;
- Agricultural land (various crops);
- Urban area;
- Peri-urban area.

For each of the above categories it is necessary to analyze constraints (historical-artistic, landscape-environmental, sensitive area in terms of pollution, etc.) and the land area available for construction of the system.

Woodlands

Existing woodlands that are located in suitable geographical areas and that have appropriate hydrogeological and pedological characteristics can act as infiltration systems if they are enclosed with a series of small embankments. The basins created would only be flooded during the fall-winter season (e.g. to reduce the hydraulic risk in the event of high water levels in the watercourse to which it connects). In addition to increasing infiltration and reducing the risk of flooding, woodlands offer phytoremediation of the infiltration water as is passes through the 'filter' of plant roots and microorganisms that live in symbiosis with them.
However, any decision to change the usage from woodland to groundwater recharge area must take into consideration the environmental and landscape value of the land in question, as well as its economic value from direct (productive forest) and indirect uses (ecosystem services offered by the woodland, including utilization, microclimate mitigation, visual appeal for surrounding populated areas, etc.).

Agricultural land

The different types of crops grown on agricultural land (e.g. arable crops, permanent meadows, pastureland, meadow-pastureland, vineyard, orchard, vegetables and flowers in greenhouses or open fields) determine the value of the land and affect its availability for recharge projects. Less valuable lands that offer limited profitability from agriculture are therefore the best candidates. Examples include marginal uncultivated land or small areas of cultivated land that could be used for aquifer recharge, offering the owners the potential to receive greater remuneration for the land than they previously received.

Urban areas

It is difficult to install groundwater recharge systems that use surface water in urban areas due to difficulties relating to construction (e.g. interference with underground services), water supply and constraints of various kinds. One strategy that is well-suited for urban areas is the sustainable management of urban runoff from meteoric water, or rather a precipitation collection and management system that channels rainwater after the first flush (or first flush water that comes from non-polluting and non-polluted surfaces), such as the roofs of residential buildings) into to subsoil.
When artisan/industrial areas are situated nearby, it is important to verify that there are no pollution sources that could contaminate the recharge water before it reaches the infiltration point.

Peri-urban area

Peri-urban areas (e.g. peripheral zones of large cities or rural areas with widespread development) typically have structures and layouts that lie somewhere between those of urban and rural areas. The feasibility of recharge projects must therefore be evaluated on a case by case basis.

When analyzing the suitability of an area for groundwater recharge from the perspective of land use, both the current use and the zoning of the property must be taken into consideration. For example, installing a groundwater recharge system on land that is currently farmland but that has been approved for development could later prove to be incompatible with the new use and economically counterproductive.

C. The availability of the land for the installation of recharge systems

The selection of the type of recharge system is also based on the surface area of land available. While an infiltration well may only require an area of a few dozen meters squared, a Forested Infiltration Area typically requires at least 0.5 hectares. These requirements can have a considerable effect on the cost of the intervention.

D. Potential water supply – proximity to natural or man-made watercourses and water quality

A relatively large quantity of water must be available at a reasonable cost (does not require construction of complex infrastructures) to supply aquifer recharge systems. This is only possible if there are natural or artificial watercourses in the area.

Natural watercourses can be rivers or streams that are able to supply the quantity of water necessary for the groundwater recharge system. They can only be used for feeding certain types of systems, like large infiltration basins (e.g. former quarries), and are not suitable for others, like forested infiltration areas or infiltration wells. This is because during high flow and moderate flow periods the water contains too many suspended solids, which would quickly block the porosity of the substrates and prevent the system from being effective.
Artificial watercourses can include irrigation canals, or rather artificial channels that bring water from a river to the surrounding countryside for agricultural use. A site that is located near an irrigation ditch of this type offers a decided advantage in terms of suitability for groundwater recharge systems.
Another factor that must be considered is the quality of the infiltration water.
The quality of the water that infiltrates into the ground in aquifer recharge zones, including artificial recharge systems, is extremely important in terms of protecting groundwater resources. Infiltration systems must therefore be supplied by donor water bodies that have chemical, physical and microbiological properties that will not have any negative impact on the aquifers. This factor can have a significant impact on the suitability of a site for installing a groundwater recharge system. It is therefore important to know the general conditions of the surface water in the intervention area and, more specifically, at the recharge site. In addition, the system must be equipped with suitable continuous monitoring instruments to detect and intercept any pollution that is accidentally released.

E. Proximity to draining watercourses - natural watercourses that have beds below the water table

If the potential site is located near a river or stream, it is essential to verify that the base of the bed is not below the water table. In such cases, regardless of the groundwater recharge system used, all of the recharge water would drain into the riverbed.
In fact, when the free surface of a watercourse is higher than the water table, water from the riverbed infiltrates into the groundwater. However, when the opposite is true, the aquifer feeds the watercourse.
Situations of this type are not uncommon. Large watercourses, for example the Brenta River, have been intensively exploited for the extraction of gravel from the riverbed. This causes a considerable deepening of the bed and inverts the direction of infiltration flow.

MONITORING AND CONTROL SYSTEMS

As has been discussed above, artificial groundwater recharge entails the installation of localized systems that transfer a portion of surface water flow towards the subsoil. This process increases the vulnerability of the aquifer, as it is connected to preferential flow routes that could potentially contain pollutants (e.g. intentional releases, diffuse pollution, occasional accidents, etc.). As such, the recharge infrastructure must be equipped with systems for detecting the presence of undesirable substances in the water allocated for infiltration. A multi-parameter probe system that can continually measure several important chemical-physical variables must therefore be installed upstream of the inlet point. This type of monitoring system makes it possible to arrange management protocols to cut off (either automatically or manually) the flow of recharge water in time to prevent any undesirable effects.
Monitoring the quality and quantity of the water allocated for aquifer recharge both upstream and downstream of the infiltration system (by means of measuring sections upstream and monitoring piezometers downstream) allows for calculation of the benefits achieved by the recharge intervention, both in terms of volumes recharged and the qualitative dynamics of the groundwater. Specifically, the efficacy of the recharge project can be verified by examining the groundwater levels and the discharge of the springs. For the AQUOR Project, multi-parameter probes were installed to continually measure the following parameters: turbidity, conductivity, temperature, dissolved oxygen, redox potential and pH.

AQUOR PROJECT INTERVENTION SITES

As part of the AQUOR Project, groundwater recharge systems have been constructed at seven sites. The table below provides information on the systems installed, the municipalities where they are located, the exact coordinates of the intervention sites and the partners that participated in designing and installing the systems.

Table 2 - Groundwater recharge sites installed as part of the AQUOR Project

RECHARGE METHOD	MUNICIPALITY	COORDINATES	LEAD PARTNER
Forested Infiltration Area	Carmignano di Brenta (PD)	45° 39′ 38″ N 11° 41′ 08″ E	Brenta Drainage Authority
Forested Infiltration Area	Schiavon (VI)	45° 40′ 40" N 11° 39′ 36" E	Brenta Drainage Authority
Sub-surface infiltration field	Rosà (VI)	45° 42′ 25″ N 11° 44′ 46″ E	Brenta Drainage Authority
Infiltration wells	Breganze (VI)	45° 41′ 54″ N 11° 33′ 14″ E	Alto Vicentino Servizi Water Company
Infiltration wells	Montecchio Precalcino (VI)	45° 41′ 04″ N 11° 32′ 20″ E	Veneto Upper Plain Drainage Authority
Infiltration channel	Sandrigo (VI)	45° 39′ 48″ N 11° 38′ 45″ E	Brenta Drainage Authority
Infiltration trench	Sarcedo (VI)	45° 41′ 41″ N 11° 32′ 04″ E	Veneto Upper Plain Drainage Authority

Schiavon (VI): Forested Infiltration Area

Photo 5 - Excavation of the channels for the forested infiltration area

Photo 6 - Forested Infiltration Area system just after completion

Photo 7 - Forested Infiltration Area after construction

Photo 8 - Sediment trap

Montecchio Precalcino (VI): Infiltration wells

Photo 9 - Excavation for the wells

Photo 10 - Installation of well

Photo 11 - Intake structure on the Monza irrigation channel

Photo 12 - Improvement of the banks and base of the irrigation channel