Managed Aquifer Recharge (MAR) - A Sustainable Solution for Water Supply

MAR – eine nachhaltige Technologie für die Trinkwasserversorgung

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Zusammenfassung

Managed Aquifer Recharge (MAR) bezieht sich auf die künstliche Wasserspeicherung im Untergrund im Zwecke einer nachhaltigen Nutzung. Diese Technologie wird weltweit angewandt. In der Wasserversorgung haben Forschungseinrichtungen zusammen mit Wasserwerken in Österreich, Deutschland und der Schweiz ein enormes Know-how im Aufbau von MAR Strukturen erworben. Ihre Kompetenz kann direkt auf Trockenregionen in Südeuropa und darüber hinaus übertragen werden. Die Europäische Kommission zeigt ein hohes Interesse an dieser Technologie und hat eine Task Force initiiert, so kann die Wasserversorgung in den mediterranen Ländern wesentliche neue Impulse erfahren. Ein generelles Ziel ist, den großen Wasserüberschuss im Winter in den Untergrund zu bringen, um ihn während der trockenen Sommermonate wieder zu nutzen. Natürlich ist eine solche Anwendung von den natürlichen und sozioökonomischen Bedingungen abhängig.

Alle gegenwärtigen Rahmenbedingungen führen zum Schluss, dass eine Schlüsseltechnologie für ein nachhaltiges Ressourcenmanagement die künstliche Grundwasseranreicherung (MAR) jedenfalls miteinschließt, um einen Ausgleich im Grundwasserhaushalt zu schaffen. Die Speicherung von Oberflächenwasser ist zumindest in den semiariden und ariden Gebieten aufgrund des Wasserverlustes durch die Verdunstung begrenzt.

Optionen für die künstliche Grundwasseranreicherung beruhen auf einen allochthonen und einen autochthonen Ansatz. Bei der allochthonen Variante wird der Wasserüberschuss eines Grundwasserhorizontes oder eines Oberflächengerinnes – durchwegs in Regen- und Schmelzperioden - in einen anderen Aquifer mit entsprechender Speicherkapazität geleitet und dort zur Versickerung gebracht. Die autochthone Variante gibt vor, dass ein Teil des überschüssigen Grund- und Quellwassers über eine Pumpstation im selben Aquifer infiltriert wird.

Von den Infiltrationstechnologien ist die Bewertung des Uferfiltrats etwas zwiespältig, da dieser Prozess nicht unbedingt der engeren Definition von MAR entspricht. *Infiltrationsbecken* sind der Atmosphäre ausgesetzte Wasserflächen mit dem Vorteil, dass die Sickerwässer in der ungesättigten Zone eine natürliche Reinigung erfahren. Sie sind die einfachste und am weitesten verbreitete Konfiguration zur Grundwasseranreicherung. Auch *Infiltrationsschlitze* dienen der künstlichen Grundwasserneubildung, entlang von verschmutzten Flüssen können sie überdies eine Barriere zur Abwehr von belastetem Uferfiltrat bewirken (z. B. auch im Wasserwerk Friesach/Graz). *Sickerbohrungen* kommen meistens bei tiefliegenden Grundwasserkörpern zur Anwendung. Zur Nutzung wird das Grundwasser entweder direkt aus derselben Bohrung gepumpt oder von Brunnen in der Nähe, wobei die Grundwassergeschwindigkeit berücksichtigt werden muss.

Summary

Managed aquifer recharge (MAR) is related to an artificial water storage in the underground in order to provide a sustainable utilization of groundwater. This technology is applied in a global scale. Although artificial recharge of groundwater in the European Water Framework Directive (WFD, 2006) is mentioned as possible supplementary measure to meet groundwater over-abstraction, “controls, including a requirement for prior authorisation of artificial recharge or augmentation of groundwater bodies” are mandatory. A basic requirement is that no deterioration of water status may take place.

A key challenge is to demonstrate that the impact of MAR on the subsurface is sustainable or reversible especially with respect to future policies on MAR including regulations on the quality of water acceptable for recharge. MAR could be tied with efforts to improve recharge in cities, e.g., reduce flood risk or elevate groundwater levels in overexploited aquifers. Within the coastal regions the main focus is directed towards avoiding saltwater intrusion. In addition, MAR can also act as a balancing tool between periods of high precipitation and seasons of strong water demand especially applied in Mediterranean regions.

With regard to Infiltration technologies the assessment of riverbank filtration looks somehow ambivalent, since these procedures do not agree with the term “artificial”, it’s still a natural process. The remaining technologies are worldwide still most common: infiltration ponds, trenches and injection boreholes.

Schlüsselwörter: Hydrogeologie, Anwendungsoptionen, Infiltrationstechnologien

Keywords: hydrogeology, options for application, infiltration technologies

Background and goal

Managed Aquifer Recharge (MAR) comprises a wide variety of systems in which water is introduced into the aquifer. The main objective is to store excess water for times of less water availability, especially in arid and semiarid regions, furthermore, to establish a barrier for purification of water and to reduce the risk of intrusion of impaired water like seawater intrusion or riverbank filtration.

MAR was following a long development of its application. On national level some 50 years ago, the city of Graz decided to construct 2 infiltration ponds at the water work in Graz-Andritz. Also, in other regions this technology was applied, but a considerable improvement was initiated by the European Commission, a task force on “Managed Aquifer Recharge” was established with the main actors in Germany, France and Austria to coordinate concerted actions for the further development of this technology. 22 demonstration sites have been investigated in total (WssTP, 2010). Most of them were dealing with underground storage measures like in Austria, UK, Denmark, Spain, Portugal, Belgium, Saudi Arabia, USA, China, Australia. Other sites include riverbank filtration with examples in Germany, France, Spain, also executed with treatment facilities. Finally, MAR is used to prevent seawater intrusion in Spain, Portugal, Italy. The results were discussed in the report of “Water Supply and Sanitary Technology Platform” (WssTP, 2010) and have been published in Grützmacher et al (2010).

Recent publications, like Dillion & Arshad (2016), are dealing mainly with ecosystems, social issues, biodiversity and regulations. Stefan & Antems (2018) developed an excellent database and global inventory of MAR sites but creating also a misunderstanding that in Europe most of MAR configurations would be oriented to water quality management. This statement relies on the large importance of riverbank filtration (e.g., Berlin) and is not reflecting the reality of MAR management in aquifer storage improvement. Furthermore, any reference to the Task Force of the Commission is missing.

Requirements of the European Water Framework Directive (WFD, 2006): Although artificial recharge of groundwater is mentioned as possible supplementary measure in the WFD to meet groundwater over-abstraction, “controls, including a requirement for prior authorisation of artificial recharge or augmentation of groundwater bodies” are mandatory. A basic requirement is that no deterioration of water status may take place.

Sustainability of MAR: A key challenge is to demonstrate that the impact of MAR on the subsurface is sustainable or reversible especially with respect to future policies on MAR including regulations on the quality of water acceptable for recharge. In addition, the application of MAR has to be considered in relation to other subsurface uses, such as cold/heat storage, industrial water use, soil and groundwater contamination and salinization. MAR could be tied with efforts to improve recharge in cities, to reduce flood risks, or restore groundwater levels in overexploited aquifers. Within the coastal regions the main focus is directed towards avoiding saltwater intrusion. In addition, MAR can also act as a balancing tool between periods of high precipitation and seasons of strong water demand, as it happens in some Mediterranean regions.

The benefit of MAR is shown in two fields (Grützmacher et al, 2010).
To combat water scarcity:

- Water stress in Europe affects 1430 million inhabitants.
- Water scarcity and drought have cost 100 billion euros in last 30 years.
- Water stress increases with climatic change.
- 42 % of abstracted freshwater in Europe is used for irrigation, 50-70 % in Southern countries.
- Population doubles during summer along the Mediterranean coast.

To avoid groundwater pollution:
In most applications, MAR acts as a buffer in terms of water availability and water quality. The key parameters that determine the extent of the system can act as a storage coefficient of the aquifer also considering the clogging at the entry point of the recharge water. Clogging occurs due to physical, chemical, or biochemical processes and needs to be regarded carefully as it may reduce the systems performance substantially. In practice infiltration ponds can be cleaned regularly by scraping off the uppermost sand layer or by wet-dry-cycling, whereas the rehabilitation of clogged injection wells requires more effort. For this reason, pre-treatment of the injected water in some cases is necessary and periodic backwashing is used to maintain the conductivity. On the other hand, re-contamination by microorganisms, which is an issue in surface spreading basins, is avoided. In other cases, infiltration water originates from karst springs at times of high flow, taking account that their water quality generally fulfils the requirements for subsurface passage without pre-treatment.

Water quality aspects of MAR are governed by:

- the quality of the infiltrated water
- physical straining of particulate and particle-bound substances
- biogeochemical degradation processes within the aquifer
- aquifer mineralogy and water-rock interactions
- the quality of the ambient groundwater

Infiltration-exfiltration relationship

All hydrogeological features are associated with the TOTH approach (Toth, 1988). The sketch in Fig. 1 shows that every drop of water infiltrating into the underground will reappear at the surface after a certain time and after a certain distance. This recharge-discharge relation is depending on a strong hierarchy of catchments. However, this structure has to be taken account whenever MAR strategies might be realized since knowledge of three-dimensional groundwater movement is essential for the decision of infiltration types as well as for the location of the technical configurations.

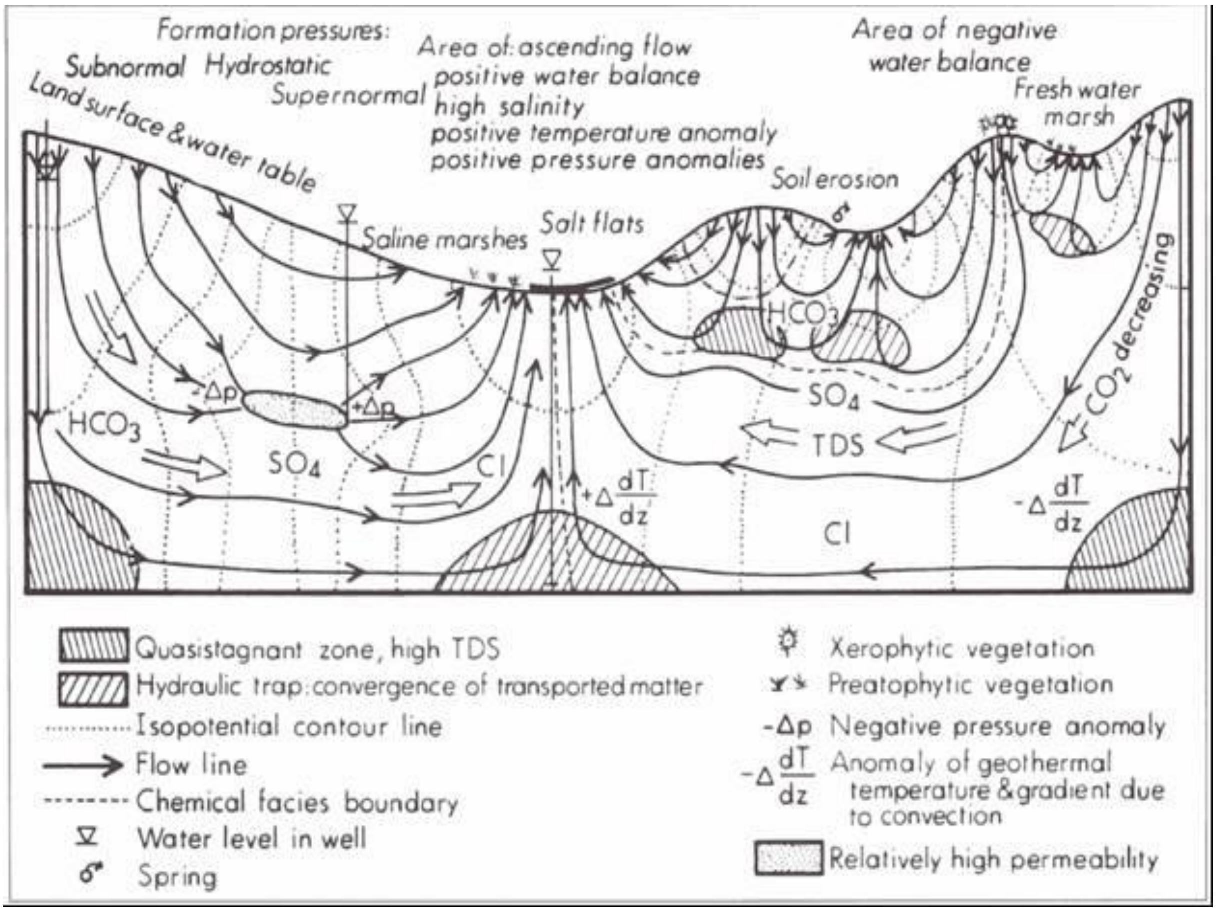

Figure 1: Recharge-discharge relation based on J. TOTH model (1988).

Boundary conditions for MAR

Several water suppliers, e.g., in Austria, Germany, Switzerland, together with research institutions have acquired an enormous know-how in the construction of artificial groundwater recharge structures and their management that can be directly applied in dry regions. The EU has exceptionally big interest in these technologies, because through this, for example, the **water supply in**

Mediterranean regions can be revolutionized. The aim is to bring the large water excess in winter into the underground to be used during dry summer months for drinking water supply and, if necessary and possible, for irrigation. Besides the need of early warning systems and emergency plans, the development of strategies to satisfy the water demands of dry regions, particularly during dry periods is recommended. In this regard the artificial groundwater recharge takes a central position. However, application of this practice depends on the natural and socioeconomic conditions.

Granular aquifers

In Friesach and Graz-Andritz groundwater fields the Graz Water Supply Authority practices artificial groundwater recharge in a **granular aquifer** for almost 50 years (Grützmacher et al., 2009). The data available from the infiltration structure and the results of hydrogeological investigations performed close to it enable to analyse the potential of artificial groundwater recharge. By considering the drinking water use, bank infiltration and surface water infiltration existing infiltration structures are optimised, and ultimately new markets are created.

This technological aspect concerns not only settlement water supply, but also sensor technology. In the development and further advancement of processes of artificial groundwater recharge more weight is given to the following points:

- Required resources: natural water reserves or biologically treated wastewater depending on the specific problems.
- Continuous surveillance of raw water regarding quantity and quality, giving much attention to the selection of suitable measurement parameters. In this connection, development of sensors is becoming increasingly important for continuous on-line recording of data.
- Conception, development and application of structures to increase and improve purification efficiency, cleaning and eventually the ability to be washed back.
- Optimisation of technology of infiltration structures with regard to infiltration and purification efficiency. In this case, a special attention is given to further advancement of the operation of polder and infiltration channels. Solutions are to be found out to the problem of algal accretion in sand basins. Also, in this case selection of suitable parameter and measurement technology is very essential to monitor the quality of infiltrating water appropriately.
- In the future, more weight will be given to the continuous monitoring of water flow starting from infiltration structures to withdrawal points. A good basis for this is the application of numerical models. It enables to consider different scenarios and Decision Support System (DSS), which need to be first calibrated using measurement data.

Hard rock aquifers

Most of the carbonate aquifers suitable for MAR applications are located at coastal regions. According to the seasonal changes of salinity, coastal **hard rock aquifers**, especially of carbonate habit, can be only utilised in time periods when the static pressure of the freshwater component is high and the fresh-/seawater interface in the aquifer is forced very much towards the sea. Overexploitations result in an increasing migration of seawater especially during the dry period. Different attempts to contain fresh water by boreholes and/or other technical constructions before mixing with sea water in most cases failed, which shows very clearly the actual limitations in the usage of those water resources. The reason for these natural conditions is based on changes of the sea water level since the Pleistocene. During glacial time sea water level dropped down since most of the freshwater in Europe was bounded in ice, and base level of karstification moved also downwards to reach the absolute drainage base, the sea. By melting of glaciers at the continent sea water level raised up, but karstification level remains still in a deep position, thus effecting sub-marine springs (Fig. 2). Due to the enormous water pressure from the recharge area during the rainy period the freshwater-saltwater interface is moving towards the sea and the submarine springs at the coastal strip comprise fresh water which can be used for MAR.

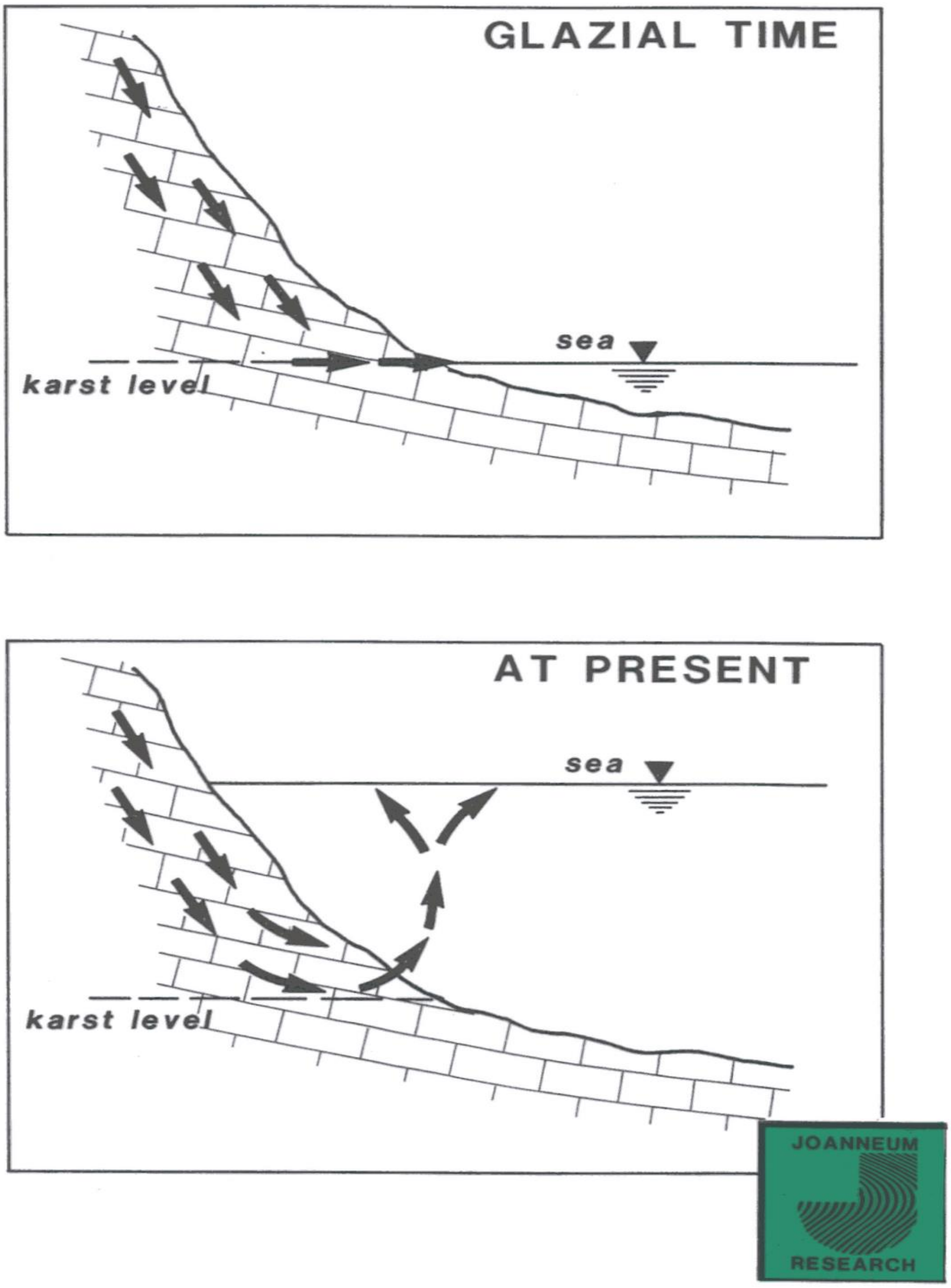

Figure 2: Changes of karst water level during glacial and post-glacial time.

Options for artificial recharge

Since artificial recharge is depending on local and regional geological and hydrogeological boundary conditions it has to be distinguished between two systems.

Allochthone recharge: Recharge into a separate system; surplus water is transported to another aquifer with a reasonable storage capacity and in case of coastal springs being not connected with the sea:

- Indication of recharge mechanism and underground storage, turnover time of freshwater components from inland and coastal aquifers respectively for both aquifer systems
- Study of physical processes in the aquifer, especially from the effects of storm events with gradual modifications for both aquifer systems
- Groundwater modelling of the allochthone aquifer in order to recognise infiltration processes
- Selection of proper kinds for infiltration punctual at the surface, punctual through injection boreholes, linear by infiltration drainages, areal by infiltration ponds

Autochthone recharge: Recharge into the same system; a part of the surplus water from the rain season is pumped back into the recharge area considering the turnover time of underground water in the natural aquifer:

- Indication of recharge mechanism and underground storage, turnover time of fresh and brackish water components from coastal aquifers respectively
- Study of physical processes in the aquifer, especially from the effects of storm events
- Determination of sites for artificial recharge (point or areal infiltration) by turnover time of about half year regarding the distance from the discharge of the system (springs etc.)

Availability of water resources for recharge

MAR systems are also classified with respect to the origin of the infiltrated water and the subsequent use of the recovered water:

- Traditional aquifer recharge systems for drinking water production using surface water from rivers (e.g., Berlin, Germany) or springs.
- Infiltrated surplus water from drainages or stormwater is often used for irrigation (e.g., Vergel aquifer, Spain).
- Treated wastewater of varying quality experiences gets additional purification during flow through unsaturated soils and the aquifer. Artificial recharge of secondary effluent to obtain water for unrestricted irrigation is mostly used in arid and semi-arid regions in USA, Israel, Australia and other countries around the world (WssTP, 2010). On the other hand, infiltrated wastewater from treatment plant effluents can serve as alternative water source for industrial use and irrigation.
- Water from desalination plants is increasingly used for aquifer recharge in arid countries.
- Infiltration of effluent industry water, process water or cooling water, for storage and reuse with the aim to achieve a certain quality and temperature.

State of the art and current practice

The actual handling with MAR is following two directions:

(i.) The hydrogeological features as presupposition for the selection of this technology in a specified area must be known, state of the art has not changed from the statement in the WssTP (2010).

(ii.) The eco-hydrological and biodiversity improvements are outlined in the publication of Dilon & Arshad (2016) so far.

Common MAR techniques used in a global frame are (Fig. 3):

- riverbank filtration
- artificial groundwater recharge – usually via pond or trench infiltration
- aquifer storage and recovery via injection wells

Riverbank filtration has a long history as a process for generating safe water for human consumption in Europe. During industrialization in the 19th century drinking water facilities in England, the Netherlands and Germany started using bank filtered water due to the increasing pollution of the rivers.
Today the water supply of many European cities and densely populated areas relies on riverbank filtration. In France the proportion of bank-filtered water was estimated to reach approximately 50 % of the total drinking water production. In the Netherlands 13 % of drinking water is produced from infiltration of surface water, such as bank filtration and dune infiltration. In Germany riverbank filtration and artificial groundwater recharge are used in the valleys of the rivers Rhein, Main, Elbe, Neckar, Ruhr and in Berlin along the Havel and Spree. In Berlin 60 % of the drinking water is derived from riverbank filtration and artificially recharged groundwater (Grützmacher et al., 2010).

Infiltration ponds are surface spreading basins providing added benefits of treatment in the vadose zone and subsequently in the aquifer. Surface spreading is the simplest and most widely applied artificial recharge method.

Infiltration trenches are also used to infiltrate water from a different source along a river if the river is too polluted and riverbank filtration has to be avoided. These Techniques have been performed for about 30 years for the protection of Graz water supply in Mur river basin.

Injection wells are often used for aquifer recharge in case of deep aquifers, insufficient available area or for sanitary aspects. For recovery the water is then either pumped from the same well or from adjacent wells subsequent to a defined transport time. These techniques are commonly applied in Australia and the USA, but also in Europe (Netherlands, Spain). First systems were operated for means of alleviating the effects of groundwater abstraction or saltwater intrusion. In the USA the first system came into operation in 1968, until 2002 a total number of 56 had been operational with more than 100 additional systems in planning.

Hydraulic barrier effect: Recharge of freshwater from different sources through well galleries or infiltration ponds along the shoreline will create a piezometric-hydraulic barrier protecting wells further inland from saline intrusion. The same MAR techniques have been used to protect drinking water wells in alluvial aquifers from accidental short-term pollution in the rivers hydraulically connected to the aquifer (e.g., the Crépieux-Charmy site providing Lyon with drinking water).

The common way of capturing infiltrated water is via wells in the influenced aquifer. Physical or bio-chemical clogging is a frequent issue here, met by a wide variety of regeneration methods. In arid or semi-arid regions, MAR may be utilized to support the discharge from groundwater well fields and springs that may not supply sufficient water throughout the year.

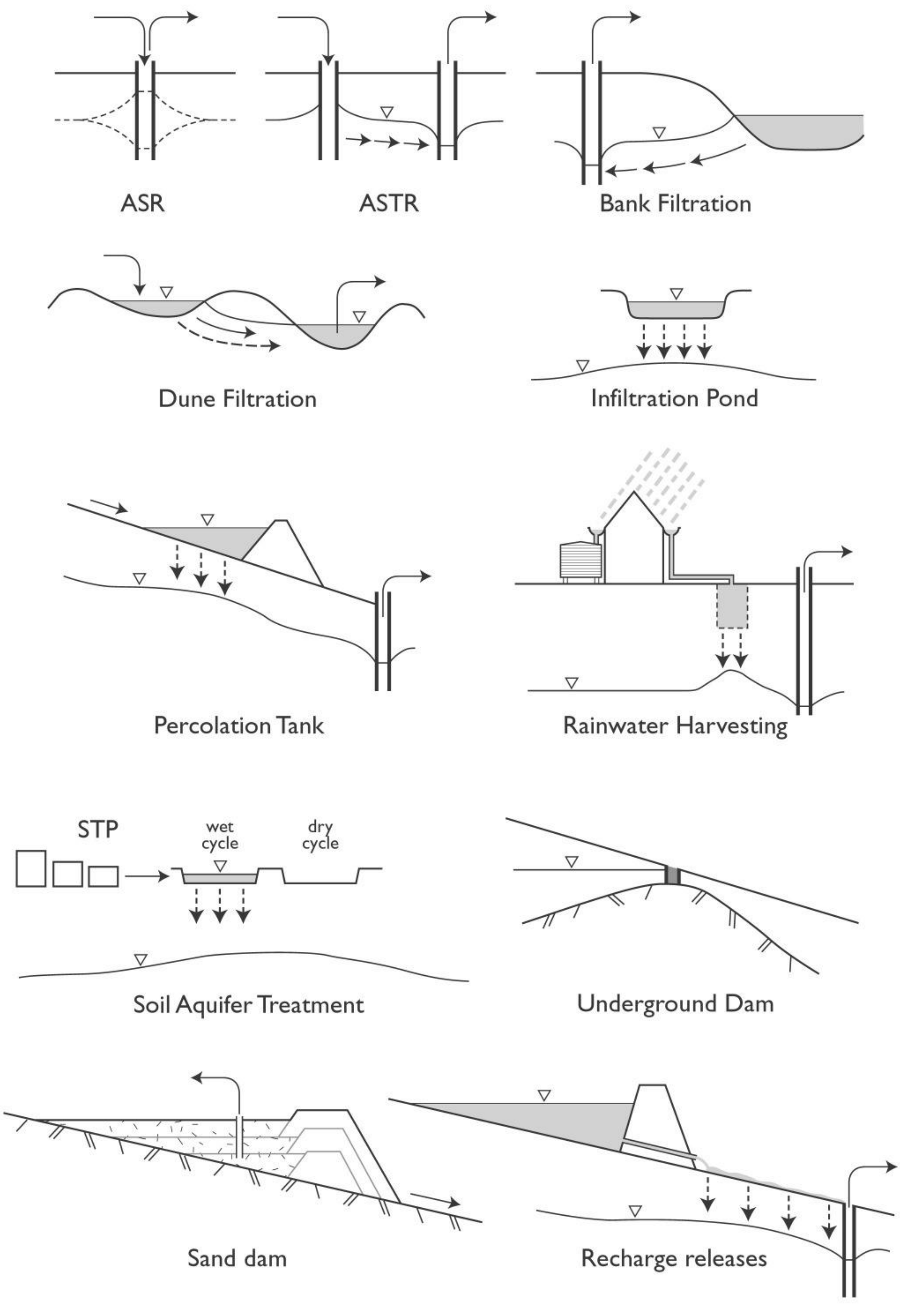

Figure 3: Infiltration technologies for MAR applications (from WssTP, 2010).

MAR applications

Inland aquifers

MAR in inland aquifers is considered as a possible countermeasure against water scarcity and aquifer overexploitation, which is explicitly mentioned in the EU Water Framework Directive (WFD, 2006). It enables the utilization of alternative resources that would not be used otherwise for drinking water and irrigation by buffering high variations in availability and demand and by acting as an additional purification step. MAR will be tied with efforts to improve recharge in cities, e.g., to evaluate groundwater levels in overexploited aquifers in urban areas. Therefore, research is needed to support formation of scientifically based regulation of MAR in order to achieve its benefits while ensuring protection and environmental flows.

There exists a wide range of fields in the application of managed aquifer recharge, but a systematic approach is insufficiently validated and conspicuously lacking, also the geochemical interactions within the aquifer need to be investigated to avoid or at least manage these processes. Here the role of rivers and sandy areas in recharge will be considered in the modelling of recharge in any area. As a consequence, MAR in inland aquifers will open new innovative lines as:

- regulatory management tool for groundwater basin scale under future climate change scenarios
- successful implementation of data base, prediction tools and technologies for optimized operation and monitoring
- adaption in WFD river basin management plans

Due to the geological and climatic features karst aquifers are characterised by large springs with sometimes enormous discharge fluctuations during the year. Thus, many karst aquifers are overexploited since the maximum water demand occurs in summertime. On the other hand, high aquifer discharge in winter causes a considerable water surplus, which is not used because of low water need in this season. This situation creates a considerable discrepancy between karst water availability and demand, which sets practical limitations to karst water exploitation and use.

Example: Cochabamba Basin, Bolivia

The basin consists of an inhomogeneous sedimentation forming a gradual lithological change of aquifers resulting in highly pervious zones alternating with semi-confining strata (Fig. 4). It is surrounded by crystalline rock formations, hydrogeologically characterized mostly by a surface drainage system from the upper highland down to the basin floor. For MAR approaches the following topics have to be considered:

- available water resources from the high plateau
- requirements for artificial recharge processes
- groundwater extraction related to MAR
- measures for groundwater protection
- establishment of a proper water management system

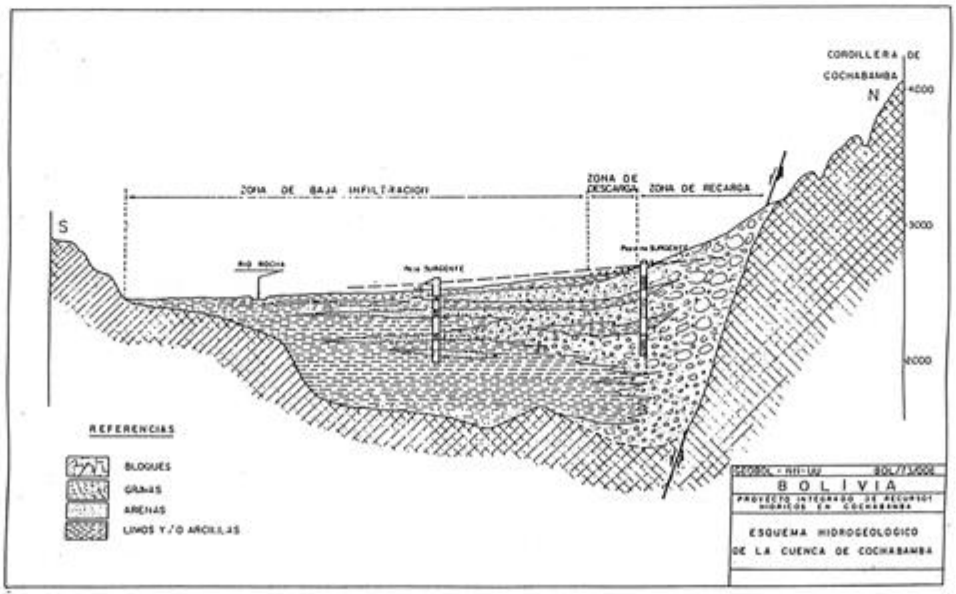

Figure 4: Cross section through the Cochabamba Basin showing gravels and sands in the northern part of the plain very well suitable for MAR (from GEOBOLIVIA).

Coastal environment

Coastal water management is closely linked with artificial groundwater recharge, which can help definitely to overcome water scarcity periods in these regions. The aim is to bring the large water excess in winter into the underground to be used during dry summer months for drinking water supply and, if necessary and possible, for irrigation.

Since karst water resources along coast lines are essential for water supply and irrigation the development of proper strategies for a sustainable use is necessary in order to preserve the ecological equilibrium. Coastal zones have seen the biggest changes in land uses, the major conflicts in water management, the most productive ecosystems and the greatest scrutiny regarding water quality standards. Considering the present mitigation measures and the climate change forecast scenarios predict further degradation of coastal zones. The complexity of this environment and thus the level of required integration are definitely high, making it a socially and economically relevant focus in need of specific technology and policy solutions.

No doubt, there is a need to implement MAR field pilots in coastal aquifers to test and validate parameters and indicators fulfilling the needs of water managers and policy makers and define the technical and economic feasibility of this technique based on rehabilitating aquifer recharge, interseasonal water storage enhancement and avoiding saltwater intrusion.

In coastal carbonate aquifers mixing processes decrease the reserve of freshwater resources from inland. Hence brackish water is not usable for drinking purposes and in most cases even not for irrigation. The **mixing processes are not limited to the coastal belt, they occur also in the inland part of coastal aquifers** depending on the evolution of shoreline since the last glacial period when the sea water level in the Mediterranean was situated up to some 80 meters lower than today. According to the seasonal changes of salinity, coastal carbonate aquifers can only be utilized in time periods when the static pressure of the freshwater component is high. Therefor the proposed priority research is based on MAR technology to open an innovative channel by:

- indication of recharge mechanism and underground storage, turnover time of fresh and brackish water components respectively
- introduction of MAR depending on geological and hydrological boundary conditions
- development of overall criteria for a well-balanced MAR due to the new extracted alternative water resources and the demand

Regarding the raw water it has to be taken account of:

- the selection of proper coastal and submarine springs.
- the utilization of spring water for MAR can only be possible during rainy season, when spring water is of freshwater type and sea water influence can be neglected.
- the rock-water interaction due to dissolution/precipitation processes in the aquifer, which can influence the subsurface pathway and the water quality.

Regarding infiltration processes it has to be considered:

- that high suspension of spring water to be infiltrated must be prohibited in order to avoid clogging problems.
- the selection of a proper aquifer with a reasonable storage capacity and not directly connected with the sea.
- the selection of target oriented technical configurations for infiltration (ponds, trenches, boreholes).
- the calculation of turnover time of artificially recharge groundwater for sustainable management of water resources.

In order to fulfil the innovative requirements of MAR the following Research and Technology Development (RTD) have been identified:

- Monitoring of freshwater-saltwater interfaces: since only freshwater components can be used for MAR infiltration procedures, coastal karst water will be solely available during the rainy season, a clear plan for water extraction is therefore essential, based on target-oriented monitoring.
- Hydrogeochemistry: rock-water interactions should be understood to be further integrated into geochemical and hydraulic modelling.
- Environmental isotope hydrology: indicating turn over time of water from infiltrating to exfiltrating point in the aquifer, related monitoring devices could be connected to real-time control for groundwater protection.
- Modelling and simulation: geochemical and hydraulic modelling, modelling of management scenarios and the effectiveness of measures.

Example: Golf of Argos, Peloponnesus, Greece

Most interesting seems the situation at a sub-marine spring near the village Kiveri at the eastern coast of Peloponnesus peninsula (Nr. 113, Fig. 5). The spring, emerging from about 8 m below sea water level just near to a steep wall of coastal limestones, has been captured unsuccessfully by a semicircle dam. The seasonal fluctuation of chloride reaches the same values as before the construction, thus affecting that mixing of sea and freshwater components occur not at the contact of the rock with the sea but in the karst aquifer itself. During wintertime, the spring water shows a totally freshwater habit, while in summer it is brackish and cannot be used for drinking purposes as well as for irrigation. Based on these conditions it was planned to construct a pipeline to the valley field behind the first mountain range associated with some ponds for sedimentation of suspended material in order to recharge the

Quaternary aquifer during wintertime. The valley is open to the sea, but near to the shore a conglomerate barrier prevents a quick outflow of groundwater to the sea.

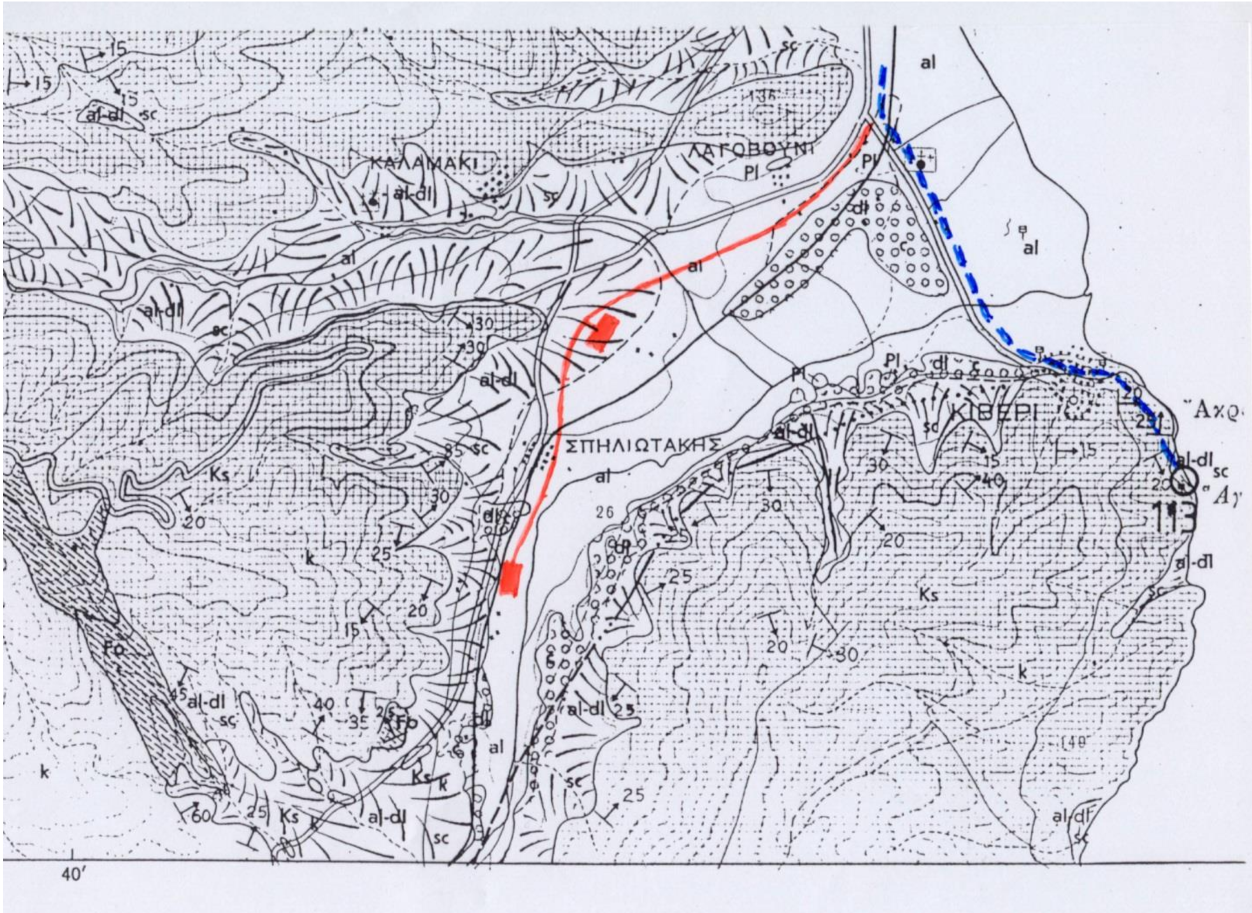

Figure 5: Location of Kiveri submarine spring (Nr. 113) in Jurassic limestones: blue dotted line: existing pipeline for irrigation in the Argos plain; red line: proposed pipeline to infiltration ponds in an inter-carbonate valley field (from Morfis & Zojer, 1986).

Example: Coastal strip Montenegro (Crnogorsko Primorje, 2004)

At present a pipeline system for water supply of the Montenegrin coast is almost finalised (Fig. 6). The water originates from the Bolje Sestre spring, a subaquatic outflow from a small lake, located north of the large Skadar Lake. Nearby the large lowland of Moraca River provides a possible good shallow aquifer, which can be used as a water body for MAR from the surplus of Bolje Sestre spring. For a better knowledge of the behaviour of this aquifer some hydrogeological investigations are necessary. In fact, you have to investigate the permeability of those sediments and the yield of a possible groundwater exploitation.

Figure 6: Water supply of the coastal strip in Montenegro from the karst spring Bolje Sestre, the overflow of the spring can be used for MAR in the Zeta Plain North of Skadar Lake.

Issues for MAR integration into European strategies

Developments in water demand: Although the per capita consumption in household and the abstraction for industrial purposes has been decreasing since 1980 there is a clear upward trend in irrigable land in the EU member states. Between 1961 and 1996 the irrigable surfaces have risen by > 5 million ha across the EU member states. Although water use efficiency measures have been proposed (e.g., planting crops with lower water requirements) it remains uncertain if these measures can compensate the ongoing increase in irrigated land. A second important factor to consider is tourism along the coasts of the Mediterranean Sea, which doubles the coastal population during summer and leads to high pressure on water resources in these regions at times during which water resources are scarce.

Implementation of the EU Water Framework Directive (WFD): In 2000, the European Commission endorsed the Water Framework Directive (2000/60/EC). The WFD commits European Union member states to achieve good qualitative and quantitative status of all water bodies (including near coastal waters) by 2015. It is a framework in the sense that it prescribes steps to reach the common goal based on integrated risk assessment and management rather than adopting the more traditional limit value approach. The WFD calls for integrated water resource management at the scale of river basins. The overall goal of the WFD represents a shift from a paradigm, focused on the exclusive uses of water. The goal is to ensure that the water demands of natural systems are environmentally balanced with the agricultural, industrial and domestic needs of societies. In particular, the WFD requires "the promotion of sustainable water use based on a long-term protection of available water resources", controlling the negative environmental impacts that water users can have upon the water cycle. At different steps in the cycle, water will be considered as a valuable finite natural resource while wastewater can be considered as a source of beneficial compounds (WFD, 2006).

MAR as a possible countermeasure against water scarcity and aquifer overexploitation: That is explicitly mentioned in the WFD and is already now implemented worldwide. Although not generating "new" water resources, it enables the use of alternative resources that would not be used otherwise (e.g., stormwater, recycled water) for drinking water and irrigation by buffering high variations in availability and demand and by acting as an additional purification step. Recharged water can also act as a hydraulic barrier to prevent saltwater intrusion or the spreading of contaminated groundwater and inhibit a regional decrease of groundwater tables. Thus, MAR should be regarded as a management tool to ensure water supplies under changing climatic and geographical regimes and as a means to achieve the goals of the EU directives - by interfering with and controlling the water cycle on basin scale, and thereby mitigating economic losses and facilitating increased economic productivity.

Technologies for project development

In coastal regions, one of the most urgent groundwater related problem is salinization due to seawater intrusion, in inland aquifers the focus is placed on water scarcity. EU countries need to balance the necessity of reaching a good qualitative and quantitative status (WFD, 2006) and the objectively hard task of reducing salinization in coastal aquifers. Apart from any suitable action course, aimed to solve this problem, it becomes evident that monitoring is the only available tool able to support the decision making during any step of such a path. In recent years geophysical methods have been increasingly applied for monitoring saltwater intrusion because they are non-invasive, very sensitive to water content and salinity, cost-effective and they provide areal information at a field scale, varying from decimeters to meters.

The selection of the most appropriate method depends on local geology and climate of the region and by economic constrains like raw water resources costs, soils costs, wastewater treatment costs, etc. Thus, climatic, hydrogeologic and economic constrains at the demo sites will lead to the appropriate infiltration methods as boreholes, infiltration basins, ponds or trenches.

The management of data from sensors to develop early warning systems in case of groundwater contamination and to develop emergency plans regarding water scarcity is based on the following aspects (WssTP, 2010):

- sensor installation, at source of water capture, at distribution network
- storage of data, either directly at the source downloaded from the data box or in an intermediate storage configuration
- transmission of data by telecom or satellite compounds
- data handling and interpretation to provide quick reaction for early warning systems and to develop data information lines within supply units

Aquifers are often well protected by layers of soil and sediments, which effectively filter rainwater as it percolates though them, thus removing particles, pathogenic microorganisms and many chemical constituents. Therefore, it is generally assumed to be a relatively safe drinking-water source.

Hydrogeological investigations at MAR sites include the collection of water samples using a submersible pump from wells. Monthly sampling campaigns are recommended in order to monitor the quality of water supplies during droughts and floods and to perform an appropriate validation of the transport model. Samples should be taken due to the depth of groundwater level and then processed in the laboratory for the microbiological control and for the detection of chemical water constituents (pH, salinity, turbidity, nitrates, ammonium and dissolved organic content).

As a kind of **alternative water utilization** MAR strategies should be implemented in the investigation site:

- to define management actions for MAR in coastal areas in order to mitigate droughts and seawater intrusion.
- to develop mathematical models for providing an assessment of soil aquifer treatment and of soil clogging during artificial recharge.
- to facilitate the implementation of MAR actions through conflict analysis and resolution.
- to apply models to quantify MAR efficiency on the protection and restoration of natural resources and ecosystems at the demonstration site.
- to place MAR configurations for an optimized raw water protection.

Could be developed as following, directed to MAR at coastal, island and inland sites:

- Experimental pilot plants realized to test MAR effectiveness will be studied. Filtration tests on the rock permeability reduction will verify, for instance, the soil aquifer treatment efficacy, under controlled operative conditions.
- Field measurements and tests at coastal and inland aquifers will be carried out in order to define hydrogeological parameters and their spatial distribution and possibilities of groundwater recharge efficiency.
- Field measurements and tests on aquifer to evaluate the impact on the groundwater temperature, due to the exploitation of groundwater as geothermal fluid.
- Integrated approach using a geophysical survey to support the traditional hydrogeological techniques in monitoring the dynamics of the freshwater-saltwater interface under artificial recharge conditions will be adopted.
- Data archive information which considers well data, IC-technology is used, and selected devices/sensor implemented. The efficiency of the project and proposed IC-technology will be tested also by monitoring groundwater in wells, by means of reliable measurements of freshwater restored in the coastal aquifers.
- Economic analyses will be carried out in order to select the best combination of IC-technologies which have to be used under assigned scenarios. Thus, it will be considered the calculations of costs for injection and/or water treatment plants, social impacts, social conflicts, etc.
- Chemical and isotope analyses will be performed to recognize the dynamics of groundwater for infiltration purposes, e.g., springs or surface water for inland aquifers, fresh waterbodies at coastal zones.

- Mathematical model simulations of water monitoring and groundwater supply will be developed in order to simulate scenarios under unfavourable conditions, like to severe droughts and groundwater overexploitation. The model results will be calibrated and validated in study areas in order to test the efficacy of all possible aquifer remediation techniques together with new pumping technologies and well instrumentations able to reduce water leakages or losses.

Conclusions

A reproduceable uptake of the economic and environmental benefits of MAR in Europe is currently being impeded by the lack of regulations and the wider communication concerning:

- quantification of the actual benefits and implementation costs
- potential environmental impacts
- policies to ensure their integration into catchment and river basin management plans
- reviewing the effects of climate change

These issues need to be addressed through appropriate research, establishing necessary communications and dissemination activities. Research is still needed in the field of hydrogeology as reflected in the WSSTP (2010). The ecological and social aspects are examined adequate in the paper of Dillon & Arshadi (2016).

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