Working Paper:
Aquifer Recharge

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"Many farmers know that their children cannot make a living from a depleting aquifer so they continue to maximise irrigated production to enable their children to complete their education and take up city jobs that offer higher returns than farming."
Dillon 2016, p. 4;

Abstract

Aquifer recharge occurs naturally through infiltration mechanisms. However, due to changes in the vegetation cover and consequently increasing soil erosion, infiltration rates tend to decrease. The recharge of an aquifer can be managed by facilitating natural infiltration processes and/or by the construction of structures that maintain recharge artificially. Several methods are available to enhance the recharge of an aquifer. The implementation of aquifer recharge schemes can massively increase groundwater levels, which is the best possible long term storage. Recharge can also help to address objectives such as improvement of source water quality, recovering of yields, creation of barriers to prevent saline intrusions and/or other contaminants, prevention of land subsidence, reducing potentially harmful runoff of stormwater. Alternatives to recover natural infiltration can be the application of ecosystem-based adaptation (EbA) measures or agricultural practice with permanent vegetation cover as permaculture. Artificial recharge methods, also called managed aquifer recharge (MAR), can be broadly categorized into: a) in-channel modifications, b) well, shaft and borehole recharge, c) induced bank infiltration, and d) rainwater harvesting. The method of recharge depends strongly on the survey of the site. Two key issues that are to be considered are the hydrogeological properties of the aquifer and the source of water. Recharge through living topsoil, as in swales, provides treatment and is by far preferable. In addition, it should not be forgotten that a humus rich soil with adequate vegetation cover provides retention and recharge without any technical intervention. However, the techniques described below are often needed to get restoration started at all.

Keywords: groundwater, aquifer, infiltration, MAR.

This is a working paper reflecting ongoing work. Comments and suggestions are welcome. Please do not cite or quote without author permission.

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Introduction

The main source of freshwater is groundwater (around 99 %) (Shiklomanov 1993). Groundwater comprises all water below the ground surface, found in pores and fractures, in the saturation zone and in direct contact with ground or subsoil (Council Directive 2000/60/EC). Large volumes of groundwater can be found in aquifers, which provide a safe water buffer by storing groundwater in the subsurface. An assessment made by Döll et al. (2012), indicates that, globally, from the total amount of water withdrawal for irrigation, households and manufacturing, groundwater contributes in 42 %, 36 %, and 27 % respectively, and in 35 % of the total water withdrawals. Döll (2009) states that around 70 % of the total withdrawal worldwide is used for irrigation. These figures give an impression of how human activities have a dependency on groundwater resources, especially in food security, due to rising population. These figures also denote how agricultural activities put pressure on land and water resources to meet food needs (ed. Conforti 2011).

Aquifer recharge occurs naturally through infiltration mechanisms. Whenever land is modified, this has an influence on the recharge quality and quantity. Some significant changes are for instance: deforestation, conversion of pasture to arable land, dryland farming, irrigated cropping, afforestation or reforestation, or urbanization (Foster & Cherlet 2014). Sustainable groundwater management must include land-use measures and actions to recover natural infiltration. Infiltration rates can be improved through the restoration of the vegetation cover and the usage of surface or subsurface structures, reducing with this run-off and soil erosion.

Additionally, when an aquifer has a continuous depletion, irreversible damages, such as saline intrusion, land subsidence, or aquatic ecosystem degradation, arise (Foster & Cherlet 2014). An increase of an aquifers stored volume or the restoration of a depleted aquifer can be accomplished by the use of artificial techniques. Artificial recharge uses infrastructures such as infiltration ponds/ditches or injection wells to facilitate soil infiltration (Jakeman, et al., 2016).

In order to warrant the quality and quantity of the water source, it is essential to have a sustainable use of groundwater. On condition that sustainable water management is established, groundwater can be a safe and permanent source of water for human consumption and economic activities. Sustainable management of groundwater must comprise a balance of recharge and abstraction rates and a seasonal and long term view (Alley, Reilly & Franke 1999). An efficient management of groundwater can also support the diminution and/or avoidance of problems such as high costs of water supply, population migration, desertification, loss of agricultural productivity and the subsequent emergence of social and political conflicts.

There are many regions without reliable water supply. Numerous of the groundwater storages are either not accessible, or abstraction costs are extremely high and several of the accessible sources have been overexploited. Especially in arid and semi-arid regions, where water scarcity is of major concern, the implementation of a sustainable Managed Aquifers Recharge (MAR) scheme can play an important role to restore the groundwater balance. This also supports the control of abstraction in an aquifer and the increase of water supply quality.

General Concepts about Groundwater and Aquifer Recharge

The recharge of aquifers forms part of the hydrological cycle. Precipitation (as rain or snow) that falls on the land surface can drain into streams, evaporate or, if the surface soil is porous enough, infiltrate into the ground. First, water seeps into the belt of soil water at the top of the vadose zone, where roots of plants are located. The fraction of water, which is not drawn by plants, is pulled down by gravity until it reaches the top of the saturation zone, becoming groundwater. The top of the saturation zone is known as the water-table (Fetter 2001).

An aquifer is distinguished by its subsurface geological layer formation either of water-bearing permeable rock or unconsolidated material (gravel, sand, or silt), and also by its thickness and areal extent. These characteristics, among others, determine the amount of water an aquifer is able to store (Gale & Dillon 2005). Groundwater is moving in and out of the aquifer's geological layers, allowing a significant flow of water in sufficient quantity that can be used as water supply. The process by which water is added from the outside of the saturation zone into the aquifer is called groundwater recharge. This movement may occur naturally or artificially (Council Directive 2000/60/EC 2000; Dillon, P et al. 2009).

The recharge process of an aquifer can occur directly or indirectly. Groundwater recharge can be local, occurring from infiltration via surface water bodies, or diffused, by percolation of precipitation through the unsaturated soil zone across the landscape (Döll & Fiedler 2008). The recovered groundwater can be used for irrigation, industry, as a supply of drinking water or for environmental uses. There are different methods and types of structures that can enhance the recharge of an aquifer. In order to have a sustainable recharge scheme, the technique or combination of techniques must be selected in consistency with the conditions of the site, the water quality for recharge and the required quality for the end-use.

A correct site assessment leads to a correct choice of which recharge method to apply and where it must be located in order to get the highest cost-benefit. Two key issues are commonly discussed by different manuals and articles before establishing a recharge scheme: hydrogeological characteristics and water quality (Dillon, PJ et al. 2009; Gale & Dillon 2005; Smith et al. 2016; Tuinhof et al. 2003). An overview of these subjects is discussed in the following sections. Moreover further information of surveying methods and groundwater analysis techniques are given by Kinzelbach & Aeschbach (2002) for arid and semi-arid areas, and also by MacDonald, Davies & Dochartaigh (2002) for low permeability areas in Africa.

Hydrogeological Characteristics of the Site

In order to avoid misconception, mismanagement, and/or incorrect decision making of groundwater resources, numerous literature sources point out the importance of hydrogeological background concepts (Gale & Dillon 2005; Smith et al. 2016; Tuinhof et al.

2003). A technical understanding of the aquifer recharge mechanisms and groundwater concepts such as water-table, aquitard, aquiclude, unsaturated zone or vadose zone, alluvial basin, storativity, transmissivity, specific yield, residence time, abstraction, confined, unconfined or semi-confined aquifer is essential. Foster et al. (2003) and Harter (2003) give an overview of relevant hydrogeological concepts related to aquifer recharge. More details can be found in the UNESCO document *An international guide for hydrogeological investigations* by Kovaleschy, Kruseman & Rushton (2004).

Foster et al. (2003) explains that the geological structure of the aquifer defines characteristics such as storability, transmissivity, flow regimen and residence time. Furthermore, the storage capacity of an aquifer may range from 30 % for highly porous unconsolidated to 10 % for highly consolidated and down to 1 % in case of crystalline rocks (Smith et al. 2016). The characteristics of the catchment area for the recharge define the infiltration rates into an aquifer. Characteristic of the landscape, such as natural vegetation or erosion, can slow down or increase the runoff respectively and subsequently have an impact on the recharge rates. There is a critical link between land-use and an aquifer's recharge mechanisms, which is discussed in detail by Foster & Cherlet (2014). Depending on the available hydrogeological data of the recharge site, one may be able to estimate the storage potential, propose a recharge scheme and consequently its cost-benefit.

Water Quality for Recharge

In order to assess the impact of water quality by recharge enhancement, three key issues should be taken into account: natural quality of the underground water, quality of the water source for recharge and anthropogenic activities in the recharge area. Some sources of water for aquifer recharge can be grouped as:

- surface water from perennial or ephemeral river flows or streams, lakes or dams
- storm runoff water from urban areas like rooftops, agricultural fields, or uncultivated land
- reclaimed water from treated effluent of industrial or domestic wastewater, or irrigation return flow
- potable supply water from high-quality treated water like from desalination plants

When recharging groundwater, the vulnerability of an aquifer depends on two main issues: the pollutant characteristics (mobility and persistency) and the hydraulic load. It will also depend on the aquifer characteristics, such as type of soil and rock, travel time through aquifer, ability to adsorb pollutants, and degree of confinement (Smith et al. 2016). If treated wastewater is used for recharge, it must be noted that even with proper biological treatment the effluents will typically contain a wide range of persistent micro-pollutants, pathogens and micro-plastic. This will restrict recharge to aquifers to heavily modified systems in an urban context, where the groundwater will also be used with advanced treatment. Infiltration with effluents into natural groundwater systems with their flow characteristics has to be avoided. Direct reuse or through storage ponds for irrigation of industrial crops will be a better option, especially for the uptake of nutrients (R Otterpohl 2017, personal information, 2 June).

Natural Recharge

Modifications in the landscape have reduced the infiltration capacity of natural recharge areas. As explained by Smith et al. (2016, p. 20), changes in the vegetation cover can impact the amount of water infiltrating into an aquifer. When soil is eroded, the run-off of rainwater increases, which subsequently reduces the rate at which precipitation infiltrates and recharges groundwater aquifers.

Smith et al. (2016) argue that the soil characteristics and vegetation in the surface determine the fraction of precipitation that becomes groundwater. As mentioned by Ansems, Khaka & Villholth (2014, p. 4), services provided by ecosystems are directly and indirectly dependent on the availability and state of groundwater resources. An integrated management of the ecosystem and groundwater have a positive impact on an aquifer's replenishment. By the implementation of some ecosystem-based adaptation (EbA) measures, the natural recharge of aquifers may be enhanced. As described by Ansems, Khaka & Villholth (2014), some measures include: protection of critical recharge zones, protection of groundwater dependent ecosystems, protection and restoration of riparian zones and floodplains, adaptation of soil and vegetation cover and investment in natural infrastructure.

Furthermore, some concepts of permaculture design also consider the enhancement of natural infiltration. Permaculture design considers factors such as vegetation type, land use, soil structure and organic content, slope and an integrated watershed usage and management. Some of the techniques permaculture design applies in conjunction for infiltration improvement are earthworks like swales, diversion drains, rain gardens, terracing, keyline system, or dams. Permaculture design also makes use of simulation of the soil food web, biodiverse plantings, and rotational grazing. A description of these methods is provided by Mollison (1992) or by Francis (2008). Additional resources of permaculture designs related to this topic can be found on Geoff Lawton's website (Lawton et al. 2017).

Artificial Recharge

In different literature sources, the terms artificial and managed are used interchangeably. Asano (1985) explains that the process of recharge, natural or artificial, is influenced by the same physical laws. Therefore, the term *artificial* applies to the availability of the water supply for recharge. Gale & Dillon (2005) mention that both terms *artificial recharge* and *managed aquifer recharge* (*MAR*) describe the intentional storage and treatment of water in aquifers.

There is a wide range of objectives and benefits of applying methods to enhance the recharge of aquifers, amongst which are to be underlined: storage of water, improvement of source water quality, recovery of yields, creation of barriers to prevent saline intrusions or other contaminants, prevention of land subsidence, recycling of stormwater or treated sewage effluent (Dillon 2005). Aquifer recharge methods have been used for decades, but currently the implementation of MAR schemes is increasing. Dillon et al. (2010) argue that aquifer recharge has an important role in securing the water supply to sustain cities affected by climate change and the increasing population rate, mainly due to the protection the aquitard gives to the water quality of drinking water supplies, but also because its function as a supply for agricultural irrigation, potable and non-potable uses.

Sprenger et al. (2015) discuss how in Europe MAR methods play an important role in drinking water supply, mainly due to their potential to treat water and attenuate undesired substances. They also describe how factors like hydraulic impact zone, attenuation zone, biotic and abiotic attenuation processes, temperature, oxic and anoxic redox conditions, among others have an impact on the source water for recharge during subsurface passage. This implies that, according to the characteristics of the aquifer, the water source, and the end-use of the reclaimed water, as part of a MAR scheme, should be considered a pre-treatment and/or a post-treatment.

In Australia and USA, the use of MAR methods is well researched and developed. The main purpose in these areas is to create a buffer of water for further usage during dry seasons for non-potable and indirect-potable reuse. The implementation of these methods is widespread and developed in guidelines and to a certain degree considered by national or regional frameworks, such as the *Australian Guidelines for Water Recycling: Managed Aquifer Recharge* and the *Sustainable Groundwater Management Act (SGMA)* of 2014 form the Californian Code Regulation (CCR).

A wide range of methods has been developed to enhance recharge of aquifers, several of them known for hundreds of years. A summary of how different authors categorised this methods is given in Table 1. Five main groups of MAR methods can be identified in Table 1. These groups of MAR vary in their design and technology and whether they intercept or infiltrate water. A brief description is given below.

Table 1 - MAR Classification

Author	**MAR Classification**					
Gale & Dillon (2005)	Spreading methods	In-channel modifications	Well, shaft and borehole recharge	Induced bank infiltration	Rainwater harvesting	
Escalante et al. (2016)	Surface systems	In channel modifications	Deep systems	Filtration systems	Rainfall	Sustainable urban drainage systems (SUDS)
Tuinhof et al. (2002)	Off-channel infiltration ponds	In-channel structures	Pressure injection	Induced bank infiltration	Village level gravity injection	

Spreading methods are applied in unconfined aquifers near the ground surface, where a large surface of permeable material is available for the infiltration of water. They are suitable for small and large scale implementation at relatively low cost. High loads of sediment in the source water can reduce the infiltration rates and increase evaporation rates (Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

In-channel modifications are structures to intercept water across streams, generally built in ephemeral sandy rivers used to enhance groundwater recharge and to control floodwater. Techniques range from small to large scale at relatively low cost without interfering with land use. Low scale structures can be built in cascade at a distributed distance in one stream to increase the infiltration rates (IGRAC UNESCO-IHE 2007).

Injection systems are structures used to directly recharge groundwater in aquifers either in shallow or deep depths. Structures used for this purpose are usually wells, boreholes, shafts, or pits. These techniques are very useful for storing significant amounts of water where land is scarce. In case of shallow aquifers, existing extraction structures (wells, pits, trenches) that run dry are regularly used for injection at reasonable costs, but this requires high quality water, to prevent clogging or contamination. Deep structures (borehole) are applied where a thick, low permeable strata overlies the target aquifer, usually to provide a water storage for drinking water or irrigation purposes. These techniques are applied at medium and large scale as drinking water supply for cities and communities, since they require complex design, construction, operation and maintenance (Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

Filtration systems, commonly galleries or boreholes, are structures located close to perennial surface bodies connected hydraulically to an aquifer. Water is pumped from these structures lowering the water table and inducing water from the surface water body to enter the aquifer system. Filtration systems are usually used for large-scale drinking water supply because of their pollutant attenuation potential (Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

Rainfall systems collect and concentrate runoff either to increase infiltration or to recharge directly into an aquifer. They are applied at low scale for domestic and agricultural purposes or at large scale for water harvesting in urban areas (Escalante et al. 2016; Gale & Dillon 2005; IGRAC UNESCO-IHE 2007).

Some of the MAR techniques mentioned by different authors are listed in Table 2. They are organized according to the classifications given in Table 1 and the overview of each group described above.

Table 2 - MAR Techniques

Surface systems	In channel modifications	Deep systems	Filtration systems	Rainfall
Soil Aquifer Treatment (SAT)	Check dams	Well/borehole infiltration	Lakebank filtration	Roof-top rainwater harvesting
Incidental recharge from irrigation	Sand storage dams	Injection Well		Rainwater harvesting in unproductive terrains
Accidental recharges by irrigation returns	Perforated /Drilled /Leaky dams	Aquifer Storage and Recovery (ASR)		Reverse drainage, shaft recharge
Infiltration fields (flood and controlled spreading)		Aquifer storage, transfer and recovery (ASTR)	Riverbank filtration	Sustainable Urban Drainage Systems (SUDS)
	Sub-surface/ underground dams	Infiltration galleries (Qanats)		Dry land intervention (soil and water conservation): keyline system , field bunds, trash lines, grass trips, micro catshments, contour ridges, retention ridges, terraces
Controlled flooding		Open infiltration wells	Interdune filtration	
Infiltration /percolation ponds/wetlands/ basins	Reservoir dams	Deep wells and well-boreholes		
	Riverbed scarification	Drilled boreholes	Underground irrigation	
Cross-slope barriers		Sinkholes, collapses		

As mentioned before, the method or combination of methods used to recharge an aquifer depends on the local conditions. A global MAR sites inventory can be found on the International Groundwater Resources Assessment Centre (IGRAC) website, which provides general information and case studies from different locations in different climate zones (IGRAC UNESCO-IHE 2015). Case studies of MAR sites in Europe are given in detail by Hannappel et al. (2014). Additional examples are provided by van Steenbergen, Tuinhof & van Beusekom (2009), where a description of the MAR sites, applied techniques and impacts are expressed.

Common topics discussed by numerous authors (Dillon, P et al. 2009; ed. Fox 2007; Gale & Dillon 2005; Vanderzalm et al. 2015) in reference to operational issues of MAR systems are: clogging, poor recovery of recharge water, interactions with other groundwater uses, and managing purge water, basin scraping and water treatment by product. A special emphasis is put on clogging of the infiltration medium. This may have an impact on the infiltration rate, the quantity and quality of recovered water, and the economic feasibility of the recharge method applied. Clogging occurs as result of physical, chemical or biological processes. A pre-treatment of the water for recharge can reduce the potential clogging problem. Dillon, P et al. (2009) gives a detail description of types of clogging and their causes, as well some methods of management and tools for predicting clogging. Bekele et al. (2015) developed a detailed evaluation and documentation of clogging processes and water quality impacts, that focused on two MAR methods: buried galleries and soil aquifer treatment (SAT).

Aquifers Recharge in Arid and Semi-arid Regions

In arid and semi-arid regions, subsurface storage of water becomes a major alternative over surface storage due to high evaporation rates. Subsurface storage enhances aquifer recharge to overcome dry seasons and droughts. The upper meters of soil in shallow aquifers in combination with low cost technologies can provide a water buffer (van Steenbergen, Tuinhof & van Beusekom 2009). Generally, shallow aquifers are unconfined and under atmospheric pressure, which results in a faster recharge (Smith et al. 2016). In arid and semi-arid regions, groundwater storage may be the only source of freshwater during dry seasons and persistent droughts.

Gale & Dillon (2005) discuss how Managed Aquifer Recharge (MAR) methods provide a cheap form of new safe water supply for towns and small communities. Their research suggests that a local water supply reduces investment in long piping systems and high energy costs for pumping can be avoided. Mutiso (2002) describe some of the water harvesting techniques for recharge applied in Kenya, which may also be applicable in other arid and semi-arid regions. Among them are: trash lines, grass strips micro catchments, contour ridges and bunds, retention ridges, terraces, earth dams and pans, and sand dams. Gale & Dillon (2005) provide some examples of application of MAR schemes in arid and semi-arid regions, among others: floodwater spreading, leaky dams, check dams, injection boreholes, interdune filtration, rainwater harvesting, irrigation channels, bank filtration, or injection wells.

MAR methods use the aquifer's potential to receive enhanced recharge for storage and treatment of water. The use of MAR methods as part of a major water management plan not only contributes to meet water demand, but also improves the quality of the water supply. Through the control of abstraction rates the restoration of groundwater balance is supported.

Conclusion

The recharge process of an aquifer is part of the hydrological cycle. The geological formation of an aquifer provides a subsurface groundwater storage, which can function as water buffer to bridge human water requirements during dry seasons. In some situations, it is even possible to store enough water to compensate for several failing rainy seasons – a situation that is not at all uncommon. Sustainable water management must comprise a balanced between the groundwater abstraction rates and the aquifer recharge conditions over the years. Aquifer recharge depends on the subsurface geological formation, but also on the surface catchment characteristics, which affect the infiltration rates into the aquifer. Soil erosion can reduce dramatically the infiltration rates.

There is a wide range of options to enhance the recharge of an aquifer by either natural or artificial methods. The selection of the correct method or combination of them will strongly depend on the site characteristics, the sort of water source for recharge and the end-use of the recovered water. In addition, costs and capacity for implementation need to be considered. Natural recharge of an aquifer can be enhanced by the implementation of ecosystem-based adaptation (EbA) measures or permaculture techniques. However, by the integrated use of natural recharge techniques combined with artificial techniques, it is possible to protect or recover groundwater resources.

Managed aquifer recharge (MAR) methods can artificially increase the availability of water for the recharge of an aquifer. These methods can be applied either in rural or urban areas. MAR methods have the purpose to improve the quality of groundwater sources, recover recharge yields, prevent saline intrusion or other contaminants from getting into the aquifer, prevent land subsidence, recycle stormwater or treat wastewater, among others. Five main groups of MAR schemes can be identified: spreading methods, in-channel modifications, injection systems, filtration systems, and rainfall systems.

Especially in arid and semi-arid regions, the application of MAR methods can have extraordinary benefits for the supply of drinking water and irrigation purposes. Several of these methods can be applied on a small scale at low cost and still have a great potential to store and treat water. This will often require coordinated activities of all villagers and farmers. In vulnerable regions, a sustainable water management that applies artificial recharge techniques and methods for the restauration of natural infiltration may warrant the security of the water supply through dry seasons and droughts.

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