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ARTIFICIAL GROUNDWATER RECHARGE. REVIEW OF THE CURRENT KNOWLEDGE OF THE TECHNIQUE

Recarga artificial de acuíferos. Revisión del conocimiento actual de la técnica

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Abstract: *Nowadays, intensive exploitation of aquifers is seen as one of the main environmental issues worldwide together with other phenomena such as climate change, changes in land use, the disappearance of species, and so on. To that respect, the artificial groundwater recharge almost stands as the only solution in order to reduce directly the effects of aquifer exploitation. To be exact, the recharge of aquifers is the technique used to introduce water into the ground in order to meet water deficits in aquifers. This study deals with the hydraulics and hydrogeological aspects related to the technique by performing an exhaustive analysis of the existing literature published in the last decades about the definition of the technique itself, the available water sources to develop it, the long list of objectives that this technique shows, the phases of the hydrodynamic mechanism, the different technology developed recently in order to introduce it (surface and underground systems) and the most important issues related to it (clogging, emerging contaminants…). This way, this study aims to improve the knowledge acquired on artificial groundwater recharge in order for this technique to be taken into consideration as a valid option when reducing intensive exploitation of aquifers, especially in arid and semi-arid areas.*

Key-words: *artificial groundwater recharge, surface and underground systems, clogging, emerging contaminants.*

Resumen: *: La explotación intensiva de acuíferos se contempla en la actualidad como uno de los principales perjuicios medioambientales existentes a nivel global, junto con el cambio climático, los cambios en los usos del suelo, la desaparición de especies, etc. En este sentido, la recarga artificial de acuíferos se postula prácticamente como la única solución capaz de mitigar de un modo directo los efectos de la explotación intensiva de acuíferos. Concretamente la recarga de acuíferos es la técnica mediante la que se facilita la introducción en el terreno del agua con el fin de satisfacer los déficits hídricos existentes en los acuíferos. El presente trabajo aborda los aspectos relacionados con la hidráulica y la hidrogeología de la técnica realizando un exhaustivo análisis de la literatura existente, en las últimas décadas, en cuanto a la definición de la misma, las fuentes de agua disponibles para su desarrollo, el amplio elenco de objetivos que presenta, las fases del mecanismo hidrodinámico, la diferente tecnología desarrollada hasta la fecha para implementarla (dispositivos en superficie y en profundidad) y sus principales problemas asociados (colmatación, contaminantes emergentes…). De este modo, el trabajo pretende mejorar el conocimiento existente de la recarga artificial de acuíferos con el fin de que en las próximas décadas dicha técnica sea contemplada como una opción válida con la que reducir la explotación intensiva de acuíferos especialmente en zonas áridas y semiáridas.*

Palabras clave: *recarga artificial de acuíferos, métodos en superficie y en profundidad, colmatación, contaminantes emergentes.*

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Currently, groundwater overexploitation and intensive aquifer exploitation are terms that hydrologists, managers and journalists use as synonyms. Overexploitation may be defined as the situation in which, for some years, average aquifer extraction rate is greater than, or close to the average recharge rate (Custodio, 2002). However, intensive exploitation is produced when the natural behavior of the groundwater component has been significantly changed, as well as the relationships with other water bodies (Konikow and Leake, 2014; Custodio *et al.,* 2016). In practice, an aquifer is often considered as overexploited when some persistent negative results of aquifer development are felt or perceived, such as a continuous water-level drawdown, progressive water-quality deterioration, increase of extraction cost, or ecological damage (Custodio, 2002). Therefore, it is more suitable to refer to this situation by using the term "intensive aquifer exploitation".

The intensive exploitation of aquifers is in today's international context considered to be one of the most relevant issues regarding water resources management with direct negative consequences on both agricultural and urban water demands which, in turn, are the main causes for the state of exploitation observed in certain hydrogeological formations (aquifers) nowadays (Konikow and Kendy, 2005; Gleeson *et al.,* 2010). Besides the socio-economic impacts, the above-mentioned issue also causes a series of interrelated environmental impacts as hydrological impacts due to the depletion of resources, ecological impacts due to the extinction of a base flow in related ecosystems, such as wetlands that change the biodiversity of these areas, and so on (Candela *et al.,* 2009; Rodríguez-Estrella, 2014) as well as a series of feedbacks due to today's climate change (Green *et al.,* 2011; Pulido-Velázquez *et al.,* 2015).

In particular, the regions that show higher rates of groundwater exploitation worldwide are located in large areas used for irrigation purposes in India ($68 \cdot 10^3$ hm^3/year), Pakistan ($35 \cdot 10^3$ hm^3/year), United States ($30 \cdot 10^3$ hm^3/year), Northern Iran ($20 \cdot 10^3$ hm^3/year), Northern China ($20 \cdot 10^3$ hm^3/year), Southern Mexico ($10 \cdot 10^3$ hm^3/year), the central region of Saudi Arabia ($10 \cdot 10^3$ hm^3/year) and water stressed areas around the Mediterranean Sea as Tunisia, Algeria, Libya, Israel, etc. (Wada *et al.,* 2012; Custodio *et al.,* 2016). In Europe, aquifers with highest rates of intensive exploitation are located in the Southeast of the Iberian Peninsula (Levante area) and Gran Canaria and Tenerife islands, in the Canary Islands archipelago. Specifically, in southeastern Spain, Segura River basin and also Júcar and Sur basins present high levels of groundwater exploitation, in particular in the provinces of Murcia, Alicante and Almeria. Detailed information can be found in Senent-Alonso and García-Aróstegui (2014), Custodio (2015) and Custodio *et al.* (2016).

Over the last decades, the artificial groundwater recharge technique, also commonly known by the acronym "AR" (Artificial Recharge) and "MAR" (Management of Aquifer Recharge) according to Fernández-Escalante *et al.* (2005a), has been developed internationally. Nowadays, the AR almost stands as the only technique capable to reduce directly the intensive exploitation of aquifers, as well as its environmental and socio-economic impacts (Galloway *et al.,* 2003; Konikow and Kendy, 2005). In particular, the AR can be defined as a water management tool that includes a series of techniques that make the unnatural introduction of water into an aquifer possible, either introducing water directly or inducing it, in order to increase the availability and guarantee levels of water resources and/or improve the quality of groundwater in the aquifers. This voluntary introduction of water in aquifers is performed through construction works specially programmed for this purpose. Likewise, aquifer systems must be surrounded by materials of low permeability that increase water accumulation and storage in these formations (Bouwer, 2002; Serieys, 2004).

Regarding the water sources that take part in the recharge process, there are numerous and various sources from rainwater, surface water that flows through perennial and seasonal riverbeds as well as ephemeral channels, or that is found in natural water reservoirs such as lakes, lagoons or any other humid land; water coming from other aquifers and aquitards; water related to human work and anthropogenic activities that produce water surplus and the return of irrigation water, water leaks in water supply networks, clean-ups and irrigation, and so on (Senent-Alonso, 1984; Murillo-Díaz, 2004). Depending on the type of water source, the artificial recharge is performed with systems located on the surface (ponds, grooves, trenches) or deep underground (recharge wells, radial drainage wells, and others), these being usually more expensive than surface methods (Serieys, 2004; Foreman, 2014).

In addition, the technique is nowadays widely implemented in a large number of countries. In some countries (Germany, England, Netherlands, United States and so on) it is even an essential process in water resources management (Fernández-Escalante, 2004; Biswas, 2008). In fact, this technique is often one of the most economical drinking water supply mechanisms in cities and small communities (Dillon, 2005). In Spain, many artificial recharge processes have been performed so far, though the technique is not considered as relevant in water resources management (Fernández-Escalante *et al.,* 2005a).

To sum up, it is particularly important to develop techniques, as for example the AR technique, that will allow a direct reduction of the exploitation of aquifers that, to a large extent, supply water and meet urban and agricultural demands in arid and semi-arid areas, such as the Segura River basin in drought periods. To be exact, in this basin in particular and due to the high exploitation level registered in many bodies of groundwater (Jódar-Abellán *et al.,* 2016a), it has been impossible to reach the environmental objectives regarding the good ecological status of water bodies set by the Directive 2000/60/CE (WFD, 2000) for 2015. Therefore, it is very unlikely for this trend to change over the additional time extensions granted by the directive (until 2021 and 2027). For this reason, this study aims to summarize the existing knowledge on artificial groundwater recharge in order for this technique to be implemented as a valid option to reduce the intensive exploitation of aquifers in specific areas, such as the Segura River basin.

Water sources for artificial groundwater recharge

A determining factor, which is totally necessary to undertake any type of experience in artificial recharge or supply of aquifers, is to have water surplus. In this paper, it is considered that there is water surplus when water abstraction does not affect negatively associated ecosystems, river baseflow, and others. Usually, the above-mentioned recharge is practiced thank to surface or groundwater surplus in order to make the most of the natural advantages of the aquifers such as additional regulation capacity, physicochemical and biological treatment processes, natural transmissivity, better protection against pollutants, and so on (Rodríguez-Vicente, 2013). This way, the water used in artificial recharge mainly comes from the following sources:

- Infiltration of rainwater or effective rainfall. Discontinuous surface runoff water can be directly used or used after undergoing some specific physicochemical treatment. However, when making the most of this type of water, the available water flow will have to be controlled as, for instance, in Mediterranean areas in which rainfalls are usually concentrated in relatively short periods of time and make it necessary to build small weirs or dams by the riverbed (Martín-Rosales *et al.,* 2007). Another option is the one that inflatable dams offer, as they get filled up with air after the rain, create a barrier and accumulate water for its later infiltration (HTCC, 1994; Murillo-Díaz, 2004).
- Infiltration of surface water, as it happens when a river provides water supply to an aquifer. As for the previous case, this continuous surface water (permanent fluvial stream) can be treated previously (Pérez-Sánchez, 2013; Rodríguez-Estrella, 2014).
- Water coming from anthropogenic activities and work that originate phenomena such as infiltration of water runoff and return of irrigation water; leaks in water supply networks as well as urban an irrigation clean-ups; infiltration in dams, deposits and ponds; infiltration of sewage directly discharged into the ground and through ditches, cesspits, etc. All of these, together with domestic wastewater (rarely industrial wastewater) when treated to a specific treatment level, can be reused o mixed with water from other sources (Bouwer, 1994; Wada *et al.,* 2012; Megdal and Dillon, 2015).

  In particular, treated wastewater offers a wide range of advantages due to the fact that the available daily flow is more or less constant, apart from touristic areas, which is fundamental for the design of a recharge project. In fact, the composition of these types of water varies very little, except for when important industries are located in the area. In the same way, there are many studies on the impact on human consumption of wastewater produced partly in aquifers. However, according to HTCC (1994), FCIHS (2011) and Green *et al.* (2011), so far results have not shown any sign of adverse health effect in populations supplied with groundwater with a percentage of wastewater (usually of 25%).

  Nevertheless, the irrigation water demand is the parameter that determines to a greater extent the recharge of aquifers, as they are exploited by agriculture especially in summer (Jaafar, 2014).
- Water directly introduced thank to construction work, as when building "artificial wetlands" in order to collect rainwater in a river basin and, after natural sedimentation, recharge via direct infiltration (if the wetland is located above the aquifer and permeability is suitable) or via pumping and injection from wetlands to aquifers. According to some authors this option is highly interesting due to the fact that it increases the landscape value in residential areas. In the same way, these wetlands are built for wastewater (Bouwer, 2002; Fernández-Escalante *et al.,* 2005b).
- Lateral or vertical water supply from other lateral aquifers or overlapping aquifers, as long as there is enough gradient (Senent-Alonso, 1984).

On the other hand, water sources required to supply aquifers can be classified as follows: 1- Natural recharge, without human intervention; 2- Induced recharge that can be either 2.1- Voluntarily or intentionally induced, 2.2- Involuntarily or unintentionally induced (Martín-Rosales *et al.,* 2007); 3- Artificial recharge with human intervention that can be either 3.1- From planned to deliberate, 3.2- Accidental due to irrigation, uncontrolled flowing wells, distribution networks, sewage systems, cesspits, industrial wastewater, and so on (Senent-Alonso, 1984; Murillo-Díaz, 2004).

Objectives of the artificial groundwater recharge

The artificial groundwater recharge is a highly important technology when dealing with managing a joint use of water resources (Biswas, 2008; Pérez-Sánchez, 2013). For this reason, this technique can be used in order to achieve different goals that, in turn, can be classified into four major categories (Table I).

Table I reflects how the four major categories in which the different objectives of the technique are included do not show a clear separation. For instance, the creation of hydraulic barriers against seawater intrusion is intended to modify the water quality, restore the disturbed equilibrium and provide protection to aquifers against eventual disturbances at the same time. Some of the main objectives mentioned above are explained below.

Construction of hydraulic barriers against seawater intrusion with injection in wells

Water injection in coastal aquifers allows a reduction of seawater intrusion (Custodio, 2015). For this reason, on occasions, pumping wells located between injection wells and the coastline are used at the same time. Logically, pumping lowers the salt-freshwater interface while injection produces a rise in the piezometric level of freshwater. Despite the fact that part of the injected water flows off into the sea, the amount of water collected is larger when the gradient towards the aquifer is higher than the gradient towards the sea. Therefore, the water flow that runs towards the first one is bigger as well (Fernández-Escalante, 2004; Foreman, 2014).

This recharge system is not the most suitable for aquifers with high levels of hydraulic conductivity (as conductivity shows how easy it is for the environment to allow the movement of water through it). This lack of suitability is due to the fact that conductivity sufficiently prevents the piezometric level

Increase in resources and optimization of resources	Modification of water quality	Restoration of the disturbed equilibrium	Protection against eventual disturbances
Reduce or eliminate the decrease in groundwater level due to pumping	Improve the situation of costal aquifers by creating hydraulic barriers against seawater intrusion	Compensate for level decrease due by intensive exploitation	Protection against saline intrusion as a consequence of important coastal exploitations
Use an aquifer as a regulator reservoir or deposit by using its large storage capacity	Modification of water qualityfor a later recollection	Impact on civil engineering works	Impact on civil engineering works
Use an aquifer as a distribution network	Prevent lower quality water in aquifers or polluted water from spreading into good quality water catchments	Land subsidence	Land subsidence
Production of drinking water			
Compensate for the loss of natural recharge in an aquifer due to human activities, such as channeling, water diversions, civil engineering works, and others	Urban wastewater removal and treatment. Wastewater will be treated and go through the ground automatic purifier	Conservation and restoration of ecosystems related to aquifers (wetlands)	Conservation and restoration of ecosystems related to aquifers (wetlands)

Table I.- Main objectives of the artificial groundwater recharge.

		Parameters		
Name	**Acronym**	**Unit**	**Determinations**	**Quality Standards**
Total suspended solids	TSS	ppm	[5 – 11][1;3;4]	[< 10][1;3;4]
Total dissolved solids	TDS	ppm	[101.8][1;4;6]	[< 150][1;4;6]
Total organic carbon	TOC	mg/l	[5.5 – 19][1;3;4]	[< 16][1;3;4]
Dissolved organic carbon	DOC	mg/l	[1.8 – 5][4;6;7]	[< 4][4;6;7]
Dissolved oxygen	DO	mg/l	[5.1 – 11][2;4]	[< 8][2;4]
Carbon dioxide	CO_2	mg/l	[0.5 - 0.9][4;5]	[< 0.5][4;5]
Hydrogen potential	pH	-	[8][4;6;7]	[< 7.5 – 8][4;6;7]
Chlorides	Cl^-	mg/l	[100][4;6]	[< 100][4;6]
Sulphates	SO_4^{2-}	mg/l	[200][2;6]	[< 50][2;6]
Nitrates	NO_3^-	mg/l	[2][1;6;7]	[< 10][1;6;7]
Nitrites	NO_2^-	mg/l	[5.3 – 6][5;6]	[< 5][5;6]
Conductivity	C	µS/cm	[191][3;6]	[< 200][3;6]
Electric conductivity	EC	mS/m	[70][3;6]	[< 60][3;6]
Water temperature	T^e	ºC	[5.9][6;7]	[≅ soil temperature][6;7]
Soil temperature	T^e	ºC	[6.1][6;7]	[< aquifer temperature][6;7]
Alkalinity	-	mg/l CO_3Ca	[64][2;6]	[< 200][2;6]
Supersaturation	-	mg/l SiO_2	[35][2;5]	[≅ 0][2;5]
Supersaturation	-	mg/l Ca $Mg(CO_3)_2$	[37.86][2;6]	[≅ 0][2;6]
Salinity	-	EC^e	[4 – 16][2;5]	[Avoid natural salinization][2;5]
Sulphide	H_2S	mg/l	[≅ 0][4;5]	[Avoid H_2S][4;5]
Membrane failure rate	MFR	s/l^2	[25 – 30][2;4]	[< 3 – 5][2;4]
Bacteria and viruses	-	UFC/ml	[not determined][1;3]	[Limit to be established][1;3]

Table II.- Proposal of quality standards for recharge water in artificial groundwater recharge. Source: adapted from experiences of: 1-Bouwer (1994); 2-EWRI-ASCE (2001); 3-Bouwer (2002); 4-Fernández-Escalante (2004); 5-NWQMS (2009); 6-Tredoux *et al.* (2009) and 7-Rodríguez-Escales and Sanchez-Vila (2016).

from increasing, as the injected water will run more easily sideways in such conditions (FCIHS, 2011; Foreman, 2014).

Using an aquifer as a distribution network

In minor aquifers in which the pumping exploitation has caused a decrease in piezometric levels leaving enough space for a recharge, levels can be maintained with artificial recharge and a higher exploitation level can be reached compared to the levels reached when working in natural conditions (Jódar-Abellán and García-Aróstegui, 2016b). This way, if an aquifer is recharged in times of major drought (summer) and it is exploited during the rest of the year for the different uses for which the water withdrawal may be intended (agriculture, farming, human consumption…), in the first place, it will work as a way to prevent the aquifer from disappearing. This is due to the fact that the artificial recharge also helps controlling the aquifer levels so they do not get lower than the minimum levels, in which case a point of no return would be reached and the aquifer would inevitably disappear. In the second place, when pumping water, the water resource can be adapted to the demand according to the different purposes intended (Green *et al.,* 2011; Wada *et al.,* 2012; Megdal and Dillon, 2015).

Improving the quality of water in the aquifer

In general, the water supplied to groundwater recharge facilities (designed to supply the aquifer with water from different sources) shows variable physical, chemical and biological characteristics (Senent-Alonso, 1984). For this reason, it is advisable to install the following devices at the entrance of the facilities:

- Pre-treatment devices to eliminate or reduce the amount of undesirable substances (Custodio, 2015).
- Safety and control devices to throw off or prevent water which treatment cannot be guaranteed up to a certain level from getting into the facility (Bouwer, 2002; Rodríguez-Vicente, 2013).

In groundwater recharge facilities, the main regular inspections to be performed on recharge water focus on the physicochemical properties of the main components, nitrogen and phosphorus compounds, organic compounds, heavy metals, bacteriology and virology, radioactive elements, and so on (Bouwer, 1994; Sidhu *et al.,* 2015). This way, quality water can be obtained (controlling pollutants and pathogens) to feed aquifers. For example, the artificial recharge of aquifers in which water shows excessive salinity makes it possible to lower these levels in order to obtain a more suitable quality water for irrigation purposes (HTCC, 1994; Dillon, 2005).

At present, there are no quality standards established by the Spanish law for water that feeds aquifers artificially. However, in other countries such a regulation has indeed been established (Fernández-Escalante, 2004; Megdal and Dillon, 2015). In Table II (see pag. 88), there is a proposal of quality standards, basically considering the concentrations of the main substances that cause clogging of the pores in the aquifer (especially total organic carbon and suspended solids) or threaten recharge systems (due to aggressiveness of water, dissolved gases and temperature).

Fighting against land subsidence

Land subsidence is an environmental problem produced by intensive groundwater exploitation of the water table aquifers. Pore-pressure decrease can derive in land subsidence where sediments are unconsolidated. However, if lithology and thickness do not alter abruptly, subsidence only produces smooth surface-elevation changes, but otherwise may cause large differences. For this reason, subsidence may changes from almost imperceptible to many meters. In some cities, high buildings suffered relative movements and some of them got cracks (Custodio, 2002; Custodio *et al.,* 2016).

The artificial recharge helps reducing or stopping land subsidence caused by intensive exploitation of aquifers although the initial levels of land cannot be restored. In some regions, this problem is so serious that governments encourage financially companies and institutes in charge of recharging aquifers artificially (Dillon, 2005; Pérez-Sánchez, 2013; Senent-Alonso and García-Aróstegui, 2014).

Natural treatment of wastewater

Natural treatment being applied to treated wastewater by introducing treated wastewater in aquifer formations has been widely implemented in a large number of countries with a reduction in water treatment costs thank to the self-purification capacity of the land (Bouwer, 1994; Rodríguez-Estrella, 2014). This wastewater reuse is especially relevant in arid and semiarid areas in which it may be used for irrigation purposes on occasions (Pérez-Sánchez, 2013; Megdal and Dillon, 2015).

An example could be the well recharge performed in dunes in Netherlands where polluted water from the Rhine

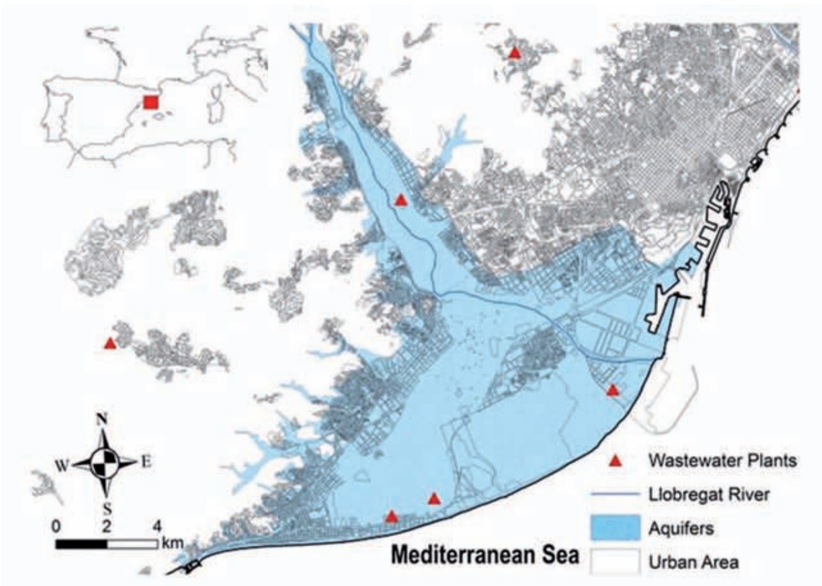

Fig. 1.- Location of Llobregat delta deep aquifer (Barcelona, NE Spain).

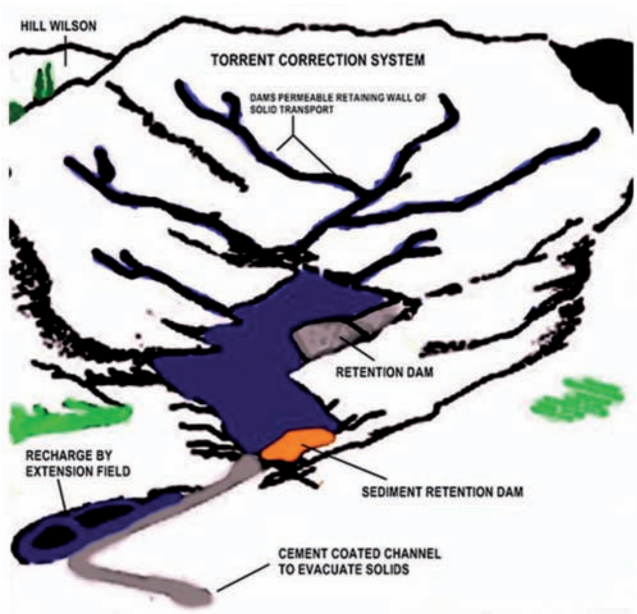

Fig. 2.- Stormwater flood control and artificial recharge system in the Santa Anita valley (California, United States). Adapted from Custodio and Llamas (1983).

River is clarified, chlorinated and finally injected into the dunes. This way, water quality is improved, obtaining temporary storage as well as controlling seawater intrusion processes (Fernández-Escalante, 2004; FCIHS, 2011).

In Spain, numerous artificial recharge experiences have been developed in the Llobregat delta deep aquifer (Barcelona province). The objectives are destined to meet various demands, construct hydraulic barriers against seawater intrusion, improve water quality, etc. In the case of water quality, normally before injection into the aquifer, the water receives a pre-treatment and sometimes a tertiary treatment (ultrafiltration, reverse osmosis, etc.) in wastewater treatment plants (Fig. 1, see pag. 89). This experiences and projects can be found in Iríbar *et al.* (1997), Cabeza *et al.* (2012), Candela *et al.* (2016), among others.

Flood spillway with artificial recharge

Spillways, also called overfalls, are structures, usually in dams, over which excess flood water flows. Sometimes the excess of water (overflow) spills over the ordinary limits of a surface water reservoir (main spillway). Normally, to prevent this situation, emergency or auxiliary spillways are constructed. However, in some cases, artificial groundwater recharge has been the solution to this problem (Galloway *et al.,* 2003; Jaafar, 2014).

A typical example of flood regulation with artificial recharge can be found in the plains of California (United States) where dams retain solids and reduce the slope of the torrent (Fig. 2). Next, a retention dam temporarily stores stormwater runoff and sediments are extracted on a regular basis. Downstream, in the sediment retention dam, water is clarified through settling. Then, water from this dam is infiltrated into the recharge areas in which it slowly flows through the trenches coinciding with the infiltration capacity in underlying aquifers. Therefore, the natural recharge of groundwater has been considerably improved (Custodio and Llamas, 1983; Dillon, 2005; Foreman, 2014).

Hydrodynamic mechanism in the artificial recharge

During an artificial recharge experience, the water content in the subsoil and the water table level considerably change. In general, the hydrodynamic mechanism of the artificial recharge consists of the following stages:

- Stage I. Creation and expansion of the infiltration bulb.
- Stage II. Bulge of the piezometric surface.
- Stage III. Steady state recharge.
- Stage IV. Disappearance of the crestwater once the recharge is done.

Firstly, the "creation and expansion of the infiltration bulb" takes place. This stage happens between the time in which water flows into the pond and the moment in which the aquifer starts receiving these supplies. In the unsaturated zone of soil, the water flow is mainly vertical due to the fact that the water supplied is filtered little by little into the formation, occupying a bigger percentage of empty spaces and humidifying the soil. This way, a humidification bulb forms and goes down (Fig. 3). Also, if the entrance flow is reduced, the unsaturated zone of soil will not get humidified, so the wet front of the bulb will not reach the saturated zone. However, if the flow is high enough, gradual under soil humidification will take place until it gets to the saturated zone (Bouwer, 1994; Fernández-Escalante, 2004).

Immediately after, the "bulge of the piezometric surface" happens once the wet front comes into contact with the upper part of the saturated zone. Consequently, all the supplied water is stored creating a crestwater that is constantly growing (Fig. 4). The crestwater continues growing until reaching a control limit or dynamic level that coincides with the lower limit of the recharge pond, so to stop upright spreading. Thus, the body of water will keep up expanding laterally until reaching a drainage area such as a river (HTCC, 1994; Bouwer, 2002).

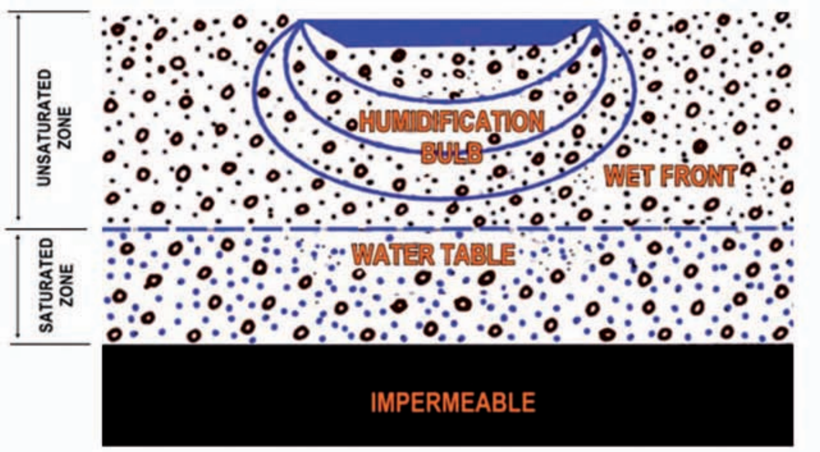

Fig. 3.- Stage I. Creation and expansion of the infiltration bulb in artificial groundwater recharge.

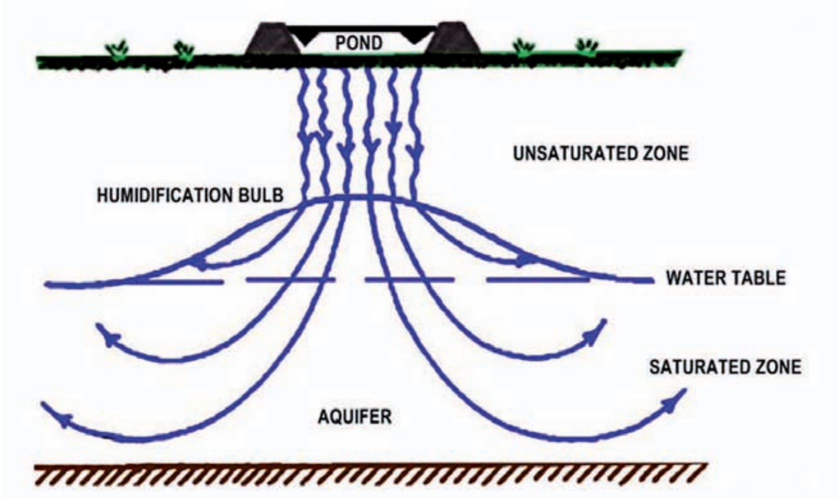

Fig. 4.- Stage II. Bulge of the piezometric surface.

This way, once the control limits reached, there is no change in the volume of water and there is as much water getting into the aquifer as water being discharged. Such a recharge is therefore called a "steady state recharge" (Senent-Alonso, 1984).

Finally, once the recharge is done, "the crestwater disappears" as the water stored over the piezometric level stays temporarily in the ground. In particular, once the recharge is finished, water is drained gradually towards the side controls until adaptation to the natural piezometric surface (Fernández-Escalante, 2004; Murillo-Díaz, 2004).

Main artificial recharge methods

The artificial recharge needs construction works to be done in order to connect the aquifer to a water source of a higher charge than the charge of the mantle or aquifer. Basically, there are two ways of performing this recharge:

- Surface methods or infiltration systems in which water spreads looking for a large land-water contact surface. They are used in unconfined aquifers that do not show impermeable levels close to the surface, which allows water to flow into the aquifer (Bouwer, 1994; Rodríguez-Vicente, 2013). They can be classified into two groups: 1- Dead water, where ponds (bottom infiltration) and ditches or "pits" (lateral infiltration) stand out; 2- Semi-sealed water or currents where trenches, canals, flood areas and riverbeds in good conditions can be found. Riverbeds can be divided into: meandering canals, weirs, scarification and dams in permeable channels.
- Deep underground systems or injection methods with which water is injected into the aquifer usually with wells or boreholes and radial drainage wells. They are usually used in lands formed due a rotation of permeable and impermeable levels (Dillon, 2005; Pérez-Sánchez, 2013).
- Induced recharge. It is a third method that consists of increasing the recharge of the aquifer by extracting water out of a device intentionally. However, this alternative is less frequently used. In fact, it can be considered as a particular recharge case, performed following surface methods consisting of inducing natural infiltration that takes place in rivers, lakes or reservoirs, by using pumping wells close to these bodies of water (Senent-Alonso, 1984; Bouwer, 2002).

Surface methods or infiltration systems

Ponds. Ponds are extended systems, not very deep, of a very large surface and dug in the ground (with or without artificial bed made of gravel or sand) that make water infiltration possible as water flows mainly into the bottom of the pond. Their depth is usually of 1 m to 1.5 m due to the fact that the pressure exerted by water of higher density would cause compaction of the bottom of the pond stopping infiltration into the aquifer, a phenomenon that could be due to fine sedimentation for example. This makes infiltration capacity varies between 1 m/day and 5 m/day, for which this artificial recharge method is the most commonly used surface method.

This way, the main objective when designing ponds is to make water infiltration happen. Another objective is to treat water, which is an action performed at four levels: in the pond itself, through a filter, in the unsaturated zone and in the aquifer. In order to achieve optimal filtering, the amount of oxygen in the water must be high.

Usually, different ponds are linked by gates (Fig. 5), so they can be isolated from each other when regular maintenance is performed without affecting the performance of the recharge facility (Custodio and Llamas, 1983; Dillon, 2005).

Recharge ditches or pits. Recharge ditches are excavated deeper underground compared to ponds and, although they are alike, they are only feasible when aquifers show a deep piezometric level. In the ditches, lateral infiltration is performed through the walls of the ditch, as sediments are deposited at the bottom (Fig. 6). Still, recharge ditches are emptied and cleaned less often than ponds are (Senent-Alonso, 1984).

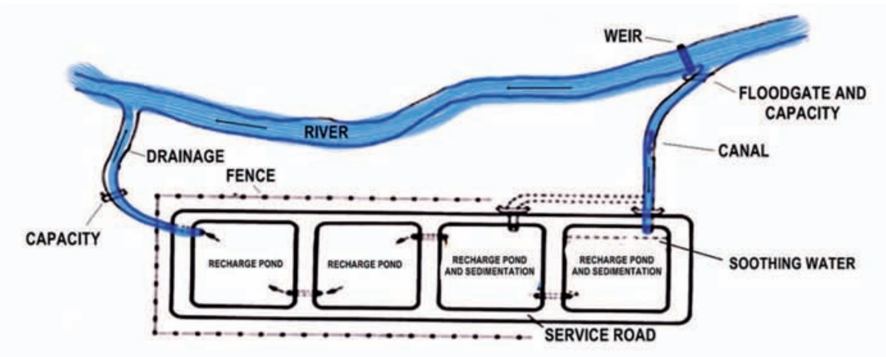

Fig. 5.- Artificial groundwater recharge with ponds in series. Adapted from Custodio and Llamas (1983).

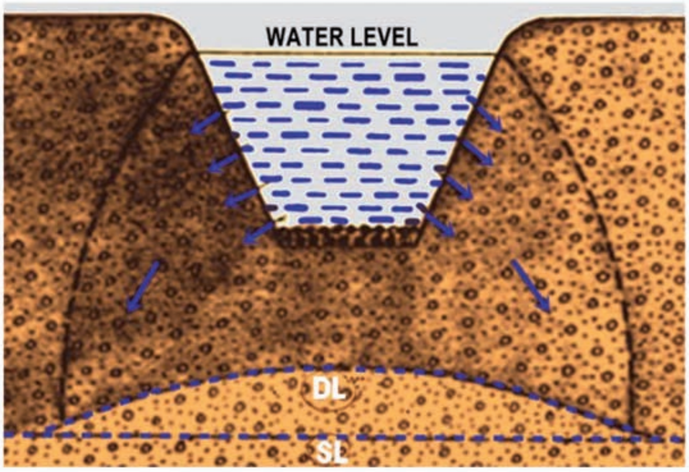

Fig. 6.- Water infiltration in recharge ditches. SL: Static piezometric level once the recharge is done; DL: Dynamic piezometric level when artificial recharge being performed.

In particular, in semi-arid areas, where rainfall is intermittent and sometimes very intense, the floodwaters may be recharged into aquifers using these existing structures (recharge ditches or pits) without the need for heavy investment. However, appropriate maintenance is required. Sometimes, whose initial design does not contemplate aquifer recharge, but they can be a valid option for this purpose (Martín-Rosales *et al.,* 2007).

Trenches, canals, meandering canals, weirs, riverbed scarification and permeable channels. Trenches are artificial recharge devices frequently divided into branching nodes through which water flows. It is advisable for this type of ditch to be located where the land slope is of 1 to 2% for water to reach a specific water flow speed in order to prevent fine sedimentation from forming deposits on the filtering surface. In this case, deposits would cause clogging phenomena. However, excessive water speed would cause erosion of the land (Custodio and Llamas, 1983; Bouwer, 2002).

Canals are not very deep systems that follow the land topography. Infiltration takes place at the bottom and through the lateral walls of the canals, showing different levels of importance that will vary according to the width of the canals (Senent-Alonso, 1984).

Meandering canals are L-shaped soil walls located on each side of a riverbed. By building meandering canals, contact time and contact area between water from the river and land can be increased. These infrastructures make water meander, so to lower water speed by increasing the river's natural infiltration (Fernández-Escalante, 2004; Serieys, 2004).

Weirs are inflatable rubber dams or earth dams. Earth dams must be provided with an overfall in order to prevent them from fast erosion. Due to the construction of weirs, contact time and contact area between water and land can be increased (Martín-Rosales *et al.,* 2007).

Riverbed scarification consists of raking (scarifying) the riverbed, removing fine materials and improving infiltration. In particular, scarification must be done at a shallow depth and in the same direction as the current.

Permeable channels are reservoirs with a not completely impermeable bed that makes groundwater recharge possible. Although reservoirs with water run offs are an inconvenient at first, on occasions these structures are built for this purpose (Fernández-Escalante *et al.,* 2005b; Pérez-Sánchez, 2013; Rodríguez-Vicente, 2013).

Underground systems or injection methods

Recharge wells and radial drainage wells. Recharge wells are deep boreholes through which water is injected into the aquifer. This system is used when the mantle is confined, although it is more common now to use dry wells or perched wells that do not intercept the piezometric level, as they are located only in the unsaturated zone. These systems are built from 10 to 50 m underground and of 1 to 2 m in diameter. The main drawback shown in wells, and especially in dry wells, is clogging.

A well can inject between 60 and 65% of water that would get extracted through pumping with same decrease. During the injection process, turbulent underground water becomes laminar. This change in water state causes major head losses compared to the ones encountered while pumping. Also, pumping injections can let air bubbles in the aquifer (Murillo-Díaz, 2004; FCIHS, 2011). Logically, when injection stops, the level goes down drastically, which could allow air out, causing an explosion that could damage the well. In order to prevent any damage from being done, the injection tube stays in, stopping air from getting into the aquifer.

In the same way, the screens of the injection pipes are drilled along the whole depth of the aquifer in order to get the greatest filtering surface. In the event of having priority water getting in during piping, this water shall be stopped from running in, so to prevent an area of higher water speed from forming, as it would enhance clogging processes.

As for radial drainage wells, drains and galleries are installed at the bottom of the well where water is introduced (Fig. 7). In general, they are located under or in the piezometric level (Dillon, 2005; Fernández-Escalante *et al.,* 2005b; Foreman, 2014).

Problems associated with artificial recharge and solutions

Clogging and emerging contaminants

Currently, clogging is the main problem associated with artificial recharge systems. However, along the last decades, other issues related with water quality have been found (emerging contaminants, changes in redox conditions, etc.).

Emerging contaminants are substances which presence in water is not necessary new but they are a source of concern due to their possible effects on human health and on environment. At present, many of these contaminants are not included in the European regulation. Emerging contaminants include pharmaceuticals products (ibuprofen, diazepam, carbamazepine, ciprofloxacin, hydrochlorothiazide, etc.), personal and care products (parabens, triclosan), pesticides, hormones, flame retardant, and so on (Cabeza *et al.,* 2012; Rodríguez-Escales and Sanchez-Vila, 2016). Usually, they appear in low concentrations (μg/l, ng/l). In some artificial recharge experiences, treated wastewater, normally injected through wells into aquifers, suffer environmental changes due to variations in temperature, pH, redox conditions, etc. into these hydrological formations. Some of these changes can increase the negative effects of emerging pollutants (Cabeza *et al.,* 2012; Candela *et al.,* 2016).

Clogging is defined as the decrease in porosity. It is usually observed in facilities when there is a decrease in the recharge flow. It is the most important issue when dealing with artificial recharge performed with surface systems (Senent-Alonso, 1984; Rodríguez-Vicente, 2013). Clogging can occur due to the following processes:

- Physical or mechanical processes due to: 1- Retention of suspended solid particles (sediments) in supplied groundwater. In surface recharge systems (as for example in ponds) there is soil compaction; 2- Release of dissolved gas, generally due to contact between supplied groundwater with warmer water from the aquifer; 3- Air intake with supplied groundwater. Air bubbles block the water flow as if they were solid particles or grains (Bouwer, 1994; Serieys, 2004; Foreman, 2014).
- Chemical processes due to precipitation of minerals that can cause: 1- Dispersion and clay swelling due to ion exchange; 2- Precipitation of metal salts or alkaline earth salts usually due to an increase in water pressure, temperature and oxygen content. The most common clogging components are carbonates, calcium sulphates, ferric hydroxides and manganese hydroxides (Serieys, 2004; Tredoux *et al.,* 2009).

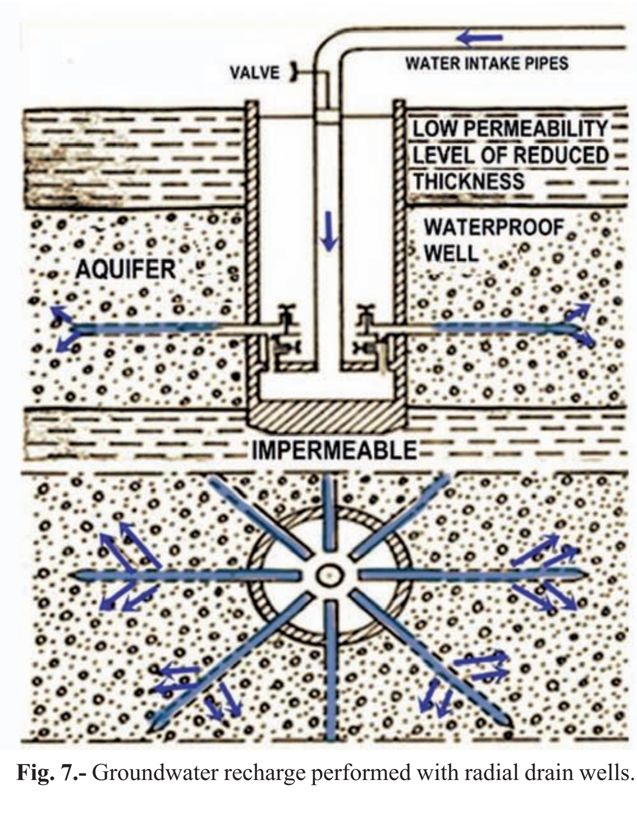

Fig. 7.- Groundwater recharge performed with radial drain wells.

- Biological processes due to: 1- Seaweed invasion clogging (in ponds). Its growth depends on temperature and brightness. For this reason clogging is quick and more intense in summer; 2- Bacterial clogging. Bacteria form polysaccharide coatings and organic matter. There is research on the fact that: 2.1- proliferation of bacteria happens when injected water contains organic matter and after occurs develop of bacterial activity; 2.2- clogging compounds are made with hydroxide and iron sulfide; 2.3- gelatin originates on the recharge filter due to aerobic ferruginous bacteria, although these can be destroyed by chlorination; 2.4- in anaerobic conditions, there are sulphate-reducing bacteria that are more difficult to destroy compared to the ones mentioned above, etc. (HTCC, 1994; Fernández-Escalante, 2004; Foreman, 2014).

Solutions to clogging and emerging contaminants

Nowadays, clogging and emerging contaminants are probably the main problems related with artificial recharge experiences. However, solutions to these problems are not extended equally.

In the case of emerging pollutants, there is not a general solution to decrease their concentration in wastewater when they are introduced into aquifers. In some experiences, reduction of the contaminants concentration in groundwater appears to be driven by the dilution process and hydraulic characteristics of the aquifer media, while the attenuation or degradation process are much less important (Candela *et al.,* 2016; Rodríguez-Escales and Sanchez-Vila, 2016).

On the other hand, as clogging is probably the principal problem in artificial recharge experiences, there are many solutions to reduce clogging effects over surface and underground recharge systems. In general, clogging can be reduced by:

- Stopping air from getting into the injected water due to the water free fall into the borehole. In order to achieve it, water is introduced through submerged piping under the piezometric level.
- Periodically stirring and removing the mud layer with sweepers (Serieys, 2004; Rodríguez-Vicente, 2013).
- Removing the sand from the filter and changing the filter when needed.
- Pumping desilting. The direction of the flow in the injection well is reversed through daily or weekly pumping for 15 minutes and with a flow 4 times as big as the recharge flow. Air shall not get into the filter bed or the soil at any time (Senent-Alonso, 1984).
- Establishing concentration limits for specific parameters.
- Increasing the hydraulic head pressure and therefore increasing the water speed in the aquifer, so that the crepine will break seaweed and bacterial genes (Bouwer, 1994; Foreman, 2014).
- Injection of "buffer water" before injecting the water in order to create a buffer zone which would eventually prevent reactions between groundwater and injection water from happening. Thus, reactions causing clogging would be avoided.

- In order to fight biological clogging, the following actions can be taken: using algaecides that can be harmful due to the fact that they deteriorate water quality; increasing the water surface in order to reduce brightness intensity in the bottom and reduce the proliferation of seaweed; modifying the recharge system by turning ponds into canals as most of the seaweeds that originate in ponds are species that live in dead water (Bouwer, 2002; Tredoux *et al.,* 2009).
- In surface recharge systems, the infiltration area of a riverbed can be increased (widening, flattening and scarifying it) and canalizations can be formed in the riverbed (HTCC, 1994).
- Pre-treating the injected water in order to remove all the suspended solids through settling or pre-filtering. If the aim is to avoid any case of irreversible clogging, there will be need of removing suspended particles and chlorination. A very useful option to elevate deposition of suspended solids consists on increase the distance covered by recharge water. This option can be implemented with walls built into a big settling-basin (Rodríguez-Vicente, 2013; Foreman, 2014). In this case, water speed decreases improving deposition of these particles (Fig. 8).

Fig. 8.- Settling-basin with walls to improve deposition of suspended solids.

Conclusions

Currently, intensive exploitation of aquifers is considered one of the main environmental problems in the world, which can increases also its negative situation due to the present global change (climate change and changes in land use). This issue can be reduced directly through artificial groundwater recharge or, indirectly, with the increase of water resources due to different technologies as desalination of marine water, water transfers from others regions, etc. Other option consists on increase water price to reduce its demand, but this decision always has negative effects over local populations and users (farmers).

On the other hand, throughout the study, it has become obvious that nowadays artificial groundwater recharge let us not only achieve its main goal, which is to recharge aquifers in times of water surplus, but to also be used as a crucial part of other processes and technology related to water management, such as water treatment (purification, disinfection, etc.), fighting against land subsidence, and so on.

In the same way, although this work focuses on hydraulic and hydrogeological knowledge on the technique, other studies are required in order to design artifitial recharge facilities properly. Some of these studies involve economic viability analysis to value the convenience of the different recharge methods in a specific area, together with political and legal analysis to supply recharge facilities with water. This last aspect is particularly arduous in regions with water resources scarcity, as in arid and semi-arid areas, for instance.

Traditionally, artificial groundwater recharge has been developed in humid regions with high water surplus to recharge aquifers. Probably, water resource scarcity is the main reason due to this technique has not been aplied in arid and semi-arid areas. In particular, these areas usually show a high level of exploitation of aquifer formations. For this reason, the development of artificial groundwater recharge projects will help mitigating water deficits in local or specific aquifers, while reaching the environmental objectives set by the Directive 2000/60/CE (Water Framework Directive). Some references of this paper show successful experiences of artificial recharge in semi-arid areas. However, in order for these recharge projects to be approved by society in areas of water resources scarcity, the different interested parties (members of the communities of irrigators, political representatives, and others) must be well informed of the suitability of the above-mentioned technique, and address allegations and give suggestions on the projects. These ideas are considered in the "Integrated Management and Joint Use of Water Resources Approach" where aquifers are estimated as groundwater reservoirs which can supply water demands during scarcity periods (droughts). This is posible because of aquifers, previously, have been artificially recharged in humid periods.

Futures research of artificial recharge could try to improve the efficiency of artificial and groundwater systems reducing basically cloging effects. Obviously, in part, it depends on different materials of terrain, aquifers, and so on.

Likewise, at the present time, it is not certain the decrease in concentrations of emerging contaminants when they are present in water that have been introduced into aquifers. Sometimes, these contaminants increase their negative effects into aquifers due to environmental changes (variations in temperature, pH, redox conditions, etc.). In other cases, emerging pollutants reduce their concentration in groundwater by a dilution process and hydraulic characteristics of aquifers.

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