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5.1. Integrated Urban Water Management and Investigation of New Resources for Regions under Water Stress

D5.1.5.b Identification of control parameters in water catchment and conservation systems under high flow events (subsurface accumulation)

SEVENTH FRAMEWORK PROGRAMME

COLOPHON

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Executive summary

PREPARED project aims to facilitate the adaptation of cities to the imminent change in climate conditions. Current water management of many cities is generally designed for a regular operation within the usual ranges of quality and quantity of their resources. However, historical records analyses lead to start considering changes in their main resources that might not be supported by the actual devices and methodologies.

In this context, this deliverable tries to approach the potential affection of climate change into water resources availability, focusing on subsurface accumulation and conservation systems. This research was carried out by studying the operation of different representative case studies around the world, and, moreover, it also assessed whether the current regulatory framework in the different studied countries regarding subsurface accumulation issues is actually updated to support climate change.

The review of the operation of the different case studies suggested that there are many problems associated to the current ranges of operation, which should be taken into account for next design updates. It was found no common protocol used in the different sites to assure the correct functioning of the infiltration facilities, as their own experience has been the base to develop preventing and maintenance actions and, also, the variability in geological and recharge water properties is high from one site to another.

On the other hand, it was observed that the legal context regarding subsurface water storage is very restrictive about the quality of the recharge water, without considering local conditions that could vary greatly.

Finally, an obvious disconnection between operational actions and the regulatory framework encourages the fact that, despite more specific regulations are needed to be prepared for unexpected changes, specific studies at local infiltration facilities must be performed in order to assess their suitability for climate change. In this sense, Barcelona's subsurface water storage facilities are proposed as one of the sites whose suitability should be evaluated.

List of Abbreviations

BOD	Biological Oxygen Demand
DOC	Dissolved Organic Carbon
MAR	Managed Aquifer Recharge
MCLs	Maximum Contaminant Level
NTU	Units of Turbidity
SAT	Soil Aquifer Treatment
TOC	Total Organic Carbon
TSS	Total Suspended solids
UV	Ultraviolet
WFD	Water Framework Directive
WSP	Waste Stabilization Ponds
WWTP	Waste Water Treatment Plant

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1 Introduction

1.1 Context

Catchment and conservation systems are widespread facilities that have represented historically an alternative storage of water during drought periods or just a method to regulate a water constant supply for a better urban management.

Within this group of secondary sources, surface and underground water storage systems are considered as water reservoirs, including surface accumulation devices such as ponds or dams, and also managed aquifer recharge systems which store water underground.

Despite their ubiquity and usefulness, the majority of the underground storage systems are designed for intake flows within a specific range of quality and quantity, very conservative to date. Thus, the adequacy of the water input to these systems is subject to its quality, which probably will not be achieved in other climate conditions.

According to climate change studies and climate evolution models, the forthcoming era will be characterized by great fluctuations on rain periods and river water flows, producing very drought seasons and frequent high flow events. As high flow events are usually accompanied by a decrease of the water quality, an important volume of water is actually out of the operation range in managed aquifer recharge facilities. Therefore, a high quantity of volume could be into unprofitable resource in a near future.

Frequently, the limits and legal regulations are established in order to prevent severe damages in the infiltration and to preserve groundwater quality. Usually they are established from a conservative viewpoint, using the prevention criterion. In contrast, a better use of the available resources rely on the increase of the storage by opening the range of operation of stored water without affecting the final quality of the water recovered.

In this sense, the relation between the end water quality and the optimization of the resource volume use becomes a controversial issue which deserve further studies.

1.2 Objective

Since the implemented systems for both surface and underground water catchment and conservation are dependent on limits individually created for each country or even for each case study, the aim of this study is to review different regulations and case studies in order to find correlations between an acceptable quality and a good optimization of the water resource during extraordinary high flow events.

1.3 Scope of work

This study includes a review of the limits established in different countries for subsurface accumulation of water with the current climate conditions. These limits were approached from two points of view:

- Legal and regulatory framework.
- Operational issues of real recharge facilities.

The first point was focused on the review of different legislations from historically relevant countries were subsurface accumulation has been carried out for many years.

On the other hand, real case studies worldwide were analysed individually to evaluate which parameters are commonly controlled in their regular operation and which type of problems occur in those facilities.

The main objective of the review of both sections is to obtain a complete vision of the currently implemented measures around the world in order to find optimal operational guidelines to adapt subsurface conservation systems to the impending quality and quantity changes of the water resources that feed this kind of facilities due to climate change.

2 Legal Framework

The concept of water underground storage has several legal acceptations depending on each country regulation. Thus, requirements to introduce water into an aquifer can be quite variable, obliging to recharge with potable water in some sites or even considering recharge water as a residue in others.

Given this controverted amplitude among the different legal frameworks that regulate water underground storage, an analysis of some of the most relevant countries' regulations concerning underground water storage is discussed in this section.

2.1 United States of America

Managed Aquifer Recharge (MAR), despite being a very recurrent technique commonly performed in the whole country, has no specific regulation emitted by the national government. Nevertheless, it does exist an obligation to develop individual regulations for each state of the USA.

In this context, Table 1 summarises the main regulated parameters in some of the states where MAR is being carried out.

Table 1. Control parameters regulated in USA state recharge water legislations (Guidelines for water reuse in the USA).

	Arizona	California[2]	Florida	Hawaii	Nevada	Texas	Washington
Treatment	NR[3]	Case-by-case basis	Secondary treatment and basic disinfection	Case-by-case basis	NR	NR	Oxidized, coagulated, filtered, and disinfected
BOD_5	NR		NS[4]		NR	NR	5 mg/l
TSS	NR		10.0 mg/l		NR	NR	5 mg/l
Turbidity	NR		NS		NR	NR	2 NTU (Avg) 5 NTU (Max)
Coliform	NR		NS		NR	NR	Total 2.2/100 ml (Avg) 23/100 ml (Max)
Total Nitrogen	NR		12 mg/l		NR	NR	NS

(1) All state requirements are for groundwater recharge via rapid-rate application systems. Additional regulations for recharge of potable aquifers are contained in Section 4.1.1.10 and Appendix A.
(2) Groundwater recharge in California and Hawaii is determined on a case-by-case basis
(3) NR - Not regulated by the state
(4) NS - Not specified by state regulations

Although it is obvious that some states do not have any regulation on this topic, there are some frequently regulated parameters in the table attending to water quality indicators and type of recharged water used. Of course this is applied only to reclaimed water coming from Waste Water Treatment Plants

(WWTP). California and Hawaii have a specific regulation, which rely on a case-by-case study to determine whether the general parameters are applicable or not.

Moreover, California is one of the states that more extendedly regulates the recharge of reclaimed water. It was proposed to follow a few points as the criteria to control quality of recharge water (Asano and Contruvo, 2004):

- Microbiological quality
- Mineral content (dissolved solids)
- Toxic heavy metals presence
- Persistent concentration of organic hazardous substances.

This proposal has been changed iteratively since 1990's, while several refinements have been carried out to update and improve the criteria. The actual proposal draft for reclaimed recharge considers:

- An intensive source control approved by the Californian Water Quality control boards.
- Definition of the filtered disinfected wastewater concept, achieved by methods such as ultrafiltration, nanofiltration, microfiltration…
- Need to carry out a disinfection step when recover purposes do not include potable water.
- Recommendation of guidelines to control major parameters of recharge water quality (Nitrate, Nitrite, etc).
- Consideration of dilution effects and occurrence of unregulated organic compounds. The limits are established taking into account the percentage of supply that comes from reclaimed wastewater.

Table 2. Proposed State of California criteria for groundwater recharge with reclaimed wastewater (Asano and Contruvo, 2004).

Contaminant type	Type of recharge	
	Surface spreading	Subsurface injection
Pathogenic microorganisms		
Secondary treatment	**TSS <= 30 mg/L**	
Filtration turbidity	**<= 2 NTU**	
Disinfection	**4-log virus inactivation, <= 2,2 total coliform 100 mL**	
Retention time underground	**6 months**	12 months
Horizontal separation	**153 m**	610 m
Regulated contaminants	**Meet all drinking water maximum contaminant levels (MCLs)**	

Unregulated contaminants		
Secondary treatment	**BOD <= 30 mg/L, TOC <= 16 mg/L**	
Reverse osmosis	**Four options available depending on local conditions**	100% treatment to TOC =< 1 (mg TOC/L)/RWC
Spreading criteria for SAT 50 % TOC Removal credit	**Depth to groundwater at initial percolation rates of: < 0,5 cm/min = 3 m. < 0,8 cm/min = 6 m.**	NA
Mound monitoring option	**Demonstrate feasibility of the mound complicate point**	NA
Recycled water contribution	**<= 50 % of affected groundwater volume**	NA
NOTE: RWC =the percent recycled water contribution in groundwater extracted by drinking well water. Adapted from State of California.		

2.2 Australia

Australia does not have either a specific national regulation concerning recharge water issues, aside from the general water guidelines applicable to all the Commonwealth Nations.

However, following the same structure as the U.S.A., Australia owns specific regulation for each of the states that constitute the country. Thus, the Water Act 2007 of Australian government, amended on 2008, establishes the general rules for health and environmental protection in water, and every state defines a legal framework for MAR, and therefore, for underground water storage.

2.2.1 South Australia

South Australia has the longest history in development and application of MAR regulation in Australia. A guideline document was created (SKM-CSIRO, 2012) to provide information about implementation of infiltration systems in current conditions.

These guidelines discuss types of planning, resource and environmental approvals and licensing processes required for schemes. Referring to underground storage, point 13 in part 4 (manage and control of point source pollution) establishes the compliance of quality limits while manipulating water, and point 15 offers the exception of recharging into the aquifer out of range concentrations of contaminants if physico-chemical and microbiological reactions are proved to be effective to avoid aquifer damage.
Values are gathered in Table 4.

2.2.2 *Western Australia*

Western Australia owns a very specific MAR regulatory framework. The "Operational Policy 1.01– Managed Aquifer Recharge" (Department of Water of Western Australia Government, 2011) defines aquifer recharge processes. This document suggests considering recharge water quality, aiming not to affect the environmental values of groundwater or connected surface water systems. In this sense, the department "*seeks to maintain the environmental value of aquifers by requiring the quality of the water recharging an aquifer to be equal to or better than the quality of the receiving groundwater*".

Moreover, it also focuses on the monitoring of:

- Potential aquifer damage
- Rising of water table.
- Surface discharge if groundwater mounding is too close to the surface.
- Changes to groundwater regime.
- Changes to groundwater quality due to interaction between recharge and in-situ groundwater.
- Significant changes in groundwater temperature.
- Changes to water chemistry in hydraulically-connected surface water systems.
- Aquifer clogging
- Effects on aquifer stability, decreasing transmissivity.

Although all these topics must be taken into account, apparently there is no quantification method for any of them.

2.3 Europe

Aquifer recharge is mentioned by European legislation in 4 different directives:

- Directive 80/68/CE, relative to protection of groundwater against the contamination produced by some species (26th January 1980), amended by directive 2000/60/CE, only established that aquifer recharge should be authorized locally in a case by case basis by the competent authority (articles 13 and 15).

- Directive 2006/118/CE, relative to the protection of groundwater against contamination and deterioration, establishes a list of substances that could cause problems of contamination in groundwater, and also exceptions of that regulation in case of managed aquifer recharge. In addition, article 6.d. refers to aquifer recharge on the Water Framework Directive 2000/60/CE (WFD), being the substances to be assessed:

1. Organohalogen compounds and substances which may form such compounds in the aquatic environment.
2. Organophosphorous compounds.
3. Organotin compounds.
4. Substances and preparations, or their breakdown products, that have been proved to possess carcinogenic or mutagenic properties or properties which may affect steroidogenic, thyroid, reproduction or other endocrine-related functions in or via the aquatic environment.
5. Persistent hydrocarbons and persistent and bioaccumulable organic toxic substances.
6. Cyanides.
7. Metals and their compounds.
8. Arsenic and its compounds.
9. Biocides and plant protection products.
10. Materials in suspension.
11. Substances which contribute to eutrophication (in particular, nitrates and phosphates).
12. Substances which have an unfavourable influence on the oxygen balance (and can be measured using parameters such as BOD, COD, etc.).

- Directive 2000/60/CE, as mentioned above establishes recommendations in order to control substances that could affect negatively underground water reservoirs, but also recommends a characterisation of the recharge water, although control parameters are not limited in value (physical, chemical, volume…). In article 11.3.f, WFD gives an idea of the possible origins of recharge water:

"controls, including a requirement for prior authorisation of artificial recharge or augmentation of groundwater bodies. The water used may be derived from any surface water or groundwater, provided that the use of the source does not compromise the achievement of the environmental objectives established for the source or the recharged or augmented body of groundwater. These controls shall be periodically reviewed and, where necessary, updated;"

WFD also obliged every estate member to carry out an analysis of water quality and vulnerability of all water masses, including in this analysis aquifer recharge aspects among others.

2.4 Spain

Spanish national regulatory framework derives mainly from the European legislation, although at some points it even goes further establishing limits the European framework does not.

Thus, aquifer recharge is approached from different points of view:

- Management
- Environmental
- Planning

The Royal Decree (RD) 1620/2007 establishes the legal aspects in the reuse of reclaimed water by giving some limit values for physical and biological parameters (see Table 3).

In this regulation Escherichia coli and total suspended solids (TSS) are regulated, and nitrogen and nitrate were previously limited on RD 849/1996, amended by RD 606/2003.

Table 3 Maximum admissible values for reclaimed water quality (RD 1620/2007).

USO DEL AGUA PREVISTO	VALOR MÁXIMO ADMISIBLE (VMA)				
	NEMATODOS INTESTINALES	*ESCHERICHIA COLI*	SÓLIDOS EN SUSPENSIÓN	TURBIDEZ	OTROS CRITERIOS
5.- USOS AMBIENTALES					
CALIDAD 5.1 a) Recarga de acuíferos por percolación localizada a través del terreno.	No se fija límite	1.000 UFC/100 mL	35 mg/L	No se fija límite	N_T [1]: 10 mg N/L NO_3: 25 mg NO_3/L Art. 257 a 259 del RD 849/1986
CALIDAD 5.2 a) Recarga de acuíferos por inyección directa.	1 huevo/10 L	0 UFC/100 mL	10 mg/L	2 UNT	

RD 606/2003 forbids strictly the storage of potentially contaminant substances in an aquifer although it establishes no quantifiable limits to decide whether or not a substance is considered contaminant. This issue is assigned to the autonomic administrations which decide the pollution potential of recharge waters. Nevertheless, the local laws present a lack of specific information that leads to very strict and unfounded regulations that suggest using potable water for recharge purposes.

2.5 Legal framework analysis

Table 4 summarizes the information gathered in section 2, classifying regulated parameters and their limit values for each of the national legislations analysed.

Looking at these values it is obvious that there is an ineludible lack of specific regulation about storing water underground, specially in Europe and Spain. Managed aquifer recharge seems to have different acceptations depending on the country. Hence, definitions, implementation and operation are carried out through different protocols worldwide.

Most of the regulations focus on recovered water quality, trying to assure its maximum reliability by introducing the best recharge water quality. However, far from achieving this goal, other possible affections during the recharge actions are not considered in the legal frameworks. Infrastructure durability, maintenance and their economic and environmental consequences are missing on the revised regulations, and probably are the most frequent causes of deterioration of recovered water.

In the case of Spain, it would be relevant to create laws designed exclusively for MAR, where an unitary and specific regulation that considers: i) definition, ii) recharge methods, iii) specific recharge water quality, iv) authorizations, etc. (Sastre Beceiro, 2009).

Table 4 Worldwide analysed regulations summary table.

	RD 1620/2007 Spain	Potable Water RD 140/2003 (required quality when no other is required RD 927/1988), Spain	(GWD) Directive 2006/118/CE, Anexe 1; Confederación hidrográfica del Ebro, Aditional parameters with established limit values	FRESH AQUATIC ECOSYSTEM USES Environment Protection (Water Quality) Policy 2003 (South Australia)	Proposed State of California criteria for ground water recharge with reclaimed wastewater	D.Lgs n. 185/03 agricultural reuse of municipal wastewater (Italia)	USEPA (Envirnonment Protection Agency, USA) "WATER RECLAMATION P39)
Total Suspended solids	35 mg/l			20 mg/l	30 mg/l	10 mg/l	
DOC						100 mg/l	
Salinity				10%			
TOC				15 mg/l			
Turbidity		5 NTU network/ 1 NTU output of DWTP or distribution tank		20 NTU			1 NTU
Mean Turbidity							
Filtered turbidity					2 NTU		0,3 NTU
Conductivity		2500 µS/cm a 20°C				3000 µS/cm	
Nitrates	25 $mgNO_3/l$	50 mg/l	50 mg/l				44,3 mg/l
Ammonium (total)		0,50 mg/L	0,5 mg/l *	0,5 mg/l			
Iron		200 µg/L	0,2 mg/l *	1 mg/l			300 mg/l
Manganese		50 µg/L	0,05 mg/l *				50 mg/l
Maximum chlorides		250 mg/L	4750 mg/l *			250 mg/l	250 mg/l

(*) defined by autonomic government RD 606/2003

3 Operational issues of real recharge facilities

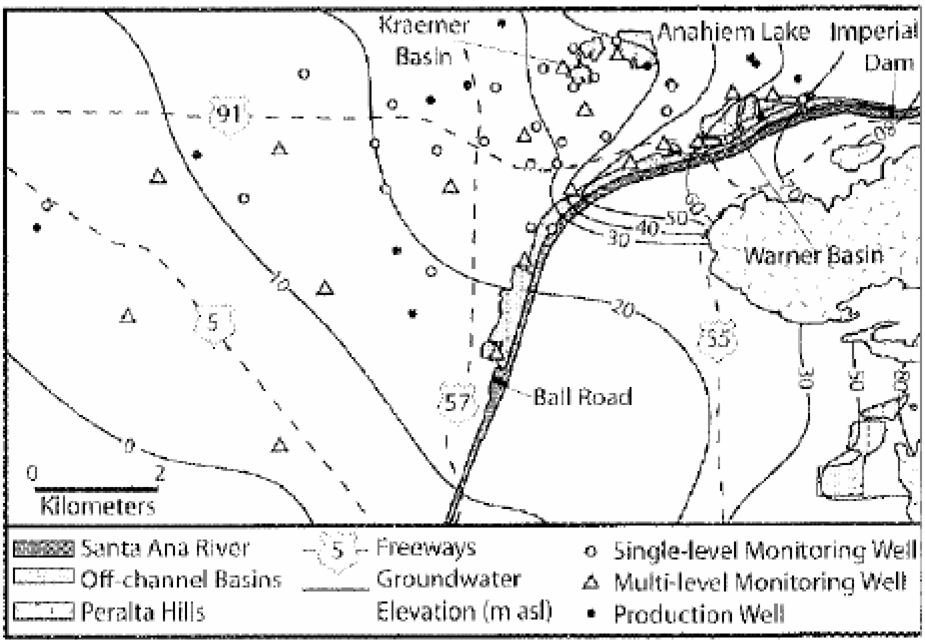
Despite the legal and regulatory liabilities of recharge water, operators have been developing protocols from their own experience and errors. This section discusses control parameters, maintenance processes and other actions carried during the experience of recharge facilities at different sites where MAR has been carried out for many years.

3.1 United States of America

3.1.1 California (Orange County)

Orange County recharge water system is located in Anaheim, in the state of California (USA). It started recharging in 1936, although the current system, designed in 1994, has been working since 2008. These facilities comprise a system of infiltration ponds which spreads along 112 Hectares.

Orange County recharge project was intended to give an extra input of water to the aquifer, which is later recovered for potable consumption. The annual contribution is quantified around 88 Hm^3. Figure 1 shows the location of recharge facilities.



(Source: Clark et al., 2004)

Figure 1 Orange County recharge system scheme (California, USA).

Infiltration ponds are dug on an alluvial lithology where water from a Waste Water Treatment Plant (WWTP) is directly spread. The reclaimed water has previously gone through a purification treatment that comprises microfiltration, reverse osmosis, UV disinfection and hydrogen peroxide, obtaining a very good water quality.

Alternatively, there is also direct recharge on the riverbed of Santa Ana River through T and L type dumps. These structures decrease river velocity and increase aquifer infiltration capacity, and also stimulate fine sediments to flow down with the river instead of accumulating and damaging the infiltration systems.

3.1.2 *California (Montebello)*

Montebello recharge system is constituted by infiltration basins installed on the Río Hondo and San Gabriel riverbanks. They are recharged with secondary and tertiary effluents coming from WWTP. Added to rainfalls, they all achieve an annual recharge volume of 160 Hm^3, which belong 40% to stormwater, 25% tertiary effluent and 35% reclaimed water. The recovered water use is mainly potable.

Ponds were constructed into an alluvial sand facies, where sand layers are interbedded with gravels and clay to fine silt aquitards. The recharge area spreads along 200 Hectares.

Operation relies on dry-wet cycles of 21 days (7 days of flooding, 7 days for infiltrating and 7 days of drying).

3.1.3 *Arizona (Phoenix)*

On the west side of Phoenix (Arizona), Salt River plain is recharged with water from secondary semichlorinated effluents.

Aquifer is mainly composed by sands and gravels, with an unsaturated zone of 17 meters of thickness.

Infiltration ponds spread along 16 Hectares and are operated following a protocol that comprises 2 weeks of flooding and infiltration, followed by 2 weeks of drying. Infiltration rates are around 0,5 m/day while the system is infiltrating, ahieving a total mean of 100 m/year.

3.1.4 *Arizona (Tucson)*

Another important infiltration system is located in Tucson (Arizona), composed by 8 infiltration ponds fed by tertiary and secondary chlorinated effluents, which are later recovered for human consumption purposes.

The total surface of the infiltration ponds is 11,3 Hectares, and two wetlands are also associated to the system (6,8 Hectares).

Table 5 shows some quality parameters measured in Phoenix (Arizona) as an example of the operational parameters that are controlled in this system. Tucson recharge system includes some basins that complete the reclamation process through a Soil Aquifer Treatment (SAT).

Besides the control of these parameters, the infiltration ponds are dragged in order to keep up with efficient infiltration rates. Thus, a “ripping” process is carried out to avoid clogging of the ponds bottom due to sedimentation of suspended solids and biofilm growth. These maintenance tasks reach 10 cm of depth, where there is a balance between permeability enhancement and the controlled increment of suspended solids due to this action.

Table 5 Quality parameters in the Soil Aquifer system in Tucson (Arizona).

	Secondary Effluent (mg/L)	*Recovery Well Samples (mg/L)*
Total dissolved solids	750	790
Suspended solids	11	1
Ammonium nitrogen	16	0.1
Nitrate nitrogen	0.5	5.3
Organic nitrogen	1.5	0.1
Phosphate phosphorus	5.5	0.4
Fluoride	1.2	0.7
Boron	0.6	0.6
Biochemical oxygen demand	12	0
Total organic carbon	12	1.9
Zinc	0.036	
Copper	0.008	
Cadmium	0.0001	
Lead	0.002	
Fecal coliforms, per 100 ml	3500	0.3
Viruses, PFU/100 1	2118	0

3.2 Israel

3.2.1 Dan Region (Shafdan)

Israel is one of the countries where MAR scientific and technological area is more developed in the world. For more than three decades, Israel has used MAR to enhance hydric resources in order to fight against the hydric deficit that affects the country.

Shafdan infiltration system contributes to the treatment process of a secondary effluent (or tertiary) from theTel Aviv's metropolitan area WWTP, by infiltrating this reclaimed water through its basins.

A dunes field is also located close to the coastline. The facies that host the dunes are formed by quaternary sands, calcareous sandstones with interbedded marls and clays. Water table is usually placed between 15 and 30 meters depth. The total infiltration surface is 111 Hectares, normally operated by 1 or 2 days of flooding, alternated with 2 to 4 days of drying. Basins bottom is dragged once every two months.

The abstraction system to recover the infiltrated water is composed by a well field located between 100 and 1500 meters from the infiltration system, allowing a residence time of 6 to 12 months. During the experience, a mobilization of iron (Fe) and manganese (Mn) has been occurring frequently, measuring up to 500 ppb of Mn in the recovered water. Mn and Fe mobilization can produce also particulated substances that could also cause problems on the recovery system.

Another common problem registered during Shafdan experience is biofilm growth both in the pipelines and infiltration basins surface.

In order to prevent this kind of problems, a specific protocol of maintenance is carried out:

- Wells isolation when Mn is over 500 ppb.
- Mechanical cleaning of effluent pipes.
- Automatic control of flood/dry periods.
- Filtration and oxidation of Manganese.

In this SAT system, a preliminary ultrafiltration treatment of the effluent avoids suspended solids and coloids potential for clogging. Also, other treatments such as sand filtration, activated carbon, flocculation, advanced oxidation and nanofiltration are carried out to assure recharge water suitability for the infiltration system

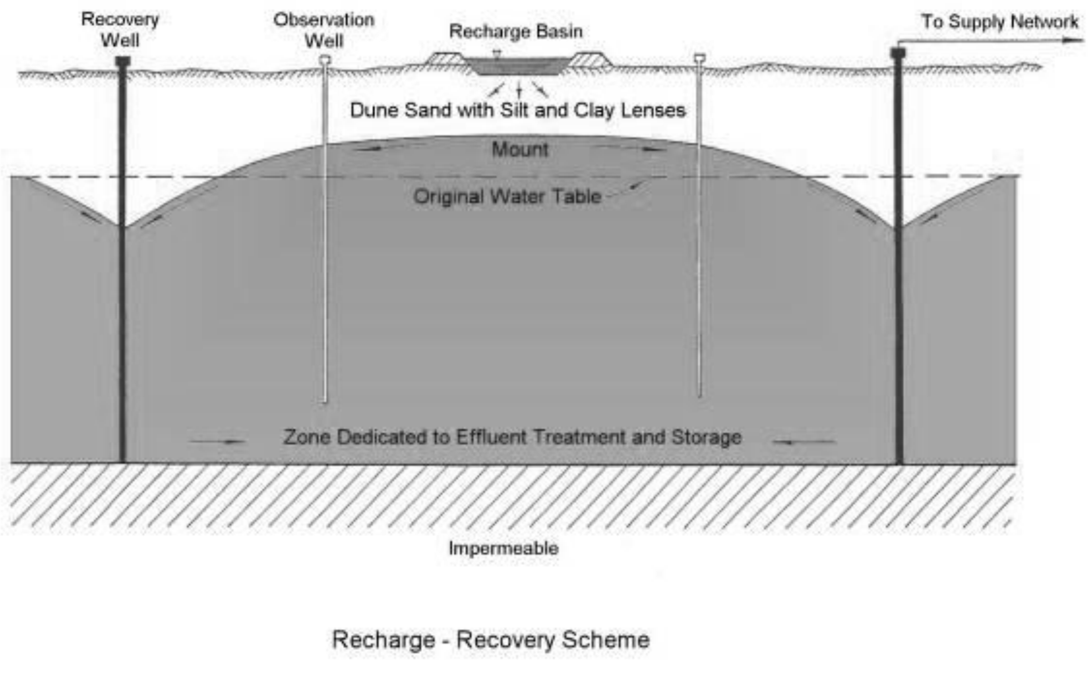


Figure 2 Shafdam (Israel) infiltration system scheme (Aharoni, 2007).

Presedimentation basins are also used with the same purpose as WWTP pre-treatments, reducing suspended solids by remaining on the sedimentation basins for at least 48 hours before entering the infiltration basins.

3.3 Australia

3.3.1 Alice Springs

Alice Springs water storing system in Australia has been operating since 2003 by Power and Water Co. in the site of the Arid Zone Research Institute (AZRI).

The recharge system was designed to infiltrate reclaimed water from the Alice Springs Waste Stabilisation Ponds /WSP), whose wastewater is treated by dissolved air flotation and chlorination. Reclaimed water is then infiltrated through infiltration basins with a total surface of 1,5 Hectares, and infiltration rates between 3,2 and 10,6 m/day, depending on the lithology.

Although this SAT system complies with the public health regulation, its long experience has put in debate the durability of the infrastructures, e.g. with regards to the basins clogging as an important issue to take into consideration in order not to increase operational costs (AUSTRALIAN GUIDELINES FOR WATER RECYCLING, 2010). It was concluded that maintenance could be easily done by operational fine-tuning.

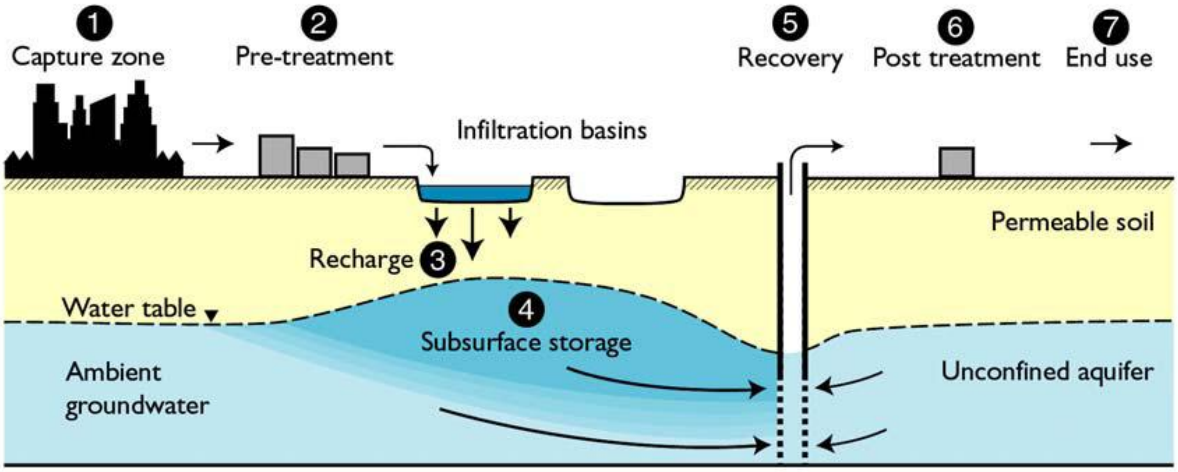


Figure 3 Alice Springs recharge/recovery system scheme.

3.4 Asia

3.4.1 Beijing (China)

Beijing water supply system is partially fed by groundwater abstraction, whose availability is increased by a surface recharge system.

Water infiltrated is treated by a WWTP. Previously it goes under an ozonisation treatment in order to reduce organic matter content and also sand filters and coagulation.

Problems reported during the operation mainly rely on the local geology where the basins were excavated. The basins have to be frequently cleaned, extracting sediments and vegetation, due to the low permeability of the lithology underneath the basin (fine clay).

In order to avoid this frequent maintenance actions, DOC maximum concentration on the recharge water has been set up to 1,5 mg/L, to reduce bioclogging.

3.5 Europe

3.5.1 Belgium (St. André)

St. André abstraction wells system was identified to be overexploited in 1990, which led to a salinization of the aquifer formed by St. André dunes.

After 10 years of research, an artificial recharge plan was implemented to mitigate this overexploitation. Despite it did not increase much the aquifer levels; it enhanced the production of potable water. At the same time, ultrafiltration systems to reduce bacteria and suspended solids were also introduced, as well as reverse osmosis to prevent saline intrusion (eliminating salts, nutrients, virus and other priority substances).

The production scheme is presented in Figure 4. Water is supplied to an equivalent population of 60000 inhabitants. With this aim, 2,5 Hm^3/year are directly infiltrated in an infiltration basins system with a total surface of 1,82 Hectares.

The final use of the recovered water is human consumption; therefore, the regulation limit values are quite restrictive for recharge water. To the end that recharge water almost could be considered as potable water.

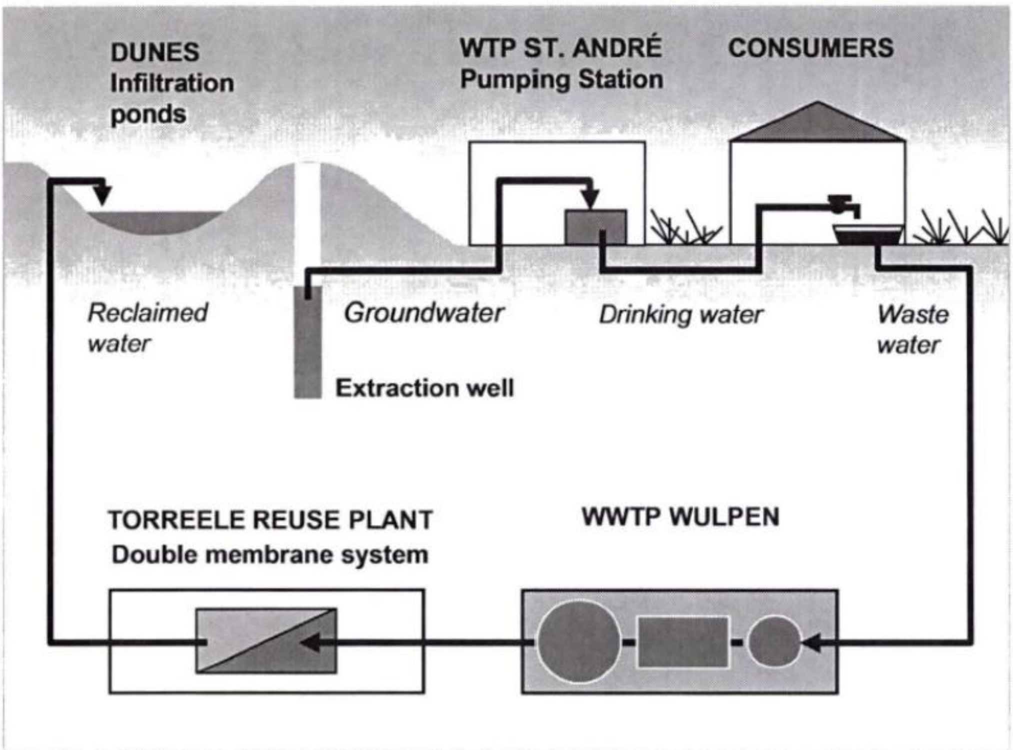


Figure 4 St. André recharge system scheme. (Kazner et al, 2012)

3.5.2 Cubeta de Santiuste (Segovia, Spain)

The "Cubeta de Santiuste" is a natural depression located on the west side of the province of Segovia, between Voltoya and Eresma rivers. It forms a vast infiltration system constituted by basins, channels and wells, used to store Voltoya river water overflow during winter, in order to enhance underground reservoir for summer.

The total infiltration surface reaches 4800 Hectares and lithology is composed by a quaternary sand formation up to 55 meters of thickness that fills a complex cavity of tertiary clays.

Along the operation experience of this system, clogging problems have frequently occurred resulting in a decrease of the infiltration rate. According to local studies (Fernández-Escalante et al., 2009), the main clogging process is caused by physical obstruction of porosity due to sedimentation of suspended solids of recharge water. Chemical and biological processes giving rise to precipitation of minerals and growth of biomass can also contribute to clogging of the infiltration basin.

Figure 5 Pictures of infiltration pond bottom surface and flooding process in Santiuste (Spain).

Such drawbacks were solved with a ploughing process of the bottom surface of the infiltration basins with a "v" structure called "caballones". This design allows the accumulation of the sediments in the lower part of the structure, increasing the infiltration surface almost two times respect to a flat bottom. Moreover, added to a flow control, fine sediment sedimentation and air reduction (pretreatment) in water, infiltration rate decreasing trend was reduced. Thus, low velocities and low turbulent regimes in water are recommended by operators.

3.5.3 Sant Vicenç dels Horts (Barcelona)

MAR in Barcelona owns a strategic role due to the importance of groundwater in Barcelona Metropolitan Area water supply during drought periods.

Sant Vicenç dels Horts recharge system, among other infrastructures, contributes to aquifer groundwater levels conservation. The infiltration system is recharged with Llobregat River water through a bypass built for this purpose. However, the system is also prepared to be fed with reclaimed water from a tertiary treatment from el Prat de Llobregat WWTP. A pipeline conducts water from the river to the infiltration pond, after 48 hours of sedimentation in a previous decantation pond.

To date, the system has been used as a pilot for different research and development studies, trying to characterize biological, chemical and physical processes occurring during the recharge.

Despite its short experience, some operational parameters have been established in order to prevent pollution and clogging problems in the recharge system. In this sense, a motorization plan was designed to control parameters in the river and the infiltration pond. See control details in the table below:

Table 6 Control parameters in Sant Vicenç dels Horts recharge system (Barcelona).

Parameter	Point of control	Limit	Units
Turbidity	Infiltration	≤ 40	NTU
Ammonium	Infiltration	≤ 1	mg/L
Chlorides	Infiltration	≤ 350	mg/L
Conductivity	Infiltration	≤ 1700	µS/cm
Turbidity	River	≤200	NTU
Ammonium	River	≤ 1	mg/L
Chlorides	River	≤ 350	mg/L
Conductivity	River	≤ 1700	µS/cm
Flow	River	≥8	m^3/s

If the recharge water came from the WWTP tertiary treatment, then the limit values would be set by RD1620/2007 as mentioned in section 2.4.

3.6 Operational experiences analysis

The study of all the previous experiences is synthetized in Table , where details and values of operational control parameters are presented for each of the experiences described in this section.

A rapid overview easily concludes that MAR is not a simple and innocuous process. Surface infiltration systems are sensible to pollution and the experience gained from the existing/current systems suggests that not only recharge water should be taken into consideration, but also aquifer local lithology and the evolution of the recharge system itself.

Despite quality problems, long term operation evidences also frequent clogging problems in the infiltration structures. Most of them are simply linked to sedimentation of suspended particles and precipiation of minerals (primarily Mn or Fe oxides). Notwithstanding, many preventing and maintenance actions have been reported in the different systems to prevent/minimize clogging problems, such as:

- Pretreatment of influent in order to reduce the content of suspended solids, organic matter, Mn, Fe... including processes of ultrafiltration, reverse osmosis, sand filters, decantation ponds, etc.

- Ploughing of the surface infiltration system bottom surface to remove fine sediments that can create impermeable barriers.

- New designs of infiltration infrastructures to increase infiltration surface (e.g. "caballones"), or to increase infiltration rates by reducing inflow velocity (T shaped dams).

Table 7 Control parameters in managed aquifer recharge experiences (summary table).

Country	Dan Region (Israel)	Alice Springs (Australia)	Orange Country (California)	Phoenix (Arizona EUA)	St André-Wulpen (Belgium)	Beijing (China)	Sabadell (Barcelona)	Sant Vicenç dels Horts (Barcelona)
Water rype	Treated Wastewater	Treated Wastewater	Purified water	Semichloride secondary effluent	recycled water	reclaimed water WWTP	River and potable water	River/WWTP
Geology	quaternary sands and calcareous sandstones with some alternating layers of loams and clays	quaternary slit, sands, clays and gravel overlying tertiary clays and sandy clays	Unconfined alluvium formed by clay, sand and rock	Gravel and sand layers	sand	clay	Alluvial zone	Alluvial zone
Total cycle time	3 - 5 days							-
Flooding time	1 - 2 days			2 weeks				-
drying time	2 - 4 days			2 weeks				-
plowing frequency	bimotnhly							-
Distance from recovery wells	100 - 1500 m							-
Unsaturated zone	15 - 30 m	10 - 20 m		17 m			7 m	
Pretreatment		Dissolved air flotation and chlorination	Microfiltration and reverse osmosis, and treatment by ultraviolet light and hydrogen peroxide.			Ozonification to decrease organic matter content	Secondary treatment	Decantation pond
Problems	Mn mobilization					Low infiltration, low permeability		-
Potential solutions						Vegetation and sediment frequent cleaning		-
Uses of water	Agricultural irrigation	Horticulture and viticulture	Potable water for human consumption		potable water		Urban irrigation and others	-
Average infiltration rates		3,2 m/day - 2 l/s (silty sand/loam) and 10,6 m/day - 5,5 l/s (sand/gravel)		0,5 m/day during infiltration time, 100 m/year taking into account all the time operated.				1 m/día
Mn	21 µg/l				<10 µg/l		7,2 - 79 µg/l	-
Conductivity					0,045 mS/cm	803 +- 221 µS/cm	1277 - 2550 µS/cm	1700
Turbidity							1,5 - 9,7 NTU	40
COD	43 mg/l					33,5+-6,4 mg/l	2 ,0 - 9,0 mg/l	-
TOC				12 mg/l	0,1 - 1,1 mg/l			-
SST	6 mg/l			11 mg/l		<5 mg/l	3,4 - 13 mg/l	-
DOC						4,4+-0,9 mg/l	5,3 - 10 mg/l	-
NH4				16 mg/l	0,03-0,38 mg/l	0,11+-0,09 mg/l	0,6 - 4,0 mg/l	1 mg/L
NO3				0,5 mg/l	<1-6,3 mg/l	28,3+-1,7 mg/l	2,7 - 6,4 mg/l	-
Cl-, Chloride					1 - 4,7 mg/l	83,6 +- 2,5 mg/l	156 - 491 mg/l	-
Iron	77 µg/l				< 75 µg/l	14 µg/l	29 - 123 µg/l	-

	Guidelines for Design and Operation and Maintenance of SAT (and Hybrid SAT) system (ISRAEL)	Bixio & Wintgens, 2006 and European Union, 1998, Proposed requirements for groundwater recharge	Perez-Parico 2001
Flooding time	Infiltration periods should be short enough (<7 days) to prevent ammonium ion from breaking through surface soils		
drying time	Drying periods should be long enough (> or equal to 4 days period) to permit the oxygen to oxidize ammonia		
plowing frequency	Systematic cleaning of the fields every 15 to 30 days can keep the fields from being clogged		
Pretreatment	UV disinfection of the filtered effluents can prevent clogging and not produce THM or NDMA		pre-filtration is required when strong clogging can occur
Problems	Algal bloom and zooplankton, can be controlled either covering the basin, spreading copper sulfate or using ultrasound devices		TSS < 10 mg/l y TOC < 10 mg/l can produce slight clogging; SST < 20 mg/l y TOC < 25 mg/l can produce moderate clogging; higher values can produce severe clogging
Average infiltration rates	maintain a good and constant infiltration rate or hydraulic loading and to avoid anoxic conditions		
Mn limit	*500 ppb*		
pH		*7-9*	
Conductivity		*0,7 mS/cm*	
COD		*70-100 mg/l*	
N Total		*<25 mgN/l*	
NH4		*<0,2 mgN/l*	
NO3		*<25 mgN/l*	
SO4		*30 mgS/l*	
As		*5 µg/L*	
B		*0,2 mg/l*	
Cd		*3 µg/L*	
Cl-, chlorides		*100 mg/l*	
Cr		*25 µg/L*	
Hg		*0,5 µg/L*	
Pb		*5 µg/L*	
Micropollutants		*<0,1 µg/L*	
Faecal coliforms		*< 10000 UFC/100ml*	

4 Conclusions

Legal framework and operational experiences analysis regarding subsurface water storage has revealed an evident disconnection between both of them.

Regulations are frequently not specific enough about this topic, and they focus on establishing control measures to protect environment from a conservative point of view. These regulations tend to generalize limits and methodologies that have not the same applicability in all recharge sites, as geology and input water quality present commonly great variability.

This study has assessed in detail MAR systems based on surface or indirect infrastructures. The review of the different international experiences confirms the lack of a standardized protocol to avoid quality and infrastructure deterioration. Within this context, these recharge sites have adapted their own rules as problems arose along many years of operation.

In this sense, despite legislation establishes all hazardous substances potentially dangerous for underground stored and recovered water, alterations on the infrastructure along the infiltration processes might happen producing changes on vadose and saturated zones. These unexpected changes could cause many adverse changes such as clogging or contaminant substances mobilization.

Although specific legislation should be emitted concerning managed aquifer recharge, it will exist always a fluctuating factor depending on the system location, water properties, etc. It must be however be recognised that even with, a more precise legislation on this kind of infrastructures, none of them would be exempted from carrying out local studies to be sure of the durability and reliability of the infiltration infrastructure.

In the case of Barcelona, regulatory framework is currently imprecise on this topic. Moreover operational control parameters are often extracted from literature without evaluating the local properties of both the aquifer and the interaction recharge water and groundwater. Therefore, it would be very helpful to address in depth these issues to gain/achieve a more accurate knowledge of the possibilities of these systems and, hence, assess the range of viable operation in order to anticipate to more adverse conditions imminent due to climate change.

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