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Wastewater reuse through soil aquifer treatment: regulations and guideline for feasibility assessment

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ABSTRACT

Soil aquifer treatment (SAT) is a managed aquifer recharge technology that involves the utilization of treated wastewater as a source. Widely implemented in countries like Australia, Israel, and Spain, SAT offers technical (flexibility), economic (lower investment cost), and environmental (lower energy consumption) advantages that invite people in other countries to assess its potential. There have been numerous research studies and experiments conducted on the process level of SAT, focusing on how to eliminate pollutants and improve water quality. However, research at the system level is limited, which hampers its widespread application, especially in developing countries. In this paper, I provide a comprehensive guideline that highlights important factors to consider when implementing SAT as a technology. Proper site selection and careful planning steps, including pretreatment, hydrogeological factors, and economic calculations, can significantly improve the performance of an SAT system. The regulatory component acts as a barrier to the expansion of SAT facilities worldwide due to the lack of harmonization in regulations. This study includes the details and results of an examination of the legal framework and establishes comparative guidelines and water quality parameters that must be met by SAT projects utilizing reclaimed water. The maintenance and monitoring of the SAT system are also essential to anticipating and addressing potential issues such as clogging. Lastly, the social aspect, which is of utmost importance, should be carefully considered. It is advisable to ensure transparent communication with end users from the early stages of the project. These key elements are interconnected, and none should be considered less significant than the others.

Keywords: Soil aquifer treatment; Artificial recharge; Water reuse; Regulations; Managed aquifer recharge

1. Introduction

Water demand has increased globally, the efforts to harness water resources are nearing their physical and economic limits. In the upcoming decades, the focus should shift towards more efficient management of this vital resource, ensuring its preservation and optimal utilization.

In this context, effective methods for management aquifer recharge (MAR) are adopted to replenish depleted aquifers and to enhance groundwater quality with recharge water [1,2]. Various water sources can be utilized for storage in a suitable aquifer, such us: desalinated seawater, river water, rainwater, stormwater, and treated wastewater.

An unconventional process that involves utilizing the appropriate properties of soil, subsoil, and groundwater

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for more purification of the infiltrated water to drinkable quality is the soil aquifer treatment (SAT) elaborated on by Bouwer (1978). The concept is to infiltrate the wastewater across the unsaturated zone and aquifers, the treated effluent is recovered later by means of recovery wells. SAT is an advanced wastewater treatment process and alternative resource available throughout the year and more especially when the water level is low and conventional resources are very solicited or even unavailable. In addition, infiltration of treated wastewater through an unsaturated zone benefit from the purification capacities of the subsoil in which biological and physiochemical processes occur naturally allowing the degradation or filtration of a certain number of pollutants. Microorganisms are filtered or die due to rivalry with other microorganisms in soil, suspended solids are purified, biodegradable compounds are decomposed, synthetic organic compounds are biodegraded and/or adsorbed, nitrogen rates are decreased by denitrification; and heavy metals are precipitated, or immobilized [3]. Compared to other technology, SAT is natural, simple, environment-friendly, and low-cost, as shown in Table 1.

1.1. SAT types

SAT can be achieved through several methods (Fig. 1). The most widely used method is rapid infiltration tough recharge basins [5–7]. Vadose zone wells and direct injection of reclaimed water through deep wells are also used when suitable land is not available and/or where the aquifers are confined [8,9].

1.2. Mechanisms and efficiency for removing contaminants during SAT

SAT is implemented worldwide for the treatment of wastewater using primary, secondary, and tertiary effluents [11,12]. Within the SAT system, various mechanisms such as filtration, biodegradation, chemical precipitation, dilution, ion exchange, and adsorption participate to the reduction of contaminants as they pass through the soil. [11,13]. High removal efficiencies depend on factors such as pretreatment, type of SAT system, travel time/travel distance, and hydraulic loading rate.

The unsaturated zone serves as a natural filter during SAT capable of eliminating nearly all suspended solids, viruses, bacteria, biodegradable substances, and additional microorganisms [14]. Through the filtration process in soil layers, the percolate from SAT systems typically contains 1–2 mg/L of total suspended solids [15].

Bacteria play a role in removing nitrogen species during SAT, both under anoxic and aerobic conditions. This process involves two steps: autotrophic nitrification and heterotrophic denitrification.

In SAT, Phosphorus is eliminated via adsorption and chemical precipitation. Table 2 illustrates the typical removal rates of various pollutants from primary, secondary, and tertiary effluent.

Additionally, SAT demonstrates effectiveness in eliminating a significant portion of trace organic compounds derived from effluents. However, a few compounds may persist at low levels (ng/L), leading to debates regarding their potential health implications [16]. The removal of organic micropollutants (OMPs) through soil percolation is influenced by three key processes: biodegradation, sorption, and volatilization. Table 3 contains a compilation of removal efficiency data for various selected pollutants in SAT, based on recent experience at different scales.

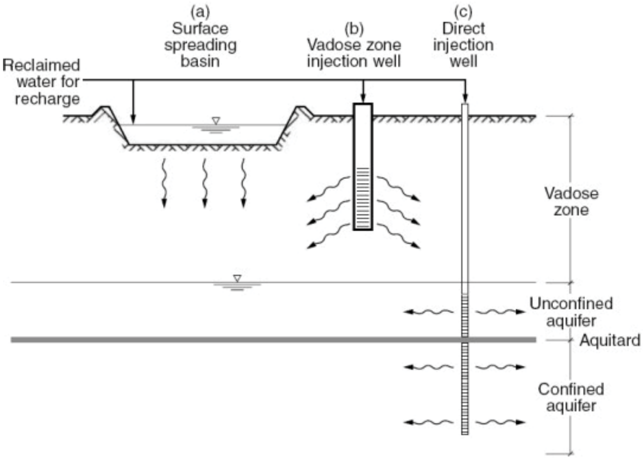

Fig. 1. SAT types [10].

Table 1
SAT compared to other advanced treatment technologies [4]

Process	Operator skill	Complexity of technology	Maturity of technology	Cost (capital + O&M)
Biological N and P removal	Low	Low	High	Medium
P precipitation	Low	Low	High	Medium
Membrane bioreactor	Low	Low/Medium	Medium/High	Medium/High
Coagulation	Low	Low	High	Low
Nanofiltration/Reverse osmosis	Low/Medium	Medium	High	High
Chlorination	Low	Low	High	Low
UV disinfection	Low/Medium	Low	High	Low
Ozonation	Medium	Medium	High	Medium
UV/H_2O_2	Low/Medium	Medium	High	Medium
SAT	Low	Low	Medium	Low

Table 2
SAT removal efficiency of different pollutants from primary, secondary, and tertiary effluent

	PE	SE	TE	References
DOC (%)	[12–62]	[15–94]	[17–82]	[17–22]
NO_3–N (%)		[–8,650–87]	[–176–22]	[11,22–25]
NH_4–N (%)	[25–99.5]	[–67–99.2]	[72–100]	[17,22–26]
PO_4–P (%)	[–22–90)	[30–99]	[–1,200–80]	[12,17,27–31,24,22]
Total coliforms (log_{10})	[1.2–5]	[1.6–4.6]		[32–34,17,22]

Table 3
Typical removals of pollutants at some SAT schemes around the world

Treatment level	Scale	Product	% removal	Country	Year	References
Pretreatment + 3 Decanters + Conventional activated sludge + 3 Clarifiers	Pilot scale	Benzophenone	100	Spain	2021	[35]
		Benzotriazole	58–92			
		Carbamazepine	69–81			
		Caffeine	100			
		Ibuprofen	91–100			
		Ketoprofen	52–82			
Tertiary effluent	Soil column	TOC	67	USA	2018	[36]
		NDMA	99			
Secondary treated wastewater	Infiltration basins	Total nitrogen	49–83	Shafdan	2018	[37]
–	Soil column	Nitrogen	80	UK	2013	[38]
		Nitrate	93–100			
		DOC	65–78			
MBR technology	Soil column	NO_3–N	51–78	China	2017	[39]
		NH_4–N	41–51			
		COD	40–50			
Stabilization ponds + Sand filtration (DAFF) + UV disinfection	Field (Recharge basins)	Chloride	49	Australia	2017	[40]
Primary treatment followed by an aerobic activated sludge process and clarifiers	Field (Infiltration basins)	BOD	98	Egypt	2022	[41]
		COD	91			
		TSS	91			
		Total coliform	99.99			
		Fecal coliform	99.99			
		Heavy metals (Mn^{2+}, Zn^{2+}, Cd^{2+}, Pb^{2+}, Al^{3+}, and Cu^{2+})	100			
Primary effluent	Soil column	SS	86.8–95.2	The Netherlands	2014	[13]
		DOC	49.4–61.5			
		NH_4–N	28.7–98			
		E. coli log_{10}	2.5–4.3			
		Total coliforms (log_{10})	2.5–4.1			
Secondary wastewater treatment	Pilot plant	BOD	64	Egypt	2016	[42]
		COD	38			
		TSS	86			

BOD: biochemical oxygen demand; COD: chemical oxygen demand; TSS: total suspended solids; DOC: dissolved organic carbon.

These values serve as indicators of the pollutant removal performance achieved by SAT.

2. Methods

This section presents the process stages to be considered by an agency or authority willing to adopt SAT. An SAT process is segmented into four phases, which include planning, investigation, design, construction, as well as operation. In each stage, several key elements need to be examined. Economic, environmental, hydrogeological, and legal (e.g., regulations and guidelines), as well as social, considerations are described. The pilot project can be tested only when all requirements are met. The model can be applied to fundamental or small projects by selecting only factors that are proper for the project. However, the technical aspects of certain tasks are not described in detail, and additional technical information is referenced in the Appendix.

3. Planning

The main factors to examine in the planning stage are (Fig. 2):

- Availability of a continuous source of wastewater able to supply large volumes of water during the life of a project, generally estimated at 20 y [43].
- Source of water: The type of wastewater effluent may include primary effluent (PE), secondary effluent (SE), or tertiary effluent (TE).
- Pretreatment: The treated wastewater from a step can undergo an additional pretreatment before SAT, it depends on the intended reuse purpose, local regulations, and recharge method.

Primary sedimentation is required for spreading basin types, while tertiary treatment (sand filtration and chlorination) should be used for vadose zone well injection [44]. For direct injection, an additional treatment (MF, RO, and UV disinfection) is applied. Other treatments like

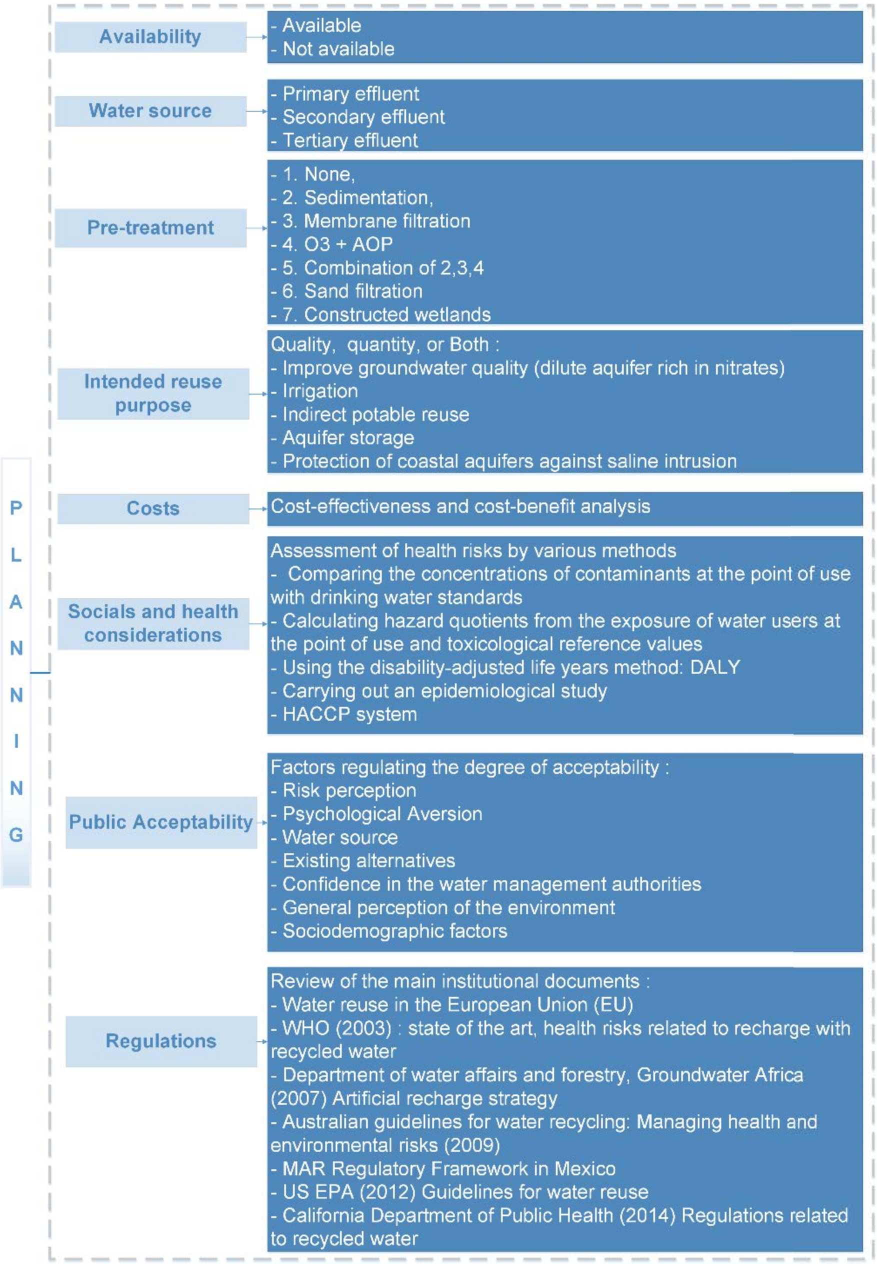

Fig. 2. Key elements to consider in the planning phase.

preoxidation, rapid sand filtration, and wetlands construction can also be implemented to improve the quality of the SAT influent and to enhance the removal of contaminants [22]. Moreover, the higher the level of treatment the wastewater has undergone in the wastewater treatment plant (WWTP), the lesser should be the pretreatment requirement.

- The intended purpose of reuse: The final purpose of recovering water from aquifers, varies in each case. It can be used for water consumption, aquifer storage, irrigation, industry, and environment protection.
- Cost: In the case of a spreading basin SAT system, the capital expenses encompass the following components: (1) the pipeline infrastructure connecting the wastewater treatment plant (WWTP) to the SAT site, (2) the acquisition of land for the SAT system, and (3) the installation of pumping systems for the recovered well.

The operation and maintenance (OM) costs essentially comprise (1) monitoring of water quality, (2) spreading basin maintenance, and (3) energy costs for OM (essentially the cost of pumping water from recovery wells). SAT cost is usually under that of the conventional treatment process. Furthermore, its operation is easy and does not need chemical or pricey equipment [45]. The type of pretreatment and/or posttreatment used relies on regulation or reuse requirements and has a significant impact on system cost.

The cost of SAT, as mentioned earlier, is slightly lower than that of conventional treatment systems. A comparative economic assessment study of SAT system with other conventional wastewater treatment process showed that SAT is economical, specifically regarding recurring OM costs. The cost of SAT is less than 40% of an equivalent in-plant treatment [46]. The prices of recycled water are subsidized in Australia by the state to promote the reuse of wastewater. In a survey, Marks [47] noted that residents expect to pay less for the use of recharge water because the water quality is low. The price of recycled water was $US0.22/m^3, 80% cheaper than drinking water.

3.1. Socials and health considerations

The primary issue associated with SAT is the possible public health risk arising from increased concentrations of pathogenic microorganisms or toxic contaminants in recharged groundwater. Therefore, risk-based management is essential [48], to ensure the protection of public and environmental health [49]. Moreover, the use of spreading basins can increase the contamination of recharge water. For example, the frequency of detection of E. coli in water increases after passage through an open-air storage. The stagnation of water can also promote the proliferation of certain vector insects and thus increase the risk of vector-borne disease transmission.

The health risks have been assessed for several artificial recharge sites in developing a specific method or using classical methods [50]:

- Comparing the concentrations of contaminants at the point of use with drinking water standards [51,52].
- Calculating hazard quotients from the exposure of water users at the point of use and toxicological reference values [53,54].
- Using the disability-adjusted life years method: DALY [55–57].
- Carrying out an epidemiological study [58].
- Application of quality management methods using the hazard analysis and critical control points plan (HACCP): system [59,60]; or the Australian Guidelines [61,62].

In general, to address the public and environmental issues related to wastewater reuse schemes, it is critical to know the intended reuse of reclaimed water, the substances existing in wastewater, and the degree of treatment needed to decrease these substances to admissible levels [9].

The introduction of minute quantities of pathogens or toxic chemicals into an aquifer that is used as a source of drinking water could lead to adverse health risks. These components can be reduced by ensuring sufficient pre- or posttreatment and/or increasing the travel time in the aquifer.

The minimum quality requirements to be met by the effluent must also be established and included as a criterion in monitoring. With respect to reuse guidelines, several are in place, ranging from the stringent California regulations to the less stringent World Health Organization (WHO). Existing regulations do not address most emerging contaminants for their intended reuses of water withdrawn after recharge, and there is a lack of toxicological reference values for assessing chronic risk associated with these contaminants. Some authors have proposed then methods to prioritize emerging contaminants or to identify those for which it is necessary to deepen the health risk analysis.

For each site, the end users of recharged water must be identified to be informed. Indeed, in some cases, opposition from residents or from associative structures may be set up against the project on the grounds that it risks having too much impact on the environment and existing ecosystems and endangering the quality of the resource. This aspect, far from the least, should be considered with the greatest caution, and it is advisable to ensure a perfect transparency and communication upstream of the project.

3.2. Public acceptance

The following factors regulate the level of public acceptance of SAT:

- The risk perception: The study carried out in England on domestic recycled water shows that risk perception is one of the key factors of social acceptability. It shows that the acceptance of the use of recycled water is mainly conditioned by the guarantee that it does not present any health risk [63]. Similar results, in Australia, showed that 92% of respondents focused on the origin of recycled water [64].
- "Psychological" Aversion: Several Australian surveys showed that aversion factor is a key factor for most respondents totally rejecting the idea of the reuse of

treated wastewater. This psychological factor is therefore considered to be a valid indicator representing the degree of social acceptance toward SAT [65].

- Water source: Surface water from runoff is better socially acceptable than treated wastewater. The work of Nancarrow et al. [66] showed that artificial recharge is not widely accepted when treated wastewater is used. By comparison, the use of this treated wastewater in other activities such as watering gardens and parks is viewed more positively. These results seem to be confirmed by surveys carried out in Australia and England. These surveys also indicate that the individuals questioned are more comfortable with the use of their own treated wastewater than that of treated wastewater from the community. This preference seems to be strongly related to the psychological aversion factor. However, other surveys appear to show the opposite results; respondents prefer to use treated wastewater from collectivises because treatment and control standards are more stringent [67], [65].
- Existing alternatives: The acceptance of the use of artificial recharge can be encouraged when water resources are threatened, as well as when acquiring this resource presents a strong challenge [68]. In Israel, the use of aquifer recharge with treated wastewater is accepted because the water resources problems are major in this country. According to the work of Bixio et al. [69], it seems that the use of artificial recharge is fully accepted when other water resource management solutions are not technically realistic and/or economically dissuasive.
- Confidence in the water service management authorities: Confidence in, on the one hand, the scientific and technical knowledge acquired around the recharge and, on the contrary, the administrative authorities in charge of controlling this activity is a key factor determining the acceptance of a recharge project. The lack of public confidence in the knowledge of artificial recharge projects involving treated wastewater is the most common reason cited by respondents who oppose these activities [65]. Recharge projects in Australia were successful because the public had confidence in the water management bodies overseeing the project, as well as in the project promoters. To build trust, the criteria for evaluating the quality of the resource must be shared by all partners and the public involved in the use of the recharge device [63].
- General perception of the environment: The Sydney Water Survey [64] reports that individuals aware of the scarcity of drinking water resources are more inclined to accept the recharge activity [65].
- Sociodemographic factors: The results of surveys in Australia and the United States statistically show that the perception of artificial recharge depends on the gender, age, income, level of education, and area of residence of the respondents. The role of these sociodemographic factors in the acceptance of artificial recharge remains, however, minor (10%–20%).

To gather public perception about the recharge using treated domestic wastewater in India, a questionnaire was delivered within professionals from different areas [70]. The results of the survey revealed that 64.4% of the respondents have approved the adoption of aquifer recharge with treated wastewater; nearly 28.4% of respondents noted that they were opposed, while 7.2% were neutral. The questionnaire also showed that the main preoccupation of respondents was the efficiency of WWTP, and not the recharge process itself. They formulated doubt as to whether effluent from wastewater treatment plants can be treated to an appropriate quality to infiltrate into the groundwater.

Ample evidence in both in Australia and the United States shows that water recycling via aquifer recharge for drinking water supplies is more publicly accepted compared to water recycling without natural storage and treatment [71]. In addition, SAT used for groundwater recharge is more acceptable in countries where the use of “unclean” water is regarded as a religious taboo [44]. In fact, SAT presents aesthetic relevance on conventionally treated wastewater because the recovered water is not just clean and odorless, but it comes from a well, a drain rather than a treatment plant or sewers. Thus, water loses its connotation of sewerage and people perceive it more as water from the soil (aquifer) than as a wastewater effluent.

3.3. Regulations

This section contains a summary of institutional documents relating to artificial groundwater recharge with treated wastewater. A review of the main institutional documents has been carried out [50].

3.3.1. Water reuse in the European Union (EU)

The report [72] handles the reuse of reclaimed water in a broad sense and does not have a specific position on the recharge of the aquifers.

Regarding more specifically SAT method, the document indicates that only Cyprus, Greece, and Spain have a framework mainly for aquifers that are not used for drinking water.

Finally, the document mentions the artificial recharge site with treated wastewater in Wulpen (Belgium), whose quality criteria have been established locally by the regional government, without the implementation of national regulations [73]. Site characteristics are shown in Table 6.

3.3.2. State of the art, health risks related to recharge with recycled water: WHO (2003)

In 2003, the WHO published a report summarizing the knowledge acquired on the health risks associated with SAT [74]. This report reviews different systems for drinking water or for other uses. It offers general recommendations for the assessment and control of health risks, with particular attention to the presence of chemical and microbiological agents, particularly for drinking water use. The WHO emphasizes that recharge water used for drinking water must comply with the criteria and guide values of the drinking water supply. However, this does not exclude a health risk linked to other contaminants contained in treated wastewater and which are not covered by the drinking water criteria but can nevertheless be found in recycled water. The WHO proposes guidelines for the use of SAT by recharge type (infiltration or injection) for the supply of drinking water.

3.3.3. Department of water, groundwater Africa (2007) artificial recharge policy

South Africa published a report in 2007 entitled strategy for artificial recharge. The document presents a summary of the concept of artificial recharge and the key parameters affecting its implementation, as well as the implementation scheme and authorization. This report is illustrated by some examples of artificial recharge sites in South Africa and Namibia that depend on the use of surface water or treated wastewater. However, the quality parameters are not discussed, and the implementation guidelines are based on those issued in other countries, including Australia.

3.3.4. Australian guidelines for water recycling (2009): managing health and environmental risks (phase 2): managed aquifer recharge

The guideline defines a framework for the design and managed aquifer recharge with the objective of protecting public health and the environment. The guideline is not mandatory and has no legal status, but aim to provide a shared national objective, allowing flexibility and adaptation to regional and local contexts, its application may vary by jurisdiction. The Australian states that are making progress in Managed Aquifer Recharge (MAR) are those that have incorporated the guidelines into their state laws or policies [75]. These guidelines address operational issues on the implementation of SAT, in particular monitoring procedures, preventive measures and the quality of the recharge water, based on the water source and intended use. Unlike other institutions, the Australian guidelines consider the abatement occurring in the subsurface by the vadoze zone and in groundwater. For this, they used the concept of an attenuation zone applied to the aquifer (Appendix A). Attenuation is the reduction of the concentration of hazards by natural processes (in particular biodegradation), which are sustainable when the system of the subsurface is not overloaded. The report provides indicative attenuation rates for certain pathogens and chemical contaminants; however, these rates are specific and must be validated for each site and vary depending on the temperature and geochemical conditions of the aquifer.

3.3.5. MAR regulatory framework in Mexico

Mexico stands out as one of the few countries with national regulations specifically addressing the implementation of managed aquifer recharge (MAR) projects. These regulations include NOM-014-CONAGUA-2007 [76] and NOM-015-CONAGUA-2007 [77], which are aimed at safeguarding aquifers. NOM-014 focuses on artificial recharge using treated wastewater, while NOM-015 outlines the requirements for infiltration activities that utilize run off to recharge groundwater. When it comes to direct injection method, the water used must adhere to standards for potable water quality. Both standards take into consideration the unsaturated zone, as part of the natural soil treatment process.

Nevertheless, the law of the Nation's Waters in Mexico lacks a specific definition for reclaimed water and fails to establish clear procedures for its management and allocation [78]. As a result, regulations and policies regarding reclaimed water remain limited, as emphasized [79]. Another review identified a significant obstacle to expanding MAR in Mexico: the frequent turnover of water district chairs responsible for water operation and supply, which hampers continuity and progress in this area [80].

Currently, over 25% of the total volume utilized for human consumption and productive activities is imported [78].

3.3.6. US EPA (2012) guidelines for water reuse

The US EPA's Water Reuse Guidelines [9] provide national guidance on water reuse in support of guidelines and regulations developed at state levels, due to the lack of national policies for water recycling in the United States. The report was updated in 2012 to consider the increase in demand for water reuse, technological advances, and changes in the regulation of these practices, particularly in cases of insufficiency of conventional water resources. It comprises the objective of drinking water supply from other uses.

3.3.7. The 2014 regulations established by the California department of public health regarding recycled water

The regulations classify two recharge methods for Indirect Potable Reuse: recharge by surface application (Art. 5.1) and recharge by subsurface application (Art. 5.2).

Tables 4 and 5 present some of the criteria imposed or recommended by the WHO, the US EPA's Water Reuse Guidelines and California regulations for the recharge of aquifers used for drinking water supply or non-potable reuse with treated wastewater in terms of recharge method (infiltration or injection).

3.3.8. Quality of recharge water

Regarding specifically the quality of water, Escalante [82] compiled the various standards as maximum allowable concentration (MAC) and tolerance scale. In water quality requirements such as California, Spain, and Mexico, a distinction is done according to the intended uses and type of recharge with different limits for each case. Spanish standards include twelve water quality categories with microbiological and physicochemical parameters depending on the intended uses. It sets limit values for nitrogen (10 mg/L) and phosphorus (2 mg/L) for the recharge of aquifers, and more stringent limit values for TSS for the recharge by injection. Greek standards are based on the same principle with four categories of water quality. Greek standards set strict limits for BOD_5 and TSS for recharge by injection.

Table 4
Guidelines for utilizing treated wastewater in SAT using the infiltration method

	Potable reuse			Non-potable reuse
	WHO [74]	US EPA [9]	California Department of Public Health [81]	US EPA [9]
Treatment	- Primary treatment and disinfection, plus soil aquifer treatment, handling of dry and wet cycles as well as hydraulic and mass charges to clogging, in the event that suspended solids are mostly mineral. - Primary advanced treatment and disinfection, plus handling of dry and wet cycles as well as hydraulic and mass charges so as to avoid soil colmatation, in the event that suspended solids are mostly mineral. - Secondary treatment and disinfection with well-operated soil aquifer treatment. - Possibly advanced treatment according to site-specific considerations.	Site-specific secondary[a] and disinfection[b] minimum may also need filtration[c] and/or advanced wastewater treatment[d].	***At least filtration step***: Coagulation and filtration to achieve an average turbidity level of 2 NTU within a 24-h timeframe. Or Microfiltration, ultrafiltration, nanofiltration, or reverse osmose to reach an average of 0.2 NTU in turbidity within a 24-h period. And Additionally, a chlorine disinfection process is employed after filtration, which ensures a sufficient CT value (the product of total chlorine residual and modal contact time). <=450 with a modal contact time. >=90 min, Or Any other process that has been shown to effectively inactivate and/or remove 99.999% of plaque-forming units of *F*-specific bacteriophage MS2 or poliovirus. Furthermore, the median concentration of total coliform bacteria in the disinfected effluent should not exceed an MPN (most probable number) of 2.2/100 mL over the last 7 d.	- Site-specific and use dependent. - Minimum: primary treatment.
Quality	The percolation of water through the unsaturated zone should result in compliance with drinking water standards.	Includes, but is not limited to, the following: - $6.5 \leq pH \leq 8.5$. - <2 NTU[e]. - Not detectable fecal coliforms/100 mL[f,g]. - >=1 mg/L residual Cl_2[h,i]. - Meet drinking water standards before infiltration into unsaturated zone.	Minimum reduction of pathogenic microorganisms: A 12-log is for enteric viruses, while a 10-log is necessary for Giardia cysts. 10-log for Cryptosporidium oocysts $Nt \leq 10$ mg/L. Total organic carbon (TOC) ≤ 0.5/RWR mg/L. RWR: Recycled water rates. - Comply with drinking water standards for the inorganic chemicals, the radionuclide chemicals, the organic chemicals, the disinfection by-products, copper, and lead.	Site-specific and use dependent.
Monitoring well	Monitoring for coliforms. pH, chlorine residual, drinking-water standards plus site-specific others.	Including, but not limited to: ***pH***: daily. ***Coliforms***: daily. ***Residual chlorine***: continuously. ***Potable water standards***: quarterly. ***Others***: depending on original water constituents.	At least two monitoring wells between the recharge zone and recovery well.	Depends on treatment and use.

Setback distances	Distance to point of extraction (600 m) or dependent on site-specific factors.	600 m to extraction wells. May vary depending on treatment provided and site-specific conditions.		Site-specific.
Travel time		≥2 months		

[a] A secondary treatment processes include activated sludge processes, trickling filters, percolating filters, rotating biological contactors, and many stabilization pond systems. Secondary treatment should produce effluents in which both the BOD and SS do not exceed 30 mg/L.

[b] Disinfection refers to the process of physically, chemically, or biologically destroying, inactivating, or removing pathogenic microorganisms.

[c] Disinfection may be accomplished by chlorination, ozonation, other chemical disinfectants, UV radiation, membrane processes, or other processes.

[d] Filtration means the passage of wastewater through natural undisturbed soil or filter media such as sand and/or anthracite.

[e] Advanced wastewater treatment processes include chemical clarification, carbon adsorption, reverse osmosis, and other membrane processes, air stripping, ultrafiltration, and ion exchange.

[f] The set of turbidity levels must be met before disinfection. The value to be used is the average for 24 h, during which turbidity must never exceed 5 NTU; and when solids are used as a measure, they must be 5 mg/L.

[g] Unless otherwise specified, the limits of the coliforms correspond to the median for 7-d experiments. The fecal coliform count must not exceed 14/100 mL in any sample.

[h] The chlorine value corresponds to residual chlorine after a 30 min contact time.

It is important to note that the permissible values for various parameters vary significantly between different standards. For instance, the allowed limit for total nitrogen is the lowest in Spain and California at 10 mg/L, while it is the highest in Mexico at 40 mg/L (a difference of 4 times). Similarly, for total phosphorus, Mexico has the highest limit at 20 mg/L, whereas Belgium has the lowest at 0.4 mg/L (a difference of 50 times). Chloride and sulfate concentrations must not exceed 300 mg/L in Mexico, while the lowest permitted values are observed in California at 125 mg/L for sulfates and 120 mg/L (2.5 times lower) for chloride. Turbidity, on the other hand, has the highest maximum allowable concentrations in Israel at 10 NTU, while the minimum and more stringent limit is found in Spain at 2 NTU for direct injection.

In general, Mexican standards tend to have more permissive concentration limits, while stricter regulations are observed in different standards, particularly in California and Spain. According to the various regulatory approaches, we concluded that the water quality parameters for SAT depend on several factors such as applied treatment, environmental conditions, and end use (drinking water supply is more demanding regarding quality than irrigation or industrial use). In this context, there is a complexity in the process to achieve scientific regulation of quality standards because any approach needs to consider not just hydrogeochemical aspects but as well all other technical criteria. Permitted values (physical, chemical, bacteriological parameters) to be respected in recharge water in relation to various guidelines and regulations are summarized in Appendix B.

4. Investigation

The general hydrogeologic evaluation of the groundwater basin should consider the following technical issues using available data and resources (Fig. 3):

- Surface topography: According to Sharma and Al-Kubati, appropriate slopes for SAT basin construction must not exceed 15%. Sites containing a slope of 0%–5% are the most appropriate [22,45,83].
- Surface soil and unsaturated zone characteristics: The soils must be fine enough to offer better filtration and better quality of the effluent as it percolates. The most suitable surface soil type for SAT is in the sandy loams and loamy or fine sand range [46]. The thickness of the unsaturated zone: The recommended minimum depth of 1–2 m is aimed at achieving an acceptable level of contaminant removal [22].
- Hydraulic characteristics: the transmissivity of the aquifer should be estimated or determined to make certain that it is sufficient to prevent undue rises of a groundwater mound below the infiltration system [84]. A high infiltration rate is recommended because it reduces the required size of the infiltration area and evaporation losses. A suitable permeability should be between 15 and 500 mm/h [7,83,85]. However, it is still difficult to maintain satisfactory infiltration rates in the presence of low permeability sediments and when the concentration of suspended solids is high.

Table 5
Guidelines for utilizing treated wastewater in SAT using the direct injection method

	Potable reuse			Non-potable reuse
	WHO [74]	US EPA [9]	California Department of Public Health [81]	US EPA [9]
Treatment	Secondary treatment, filtration, disinfection, advanced wastewater treatment.	Secondary[a] Filtration[c] Disinfection[b] Advanced wastewater treatment[d]	Reverse osmosis and advanced oxidation process.	Site-specific and use dependent secondary a min[a]
Quality	Meet drinking-water standards no detectable fecal coliforms in 100 mL, turbidity limits, 1 mg/L chlorine residual, pH between 6.5 and 8.5, others.	Includes, but is not limited to the following: $6.5 \leq pH \leq 8.5$. - <2 NTU[e]. - Not detectable fecal coliforms/100 mL[f,g]. - >=1 mg/L residual Cl$_2$[h,i]. - Meet drinking water standards.	Minimum reduction of pathogenic microorganisms: 12-log for enteric viruses. 10-log for Giardia cysts. 10-log for Cryptosporidium oocysts Nt ≤ 10 mg/L. Total organic carbon (TOC) ≤ 0.5 mg/L. - Comply with drinking water standards for regulated inorganic contaminants, disinfection by-products, organic chemical contaminants and copper and lead.	Site-specific and use dependent.
Monitoring well	Monitoring for turbidity, coliforms, chlorine residual, pH, drinking-water standards, others.	Including, but not limited to: ***pH***: daily. ***Coliforms***: daily. ***Residual chlorine***: continuously. ***Potable water standards***: quarterly. ***Others***: depending on original water constituents.	At least two monitoring well between recharge zone and recovery well.	Depends on treatment and use.
Setback distances	Distance to point of extraction (600 m) or dependent on site-specific factors.	600 m to extraction wells. May vary depending on treatment provided and site-specific conditions.		Site-specific.
Travel time		≥2 months		

[a] A secondary treatment processes include activated sludge processes, trickling filters, percolating filters, rotating biological contactors, and many stabilization pond systems. Secondary treatment should produce effluents in which both the BOD and SS do not exceed 30 mg/L.

[b] Disinfection refers to the process of physically, chemically, or biologically destroying, inactivating, or removing pathogenic microorganisms.

[c] Disinfection may be accomplished by chlorination, ozonation, other chemical disinfectants, UV radiation, membrane processes, or other processes.

[d] Filtration means the passage of wastewater through natural undisturbed soil or filter media such as sand and/or anthracite.

[e] Advanced wastewater treatment processes include chemical clarification, carbon adsorption, reverse osmosis, and other membrane processes, air stripping, ultrafiltration, and ion exchange.

[f] The set of turbidity levels must be met before disinfection. The value to be used is the average for 24 h, during which turbidity must never exceed 5 NTU; and when solids are used as a measure, they must be 5 mg/L.

[g] Unless otherwise specified, the limits of the coliforms correspond to the median for 7-d experiments. The fecal coliform count must not exceed 14/100 mL in any sample.

[h] The chlorine value corresponds to residual chlorine after a 30 min contact time.

According to Barry, a treatment upgrade which involve UV disinfection and sand filtration before recharge resulted in an average increase in infiltration rates ranging from 40% to 100% [40].

- Type of aquifer and subsurface soil profile: The aquifer for surface spreading type must be unconfined. The subsurface soil profile must be free of restricting layers [22].

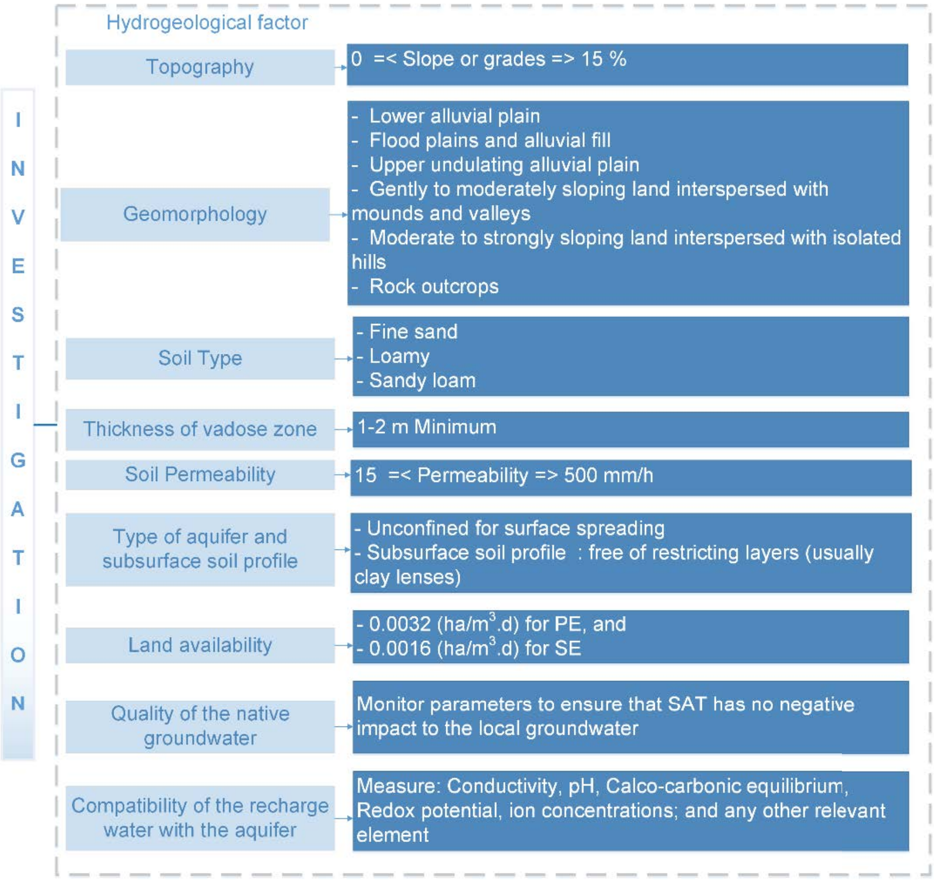

Fig. 3. Key factors to consider during the site selection process.

- Land requirement: Land availability is an important limitation of SAT implementation [86]. SAT requires a large area of land for the setup of infiltration basins. This is particularly relevant in urban areas where there is direct competition because land is expensive and limited [87].

The total land includes the area for infrastructure, a buffer (to screen SAT field from the public), on-site pretreatment, and a recovery system. An estimated area is 0.0032 (ha/m^3·d) for PE, and 0.0016 (ha/m^3·d) for SE [7]. Moreover, land availability is a problem due to saturation with the removed constituents, which implies there is a need to use it every number of years in a virgin area. Therefore, a high level of pretreatment can improve infiltration rates and hence reduce the amount of area requirement. Other parameters must not also be ignored such as the proximity of potential sources of contamination (surface and buried), geochemical compatibility of potential recharge water with formation water and minerals, the proximity of potential contamination plumes that may be affected by recharge operations and tectonic and seismic setting.

- Quality of the native groundwater: Quality should be monitored to make sure that there is no negative impact on local groundwater as a result of SAT. However, if the quality of the local groundwater is lower than the recharge water, then the impact would be positive, especially when groundwater is rich in nitrates or salinity is high for coastal aquifers [50]. The main parameters to be taken into consideration in monitoring are pH, DO, TDS, EC, major ions, trace compounds, and matching the redox potential of the recharge water with the redox potential of the native groundwater [9].
- Compatibility of recharge water: When recharge water differs significantly in quality from groundwater, this leads to negative changes in water quality such as the leaching of iron or arsenic [88]. In order to assess the compatibility between the recharge water and the aquifer, it is necessary to measure at least in the raw water for recharge, the recharge water and the native groundwater: Conductivity, pH, calco-carbonic equilibrium, redox potential (conditioned by the type of water table), ion concentrations, and any other relevant element [65]. Geochemical modeling can be used to estimate the ranges of values that do not modify the physical and chemical equilibrium in the water table.

5. Design and construction

During the design and construction stage, it is essential to consider the following elements (Fig. 4):

- Distance and elevation of the SAT site to the wastewater treatment plant (WWTP): According to Al-Kubati [22]

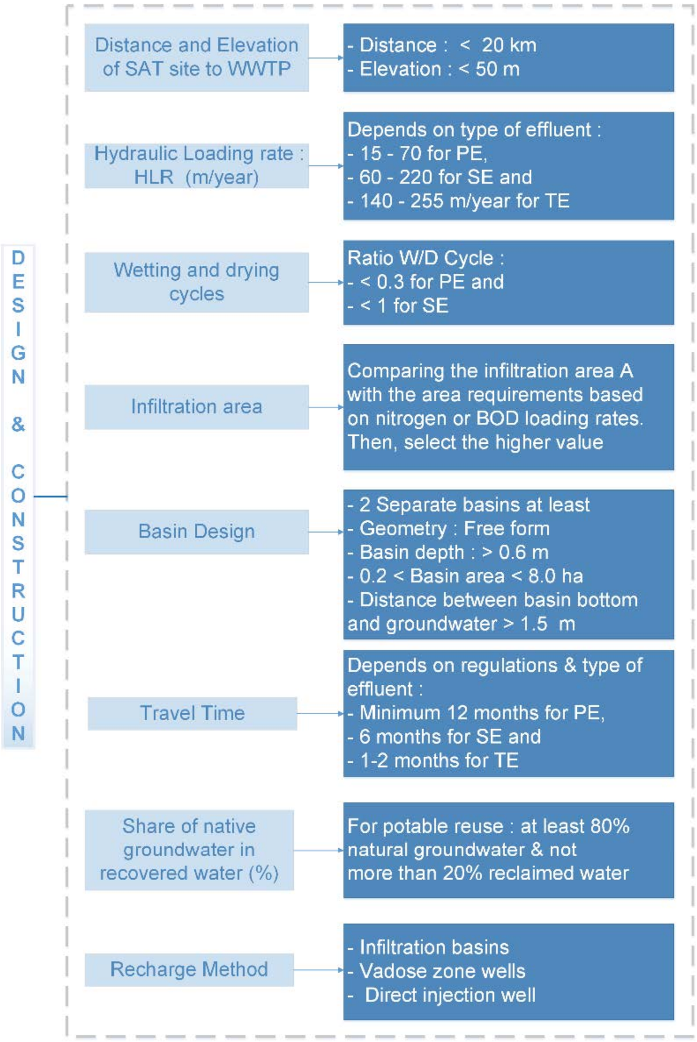

Fig. 4. SAT implementation: elements should be considered at the design and construction stage.

Sharma [45], the suitable distance from the wastewater source to the SAT site should be less than 20 km, and the elevation difference between the two sites should not exceed 50 m.

- Hydraulic loading rate – HLR (m/y): The most effective way to measure hydraulic capacities is by using long term average infiltration rates or hydraulic loading rates, considering the essential requirement for periodic cleaning and regular drying of the basin or other infiltration facility [44].

The factors that affect this parameter are the quality of wastewater effluent, the characteristics of the soils, the clogging potential of SAT system, the wetting/drying periods, the local climatic conditions mainly precipitation and evaporation, and the changes in seasonal temperature. The following ranges of hydraulic loading rates for the three different types of wastewater effluent are proposed: 15–70 for PE, 60–220 for SE, and 140–255 m/y for TE [22].

Depending on soil type, values of hydraulic loading rates were listed by [89], as follows:

  - 500 m/y for coarse clean sands,
  - 300 m/y for medium clean sands,
  - 100 m/y for loamy sands, and
  - 30 m/y for fine textured soils like sandy loams.

- Wetting and drying (W/D) cycles: Shortening of drying cycles, as a result of intensive hydraulic loading rates, reduces the quality of treatment, which is mainly due to the absence of soil aeration [90].

The activity of the wetting/drying cycle comprises the filling of the basin up to a specific depth, stopping charging by allowing water to infiltrate the soil. When the infiltration is completely achieved in the ground, the basin is dried for a period to produce natural aeration.

Surface infiltration systems should be regularly dried and periodically cleaned, to optimize infiltration rates or maximize nitrogen or nitrate removals. The flooding period of the SAT infiltration system ranges from 8 h to 14 d (wetting) to 16 h to 21 d (drying). For operational purposes, different W/D cycles are adopted. For primary effluent, the ratios are mostly under 0.3, while for secondary effluent is under 1 [22]. However, W/D cycles vary from one case to the other, even with the same type of effluent and the same project. In fact, basins in the same project typically have various performance levels concerning clogging, infiltration rates, and cleaning. Therefore, experienced operators are better positioned to find out the ideal lengths of W/D periods of their basins [89].

- Infiltration area: The infiltration area is the area required for a specific volumetric recharge rate. Factors influencing infiltration area requirements are pretreatment, volumetric flow of the effluent, and wastewater quality (i.e., nitrogen loading rate and BOD loading rate). This parameter is calculated using Eq. (1).

This area will be compared with the area requirements depending on the nitrogen or BOD loading rates, which are calculated using Eq. (2). The higher value of the two is then selected [22].

$$A = \frac{0.0365 \times Q}{\mathrm{Lw}} \tag{1}$$

where A = field area (ha); 0.0365 = conversion factor, (ha to m^2 and y to d); Q = flow (m^3/d); Lw = hydraulic loading rate (m/y).

The result reached in this formula is matched with the field area needed coming from nitrogen or organic loading rates, which is calculated as follows:

$$A = \frac{8.34 \times Q \times C}{L} \tag{2}$$

where A = field area (ac; ha).

$$8.34 = \frac{\mathrm{lb/milgal}}{\mathrm{mg/L}}$$

where Q = flow (gal/d; m^3/d); C = concentration of nitrogen or BOD (mg/L); L = limiting loading rate (lb/ac·d; kg/ha·d).

- Basin design: basin area can vary from less than 0.4 to more than 8 ha, with two separate basins at least [7,91]. Its geometry can be free form. Basin depth is recommended to be no less than 0.6 m. The distance between the basin bottom and groundwater should be minimally 1.5 m [22].
- Travel time: depends on the type of effluent: minimum 12 months for PE, 6 for SE, and 1–2 months for TE. Most of the removal of contaminants seem to happen in the initial few meters of the vadose zone, but dilution with aquifer and residence in the groundwater provides additional removals and reduction particularly for viruses, phosphorous, and the stronger micropollutants. The factors affecting this parameter are the type of effluent, pretreatment, reuse purpose, and regulation requirements. Minimum travel time is proposed in Appendix C.
- Share of native groundwater in recovered water (%): For potable reuse using SAT, recovery wells should be atleast 80% natural groundwater and not more than 20% reclaimed water [89].
- Recharge method: surface spreading is the simplest, oldest, most widely applied, and most popular method due to additional treatment and the advantage of the treatment effect of soils [92]. Surface spreading can be made only in sandy soils type and does not require too many clay layers or soils that limit the flow of water [3,7]. Vadose zone wells are used where hydrogeological properties of the soil are not suitable; while direct recharge to the aquifer is made where vadose zones have restricting layers, surface soils are not permeable, and/or aquifers are confined [8]. The two methods of aquifer recharge that are frequently used with reclaimed municipal wastewater are direct injection and surface spreading or percolation [92].

5.1. Parameters weight

For all factors listed above, every parameter has a different value and weight. A weight characterizes the suitability of the parameter. Relevant and appropriate values result in high weights. For example, concerning site grade parameters, sites with a slope of 0°–5° are the most suitable, slopes between 5°–10° are moderately suitable, and slopes of more than 15% are unsuitable. The weight values assigned to the various parameters are listed in Appendix D.

6. Operation

During the operation stage, the following elements must be taken into consideration (Fig. 5):

- Monitoring: The monitoring systems are installed, to assess the reliability of the SAT system, to follow up its evolution, and also to ensure that aquifer quality is not affected because of mixing with recharge water [93]. This monitoring involves hydrogeological properties such as permeability and groundwater level, as well as chemical and microbiological properties. The monitoring concern treated wastewater, recharge water, and native groundwater. The parameters monitored are pH, conductivity, turbidity, and redox potential (Eh). If a drift in concentrations is observed in recharge groundwater, then the system must be interrupted while the appropriate corrective measures are put in place.
- Recovery wells: The location of the recovery well depends on the travel/residence time and the desired proportion of treated water–native groundwater. It is recommended that recovery are located close to the point of use to reduce project cost, and far (>50 m) from the spreading basin to augment the residence time and flow path length of the applied effluent [92].
- Posttreatment: Posttreatment depends on the intended use application, the expected quality of recovered water, and the regulations. It can be applied as the final stage. For indirect potable reuse: posttreatment may include granular activated carbon (GAC), advanced oxidation, or membrane filtration. For agricultural reuse, only disinfection can be used. However, if iron (Fe), arsenic (As), or manganese (Mn) are likely to be present in the recharge water, then aeration and media filtration should be included as posttreatment [22].

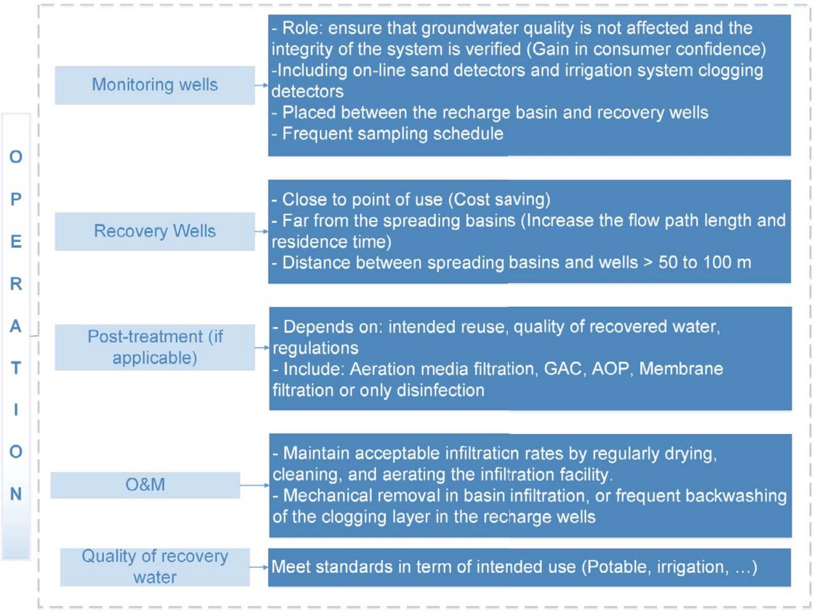

Fig. 5. Five elements are identified in the operation phase as follows: monitoring and recovery wells, posttreatment, OM, and quality of recovered water.

- Operation and maintenance (O&M): One of the primary concerns with SAT systems is clogging. This occurs in both surface infiltration and well injection systems.

During the recharge process, seepage velocity, the temperature of the water, and the environmental characteristics of the aquifer affect the development of the clogging, which exists in chemical, physical, and biological forms, making it difficult to diagnose the causes of the clogging [94]. Clogging is a result of the accumulation of suspended solids contained in the source water on the bottom and sides of the basin or other infiltration facility. The clogging layer's thickness may vary from 1 mm or less to many cm or more. Because clogged layers lead to low infiltration rates, their formation should be prevented by regularly drying, disking, cleaning, and aerating the basins or other infiltration facilities. Longer drying periods are better for increasing infiltration rates, but sometimes this rate stays low even after wet/dry cycles. Mechanical or manual removal in basin infiltration, or frequent backwashing of the clogging layer in the recharge wells after the drying period, will then be necessary to restore HLR's values to their original rates [22].

7. Results and discussion

Once SAT is confirmed as a treatment process, and to deploy it successfully, a detailed feasibility and assessment study should be conducted. This study should encompass a thorough review of technical, environmental, economic, legal, institutional, and social aspects. The main stages to consider in implementing SAT are planning, investigation, design construction, and operation. Each factor in these stages should be thoroughly checked early in the process and considered in defining the feasibility and useful life of the project. For the planning stage, protecting public health is a very critical objective in any reuse scheme followed by preventing environmental deterioration, therefore a health risk assessment should be assessed. The success or failure of water reuse projects, in particular recharge using wastewater, also depends on people's acceptance of SAT for potable or non-potable use. Many projects have failed to deliver on their cost-effective promises because they have been delayed or executed at lower capacity, due to end-user aversion to consume treated wastewater. This reveals that public perception or acceptance of wastewater reuse is a critical aspect that needs to be gauged prior to the implementation of a reuse scheme. Another interesting planning factor is the regulations. Water reuse guidelines and regulations that specify the use of reclaimed water in various applications (e.g., non-potable, industrial, irrigation, recharge) are different according to each country. Moreover, in most countries, there are currently no detailed standards or regulatory frameworks for managing aquifer recharge with treated wastewater. The absence of guidelines is a major limitation of SAT implementation [95].

For site selection, hydrogeological studies are usually the most time-consuming and critical element of the feasibility assessment. A careful evaluation of the hydrology and geology of the area can lead to the selection of a suitable structure. Soil characteristics and depth to the groundwater table, and proximity to wastewater treatment facilities are factors to evaluate when selecting an appropriate site. Equally important, the purification capacity of the SAT system is not affected by time, with proper O&M and adequate monitoring. With appropriate planning, design, site selection, O&M, and monitoring procedures, effective wastewater reclamation and its ultimate reuse in several fields will easily be obtained through SAT systems. Furthermore, its successful application has been indicated in several developed countries.

Table 6
Samples of successful SAT systems in the world

Site	Raw water for recharge	Pretreatment	Type of aquifer	Recharge mode	Travel time	Intended use	Posttreatment	Start date	Volume
Bolivar (Australia)	Treated wastewater: secondary effluents (activated sludge)	Stabilization lagoons flotation-air filtration chlorination storage basin	Confined aquifers composed of sandstones, sands and limestones	Injection (ASR)	From 28–329 d depending on cycles	Irrigation	No treatment	1999	1,200 m^3/d
Shafdan (Israël)	Treated wastewater: secondary effluents	Ultrafiltration UV disinfection	Coastal aquifer composed of sandy to limestone with intercalations of clays and silts	Infiltration by 6 basins	6 to 12 months	Irrigation	No treatment transmission by pipeline of 90 km to the point of use	1987	350,000 m^3/d
Wulpen (Belgium)	Treated wastewater: secondary effluents (activated sludge)	Microfiltration, reverse osmosis for 90% of the flow, UV disinfection for the remaining 10%	Unconfined aquifer quaternary dunes	Infiltration by basins	About 35 d	Drinking water	Chlorination aeration sand filtration UV treatment		
Nardò (Italy)	Secondary effluents activated sludge stormwater	Chlorination delivery through an open channel	Aquifer composed of quaternary deposits of sandstone, an upper cretaceous limestone formation and silty sand	Injection into a sinkhole	About 6 d	Irrigation	No treatment	2000	12,000 m^3/d
Salisbury (Australia)	Rainwater, secondary treatment STEP	Lagooning	Carbonate	ASTR	6 to 12 months	Drinking water	Aeration, GAC, membrane, UV light, ozone		3,000 m^3/d
Catalonia – Barcelona (Spain)	Secondary treatment then tertiary, for the hydraulic barrier (coagulation–flocculation, lamellar settling, filtration and disinfection)	Ultrafiltration, reverse osmosis (50% of the water), and UV disinfection before injection into groundwater	Confined deltaic coast, alternation of silts and clays	ASTR		Hydraulic barrier irrigation	No treatment	2007	- 2,400 m^3/d in 2007 - 15,000 m^3/d in 2010
Phoenix – Arizona (USA)	River water, various surface water, secondary treatment STEP		Alluvial	Manage aquifer recharge (all type)		Drinking water, irrigation, industry			
San Luis Rıo Colorado (Mexico)	The four ponds consist of an anaerobic pond, one facultative, and two maturation ponds		Unconfined the texture consists of gravels, sands, and clays	Infiltration basins		Irrigation	No treatment	2007	8.2 Mm^3/y

Table 6 (Continued)

Table 6

Site	Raw water for recharge	Pretreatment	Type of aquifer	Recharge mode	Travel time	Intended use	Posttreatment	Start date	Volume
Orange County, California	Secondary effluent	Microfiltration (MF), reverse osmosis (RO), and UV light with H_2O_2	Water bearing sand and gravel	Infiltration basins	6-months	Drinking water	No treatment	2008	100 Mgallons/d
Chapultepec, Mexico City	Pretreatment, biological reactor for sludge removal, biological membrane technology, and ultraviolet disinfection			Injection well				2017	

8. Samples of successful SAT systems in the world

Several examples of sites with different characteristics have been selected to illustrate the diversity of soil aquifer treatment (SAT) practices. These sites were chosen based on their well-documented nature and the importance of experience feedback. Table 6 provides descriptions of the characteristics of all the sites employing SAT as a recharge method. Among the ten studied sites, two are located in Australia, one in Israel, two in the United States, two in Mexico, and three in Europe (specifically, Belgium, Spain, and Italy). Out of these sites, three aquifers are confined, and two are unconfined. Recharge is carried out through injection in five sites, three sites correspond to the aquifer storage transfer and recovery (ASTR) method, and four sites recharge aquifers through basin infiltration. Four sites utilize membrane filtration as pretreatment, while six sites use disinfection methods such as UV or chlorination. Two sites employ a lagooning process. The primary objective of recharge in six sites is irrigation, with one site incorporating a hydraulic barrier (Catalonia site). The Phoenix site in Arizona, United States, has a diverse purpose of reuse, including applications such as drinking water, irrigation, and industrial use. Lastly, the Wulpen site in Belgium, the Salisbury site in Australia, and Orange County in California focus on recharge for drinking water supply.

Orange County, California is one of the world's largest facilities for managed aquifer recharge (MAR), which utilizes reclaimed water. Through the treatment process, the effluent undergoes purification to meet the standards for potable water quality. Subsequently, it is injected into the aquifer, contributing to the recovery of the groundwater reservoir while reducing salinity levels [96].

The wastewater treatment facility in Shafdan, Israel is currently serving over 2 million inhabitants and treating around 130–140 Mm^3 of raw wastewater annually to produce secondary effluents using an activated sludge process (with partial nitrification–denitrification) for unrestricted agricultural irrigation [97]. The treated wastewater is periodically discharged into spreading basins installed near the Shafdan facility on sand dunes above Israel's coastal aquifer through a 25–35-m sandy unsaturated system. Later, this water is reabstracted by recovery wells and supplied to farmers suitable for unrestricted irrigation [97–99].

In 2007, San Luis Río Colorado (SLRC) in Sonora, Mexico, established MAR facilities using infiltration ponds as the recharge method, with reclaimed water serving as the water source. This initiative results in an annual recharge volume of 8.2 million·m^3 [78]. The SLRC experience stands out as the most notable case of MAR facilities in Mexico [100].

9. Conclusion

The implementation of artificial recharge techniques has grown significantly over the past decade, across the world. However, it should be mentioned that SAT can cause side effects when not properly handled. Indeed, successful reclamation and reuse application need detailed planning steps, economic calculations, technical design, and careful social considerations and evaluations. The absence of harmonization in the regulatory framework has been identified as a significant obstacle in artificial recharge. To date, just a few countries had intensified their policies toward health protection and the environment regarding artificial recharge. This situation, which often involves a lack of clear rules and water quality standards, can lead to negative perceptions of this technology. The establishment of prerequisite requirements for infiltrated or injected water must be provided, to preserve the quality of the water resource, in particular for drinking water. Finally, before implementing such schemes at a large scale, it is necessary to carry out pilot studies on a scale allowing the extrapolation followed by the realization of preliminary tests, prior to scaling up the recharge site to an operational level. If the study results on SAT turn out to be encouraging, it is important to highlight its benefits and the user should be presented with scientific information, which can lead to obtaining a favorable opinion and building public trust.

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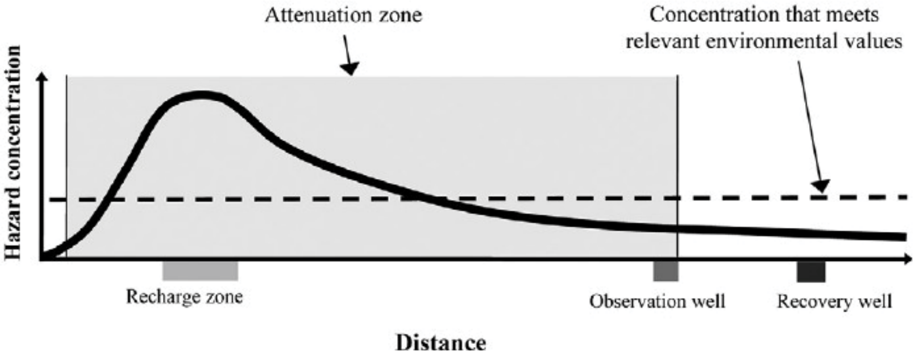
Appendices

Appendix A: Attenuation zone in aquifer



Appendix B: Guidelines for concentrations of substances in recharge water (modified from [82])

Constituent (Symbol)	Unit	Lowest permitted value	Highest permitted value
Biochemical oxygen demand (BOD_5)	mg/L	10	30
pH	–	6.5	9.5
Chemical oxygen demand (COD)	mg/L	50	80
Total dissolved solids (TDS)	mg/L	500	1,000
Total nitrogen	mg/L	10	40
Total phosphorus	mg/L	0.4	20
Turbidity	NTU or mg/L	2	10
Total organic carbon (TOC)	mg/L	1	16
Total suspended solids (TSS)	mg/L	5	150
Fecal coliform	FC/100 mL	Non-detectable	200
E. coli	UFC/100 mL	Removal or inactivation	1,000
Chloride (Cl^-)	mg/L	120	300
Nitrate (NO_3^-)	mg/L	5	50
Nitrites (NO_2^-)	mg/L	0.1	1
Sulphates (SO_4)	mg/L	125	300
Ammonia (NH_4^+)	mg/L	1.5	15
Aluminum (Al)	mg/L	0.2	1
Arsenic (As)	mg/L	0.01	0.15
Zinc (Zn)	mg/L	0.065	5
Fats and oils	mg/L	15	

Appendix C: Travel time [22]

Type of effluent	Minimum travel time (month)	Type of reuse
PE	12	Agriculture
SE	6	
TE	1	
PE	12	Non-potable reuse
SE	6	
TE	1	
SE	6–12	Indirect potable
TE	2	

Appendix D: Weight and relative suitability of factors (modified from [45], [101], [93])

Criteria	Classes	Weight
Water	Not available	0
	Available	1
Aquifer geology	Alluvial deposits (sand, gravel)	3
	Sandstone	1
	Alluvial deposits (shale, clay)	1
	Limestone	0
	Hard rock	0
Geomorphology	Lower alluvial plain	3
	Flood plains and alluvial fill	3
	Upper undulating alluvial plain	3
	Moderate to strongly sloping land interspersed with isolated hills	2
	Gently to moderately sloping land interspersed with mounds and valleys	2
	Rock outcrops	1
Top soil	Gravel	4
	Sand	3
	Silt	2
	Clay	1
Depth of groundwater	0–5 m	1
	5–10 m	2
	10–20 m	3
	>20 m	4
Site grade	0%–5%	2
	5%–15%	1
	>15%	0
Soil profile	Homogeneous in the saturated zone	2
	Heterogeneous with <2 m of clay or silt layers above the permeable layer	1
	Clay fractions > 10%	0
Permeability	>5 cm/h	2
	1.5–5.0 cm/h	1
	>1.5 cm/h	0
Distance from – WWTP	>5 km	2
	5–20 km	1
	>20 km	0
Elevation difference	>50 m	0
	<50 m	1
Aquifer type	Unconfined	1
	Confined (for spreading basin)	0
Land use	Agricultural	2
	Urban	1
Cost of land	Low	2
	High	1
Extraction possibility	Aquifer is isolated	2
	Aquifer is shared between regions/countries	1