Chapter 10
Aquifer Storage and Recovery: Key Issues and Feasibility

Gopal Krishan and Rahul Garg

Abstract Water is abundant on our planet, but its disparate occurrence at the spatial and temporal scale is causing panic. Apart from the sporadic availability of water resources, contamination is another major threat to the water supply. Developing countries like India, with a humongous population to sustain and minimum water infrastructure, stands at a vulnerable spot. As a resilient society, there is a need to devise innovative methods or improve the existing technologies of freshwater supply. This study also aims to comprehend, identify, and improve the global understanding of groundwater remediation methods based on the dilution of contaminants. We constructed a sand-based aquifer model to experiment with the well-known method of aquifer storage and recovery (ASR) as a model to ameliorate the water crisis in regions that have water scarcity and contamination problems. The benefits, historical developments, and recent advancements are thoroughly discussed. Along with the experimentation, key technical issues and methods to enhance the feasibility of the ASR are explored in detail and how the advancement in the hydrological investigation techniques facilitates the implementation of the ASR with time.

Keywords Geochemistry · Groundwater remediation · Sandbox experiment · Water scarcity

1 Introduction

In the face of climate change and the burgeoning human population, keeping an adequate freshwater supply is essential. The sporadic occurrence of freshwater resources is further exacerbated by land-use changes, vast agricultural developments, deforestation, and contamination. Groundwater accounts for 30% of all available freshwater on the earth and is still the most reliable source of water supply. In regions with no access to surface water resources, communities, agriculture, and

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industries are heavily dependent upon groundwater. However, many such areas are threatened by groundwater scarcity due to over-abstraction, climate change, and groundwater contamination, both anthropogenic and (geo)genic. All these threats make it more difficult for societies to access free water and do their daily chores. As a resilient society, we have to devise some cost-effective and efficient ways to remediate these natural resources and make them available for common use. Many methods for groundwater remediation have been invented in the last century. The use of each and every method depends primarily upon the hydrogeology and chemical, physical, economic, and social feasibility of the technique. Among them, one such technique is aquifer storage and recharge, which has emerged as a boon to semiarid areas in providing freshwater supply at a very low cost. Aquifer storage and recharge (ASR) is a water management technique for actively storing excess freshwater during wet periods and recovering it during dry periods. It presents a viable option to harness the full potential of groundwater. As the name suggests, freshwater from different surface sources like rainwater, reservoirs, ponds, rivers, and desalinated water can be stored temporarily in a subsurface environment for future recovery and use. Think of the ASR as a storage unit, either physically or chemically bound from all sides to confine freshwater within the unit. Physical boundaries are impermeable stratigraphic units that do not allow water movement. However, chemical boundaries are created by the difference in fluid properties like salinity and density; se boundaries emerge as a mixed zone in the system. Throughout the world, the ASR has been successfully implemented at numerous sites and proved very efficient. More than 175 active ASR well fields are operational in the United States (Dillon et al., 2019), followed by Australia, Europe (Sprenger et al., 2017), Latin America, the Arabian Peninsula, and South America. The ASR is more suitable and effective than other available remediation options because of several reasons:

1. Large quantities of water can be recovered. Since ASR harnesses the potential at the aquifer level, a huge volume of water can be stored and recovered from the ground, providing freshwater supply from household level to state level. The stored water can be used for seasonal or yearly groundwater supply.
2. The biggest advantage of ASR is that it is cost-effective and easy to implement. A simple injection of freshwater with prior subsurface knowledge is required to implement this method. Due to its cost-effectiveness, it's very favourable for developing or low-income communities. The easy and handy implementation makes it a very common method of remediation.
3. Stored water free from environmental or organic pollutants. If we store the excess water in open surface storage like ponds, rivers, and lakes, they are prone to developing more organic and inorganic contaminants. Several diseases like malaria and dengue may rise if large quantities of water are left open. To further use them, we need an extra step to check for contamination and clean for organic pollutants. However, ASR is closed from all sides, and it's very unlikely that they develop any organic contaminants, but care must be taken in choosing the specific site of the ASR because the presence of organic sediments in the subsurface

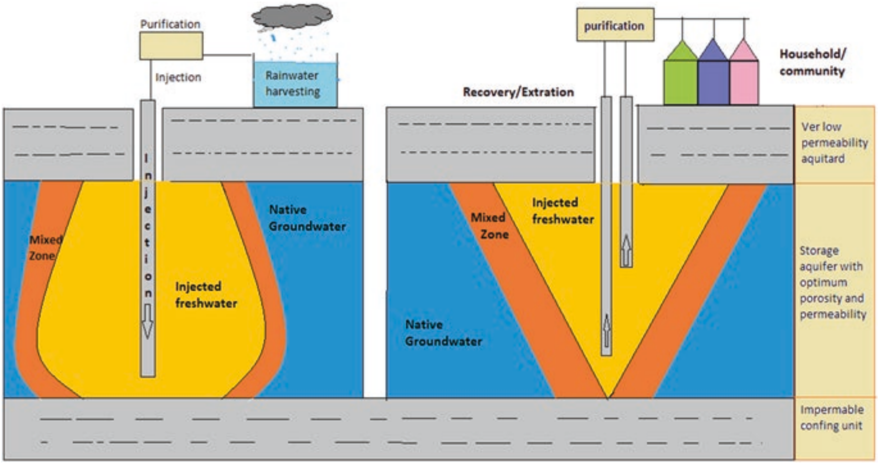

Fig. 10.1 Aquifer storage and recovery injection phase (left) and recovery phase (right)

might pollute the water. Moreover, surficial processes like runoff and dumping cannot affect subsurface storage.

4. Negligible surface footprint. Neither it needs any kind of treatment nor any large surface facility, so the surface below which ASR is operating can be used for all purposes and would not affect the community.
5. Lastly, no evapotranspiration losses in ASR operations. Since the stored water is not in direct contact with the sunlight or plant species, evaporation losses are negligible in this method. Evaporation is a major concern for water-stressed communities and significantly accounts for losses from surface storage. Some studies have shown that ET can take up to 30% of stored water which is very significant and can increase the salinity of the stored water (Fig. 10.1).

2 Historical Development

The concept of ASR in brackish water was first proposed by Cederstrom (1947), after which a lot of literature came describing the phenomenon of water bubbles. The most common factors that lead to mixing freshwater and saline water are dispersion and gravity segregation or free convection. Anthropogenic factors like sporadic pumping lead to mixed/forced convection. According to Esmail & Kimbler (1967), dispersion effects mean if two miscible fluids are in sharp contact, they will slowly diffuse into each other. After some time, initially, sharp contact will form a mixed zone. This diffusion results from the random motion of ions of two fluids. The distribution of ions across an arbitrary plane can be represented through Fick's Law. The density contrast between the native saline water and stored freshwater causes the density/buoyancy-driven flow and causes the mixing of the saline and freshwater. Since freshwater is less dense compared to saline water, it tends to flow and remain above the saline-fresh interface. The buoyancy-driven flow causes the saline water to intrude in the lower part of the ASR zone and reduces the recovery efficiency. To reduce these effects, reservoir operation must be taken care of, and sites with very low vertical hydraulic conductivity should be selected to restrict the vertical flow of groundwater. The density effect is also called “gravity segregation” or “buoyancy stratification”. He experimentally studies the dispersion and gravity segregation in the synthetic sandstone aquifer model and later confirms the observed results with then available computer programs. He finds that the density effect impacts recovery efficiency more strongly than dispersion effects. He also observed the wider mixing zone suppressing the interface tilt. He concluded that storage of freshwater in saline water is feasible under low permeability, small density contrast, low storage period, and high flow rate. The previously thought cylindrical plume is now viewed as a conical plume and reduces the recovered water volume. For this experiment, he used separate models to study the density and dispersion effects. Later Kumar and Kimbler (1970) combined both models and used a pear-shaped model representing 45° of a circle. The major objective of the experiment is to validate the assumption that previously sought the effect of gravitation segregation in the now-flowing system by expanding it to the radial flow system. Furthermore, it was found that recovery efficiency can be increased by increasing the injection-abstraction cycle.

Furthermore, a numerical modelling approach was used in an array of papers by Ward to explore the influence of controlling variables on ASR in saline water. Ward et al. (2007) concluded that widening the mixing zone reduces the density contrast and hence the impact of the density effect, confirming the assertion of Kumar and Kimbler (1970). Ward et al. (2008) further found that the greater the permeability contrast in layer aquifer and higher the anisotropy inhomogeneous aquifer restrict the vertical flow due to density effect and increase the recovery efficiency (Ward et al., 2009). Zuurbier et al. (2014) set up multiple partially penetrating wells, which inject freshwater into deeper aquifers and recover water from the open well casing in shallow aquifers to encounter the negative impacts. The numerical modelling demonstrated that 40% recovery efficiency could be achieved compared to 15% efficiency in a single penetrated well. To further investigate Witt et al. (2021) built a plexiglass tank and dyes to visualise the shape of both fresh and saline water bodies and investigate the recovery efficiency due to multiple penetrating wells. The results corroborate the previous efficiency. In order to further maximise the recovery efficiency, Zuurbier et al. (2015) experimented with horizontal directional drilled wells (HDDW) in the Netherlands, where they achieved 100% recovery efficiency of injected 4200 m^3 injected water, demonstrated by a numerical groundwater flow model.

3 Material and Methods

The lab experimentation was commenced to measure the viability of aquifer storage and recovery (ASR) as a remediation option in the saline aquifers of Mewat, Haryana. The experiment was conducted in an experimental sandbox model having dimensions: 120 cm in length, 60 cm in width, and 120 cm in height (Fig. 10.2). Separate fresh and saline water injection sources were built. Two sprinklers are used to create saturated saline conditions, and four injection wells are used to inject freshwater into the aquifer. The wide distribution of injection wells allows four different pockets of freshwater to observe for ASR phenomenon. A saline solution of concentration 8500 µs/cm was prepared of sodium chloride salt. The temperature was measured with an EC meter (Eutech). 150 litres of this saline solution at a temperature of 25 °C was inserted in the sand of size ranging between 0.075 and 1.00 mm till saturation. The sand was kept in an experimental model for a prototype artificial aquifer.

Figures 10.3, 10.4, 10.5, 10.6, and 10.7 are showing the transverse profile of the model. The x-axis represents the depth inserted for sampling. The z-axis represents the various ports in the horizontal direction. The y-axis represents the electrical conductivity value in micro-siemens per meter. The plot (Fig. 10.3) shows the spatial variation in EC just after the injection of freshwater in saline water. The middle-high in different plots represents the high salinity. The low mixing between freshwater and surrounding saline water is represented by high relief in salinity variation. The plot (Fig. 10.4) represents EC values after a few hours of injection. The H1A blue plot and H10A green plot represent the two extreme parts of the model where most of the freshwater is injected. Sharpe highs and lows can visualise the same in the curve. For instance, in the green graph between 25 and 40 cm, we

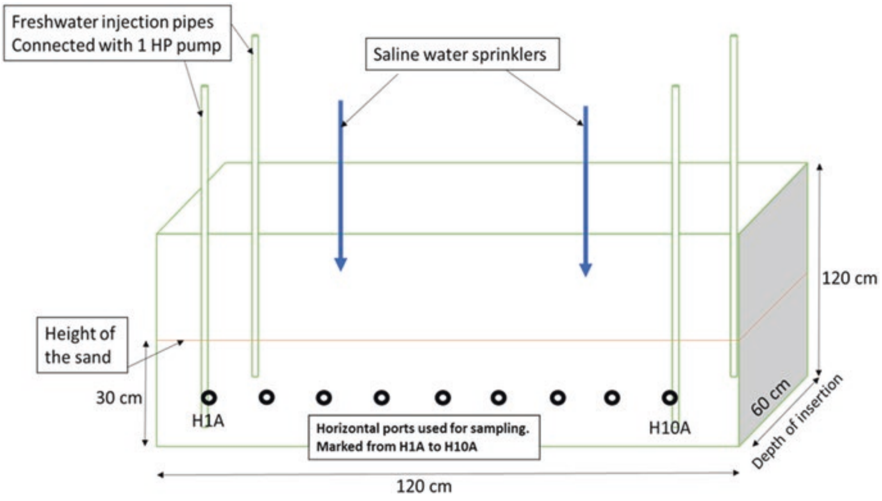

Fig. 10.2 Experimental model layout

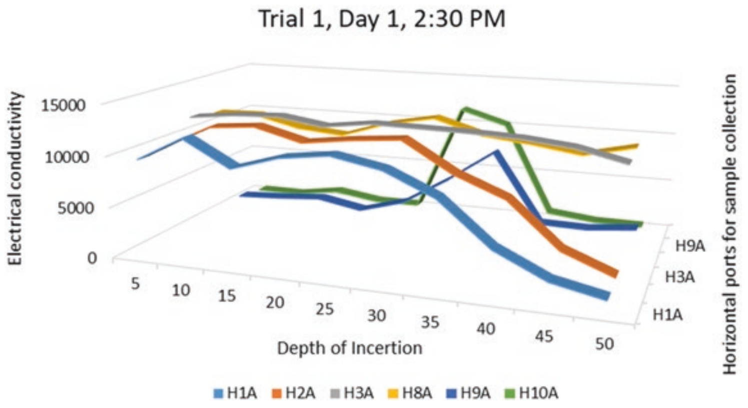

Fig. 10.3 Plot of ASR trial 1 day 1 AN

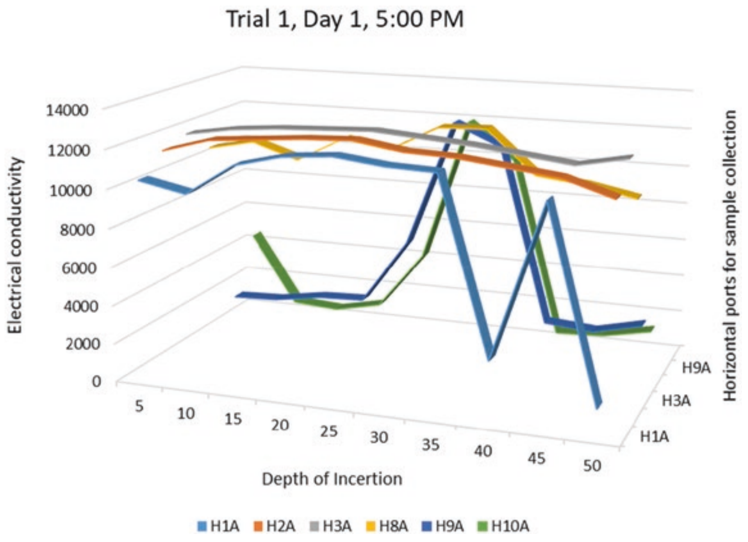

Fig. 10.4 Plot of ASR trial 1 day 1 AN

can see the maximum EC value due to placing injection points at 10 cm and 45–50 cm distance causing low salinity values at these points. Figure 10.5 shows EC values after 1 day of experimentation. Due to freshwater saline water mixing, the contrast between middle position values and values position values has subsided. For instance, the H10A, compared to the previous plot, greatly flattened at extreme ends. The grey and yellow plots are taken from extreme middle ports where no injection point was present; hence we see an overall constant profile. Figure 10.6 represents the EC observations after 2 days of injection. Still, we could obtain water of standard quality at the H1A and H10A ports at 45–50 cm depth. Elsewhere, the saline water is thoroughly mixed with freshwater. The slight lower can also be seen

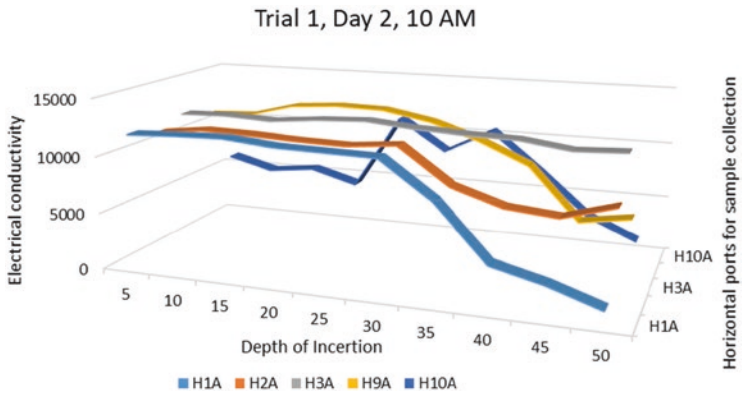

Fig. 10.5 Plot of ASR trial 1 day 2 FN

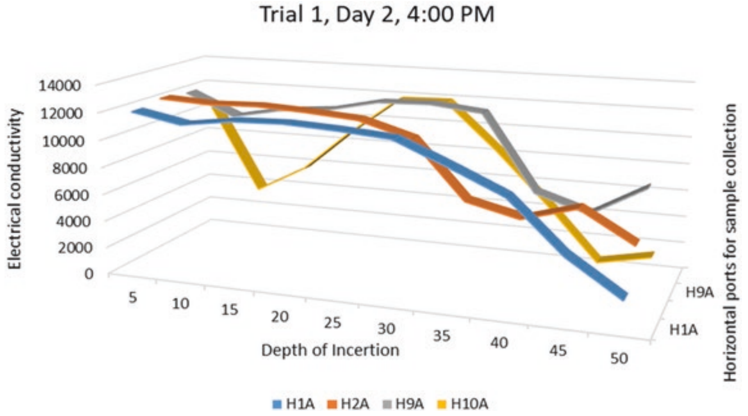

Fig. 10.6 Plot of ASR trial 1 day 2 AN

at 10 cm depth in the H10A port. After 3 days of experimentation, the injected freshwater was thoroughly mixed with ambient saline water, and the average salinity reached up to 12,500 micro-siemens per meter. Since no pockets of freshwater were found, we decided to halt our experimentation (Fig. 10.7).

4 Feasibility Issues

Although ASR operation can be traced back to 600 AD in the Indian subcontinent (Ramaswamy, 2007), the ability to store freshwater in brackish-saline aquifers is still technically questionable, mainly because of several physical and chemical reasons. These concerns hang around this method and cannot be ignored, such as fluid-rock interactions, biogeochemical reactions which arise due to the injection of

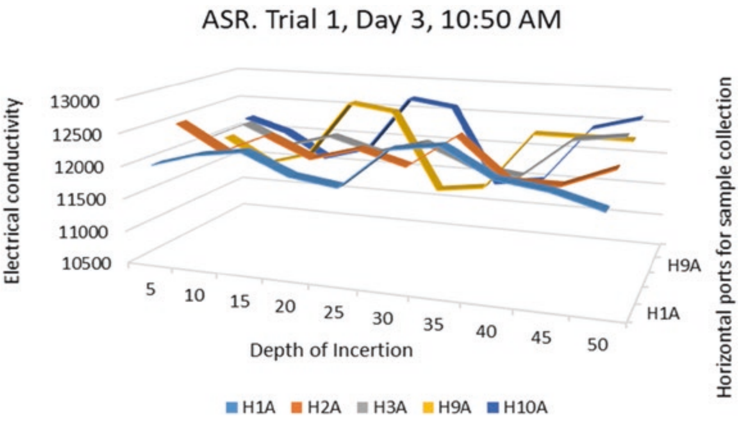

Fig. 10.7 Plot of ASR trial 1 day 3 FN

foreign substances, and interaction between stored water and native groundwater. For the proper feasibility and recovery of the stored water, the byzantine subsurface aquifer system needs to be thoroughly scrutinised, and several intricate interactions and factors need to be taken into account. This approach is not a panacea to all groundwater problems everywhere. However, it depends heavily upon the hydrogeology of the region. Factors like aquifer heterogeneity, anisotropy, grain size, dispersivity, and density contrast between native and stored groundwater. Physical, biological, and chemical clogging of water and infiltration sites causes a reduction in infiltration rates and is often a major problem in ASR sites. Another problem with ASR is liquefaction, a very shallow water table formed in geologic media and frequently shaken by the earthquake, further exacerbating the damage.

Transmissivity significantly affects the ability to recover injected water from the aquifer system in two ways. First, the transmissivity must be high enough to allow economic injection and groundwater extraction to achieve project goals and targets. Second, it should not be high enough so that the injected water is lost to aquifers and cannot be recovered. So, the site selection must consider the transmissivity effects. For instance, a Florida north lake test site attempted to test outside the prescribed transmissivity rates in a highly conductive limestone aquifer. It could not recover a significant fraction of injected water. Other risks associated with aquifer storage and recovery are subsidence. Although one of the utilities of the ASR is reducing subsidence, the abstraction of groundwater during the recovery phase poses a great threat to the subsidence of the area. In Kelley et al. (2020) a pre-feasibility study was done to minimise the impact of groundwater extraction during peak months on land subsidence. The performance of the ASR system is estimated by recovery efficiency, which is the percentage of recovered water of standard quality to the injected water. Normally it ranges from 10% to 60% depending upon hydrogeology, stored water volume, recovery time, and chemistry of native water. Reservoir operations play a significant role in the recovery efficiency of an ASR site.

4.1 ASR Feasibility Studies

The essential phase for the success of any project is the initial feasibility studies and development strategies. One can maximise the success of the project by accurately understanding the objective and following a set of logical steps. More careful attention to initial planning and details can identify and resolve the key issues well in advance, which saves time and energy and prevents losing the momentum of the project. Although the ASR project heavily depends upon site-specific hydrogeology and socio-economic feasibility, a set of phased guidelines can be followed for the implementation of ASR. The technical experts from geochemistry, hydraulics, modelling, economics, water quality, water treatment, pumping design, pipelines, and water utility systems are required for a transdisciplinary approach for an easy-going project and to maintain a balance between science and engineering. Phase 1 of development involves preliminary feasibility and conceptual design. Several elements comprise this phase. First is the clearly defined objective of recharge. Other subsequent factors depend upon the objective, failing to conclude that could lessen the benefits that could have been achieved, for instance, selection of the wrong site, etc. The objectives could be simple seasonal storage and recovery of water (Wasif & Hasan, 2020), restoring depleted groundwater levels Sheng (2005), reducing subsidence (Kelley et al., 2020), improving water quality (Appelo & De Vet, 2003), or preventing saline water intrusion (Zuurbier & Stuyfzand, 2017).

Next comes the source of water supply or recharge. Selecting a supply source is essential because of fluctuating flow rate, average flow, and quality which could impact the recharge amount and water standards. A typical situation is the peace river ASR site in Florida, which stores water from a river source that has a highly variable quality and flow. The most common method of water supply is rainwater harvesting; it is suitable in those areas that have seasonal raining periods and a dearth of dynamic surface water resources. Similarly, water demand is another key factor to assess. The location and scale of the ASR plant depend upon the community's monthly, seasonal, and annual demands. Understanding the local hydrogeology is one of the most time-consuming and important factors to consider before applying the ASR in the field, which leads to careful selection of appropriate storage zones, recharge water sources, and treatment required. The following factors in hydrogeology are needed to be considered: hydrostratigraphy, aquifer and aquitard, aquifer geometry, confining layer, lithology, aquifer physical parameters, mineralogy presence of clay, geochemical and redox environment, subsurface heterogeneities, rechargeable sites and potential zones, discharge zones, water table level, local and regional flow directions, proximity to potential contaminants plumes, and groundwater abstraction.

Maliva et al. (2019) defined optimum hydrogeological conditions for the ASR facility in saline aquifers. These are moderate hydraulic conductivity (5–20 m/d), primary porosity-dominated lithology with effective porosity higher than 5%, and low degrees of heterogeneity. The 4D operational monitoring systematic survey used the method, survey design, data acquisition, processing, and quantitative interpretation and studied the Leyden Colorado ASR facility: an abandoned mine to fill the winter surplus water and use in summer. Using the time-lapse gravity survey successfully detected the distribution and movement of general water. A set of geological, hydrogeological, geochemical, water quality, geophysics, and remote sensing techniques can be used in identifying suitable hydrogeology and field sites for the objective. The remote sensing techniques provide a good alternative to the time- and resource-consuming geophysical and geological techniques. Just like the remote sensing techniques used in reconnaissance surveys in metal exploration, Amineh et al. (2017) integrate the spatial multi-criteria decision-making and GIS for delineating suitable zones for ASR. Moreover, remote sensing and GIS can also be used to identify recharge sites and storage sites. The advancement in modelling tools has facilitated the accurate representation of subsurface processes. The groundwater models are increasingly being used to test recharge rate, aquifer parameters essential for ASR feasibility, residence time, optimum pumping and extraction rates, and locating subsurface sites for ASR establishment.

LaHaye et al. (2021) used the integrated approach of numerical modelling and geospatial technology to predict the ASR feasibility in Louisiana. They constructed a 3D numerical model based on hydrostratigraphy of the region to calculate four aquifer parameters such as depth to thickest sand layer (DS), hydraulic gradient (HG), storage zone thickness (ZT), and transmissivity (TM). The model results are further coupled with geospatial parameters like land use, groundwater quality, TDS of surface water, stream thickness, well density, cumulative crop cover, excess surface water, and groundwater availability. Wasif and Hasan (2020) used the finite-difference MODFLOW numerical model to simulate seasonal water storage in the Flemish alluvial plains of Belgium. The steady-state model was initially utilised for transient analysis, scenario analysis, and prediction simulation. The water balance component showed an increase in heads during water-stressed winter months. Moreover, the individual ASR wells achieved a recovery efficiency of 97%, and multiple wells achieved the RE of 100%. Apart from simulating the feasibility and site assessment, modelling can be expanded to other ASR management applications like simulation-optimisation, approach, and examining operation factors, for example, surface water minimising in aquifers, minimising injection time. Chinnasamy et al. (2018) use the MODFLOW to access the ASR operation protocols to prevent surface ponding during recharge and air locking during extraction and minimise pump adjustment. They run the model to do this in assumed aquifer conditions and simulate the head values. If overflow is observed, then they reduce the recharge rate by half and then run the model again to estimate the head. If no overflow is observed this time, they check for saturation head and top the model.

5 Geochemical Technical Issues

The most concerning threat and speculation over the ASR projects are the standards of recovered water quality, which encompasses a wide range of contaminants and parameters that need to be checked at pre-feasibility and continuous monitoring stages. The physical parameters are TDS, EC, Ph, Eh, alkalinity, temperature, dissolved oxygen, colour, and turbidity; the inorganic parameters include chloride, fluoride, sulphate, major ions, nitrate, phosphate, ammonia, arsenic, cadmium, etc.; the organic contaminants include TOC, hydrocarbons, total coliform, chloroform, bromodichloromethane, dibromochloromethane, bromoform, total trihalomethane, etc. Since the majority of reactions occurred at the interface of native groundwater, foreign water, and aquifer matrix or sediments, analysing their respective geochemistry is essential to track down future reaction pathways and possibilities. The first step of the geochemical pre-feasibility test is to check recharging groundwater for these parameters by extensive sampling and laboratory analysis of recharging water and native groundwater followed by the geochemical assessment. Using this data and model, simulation reactions involving various proportions of aquifer water and recharging water can be simulated to find the set of geochemical reactions like precipitation and dissolution that could cause problems like clogging of aquifers. However, these simulations often do not give conclusive results as we are unknown about the subsurface geology. So, the next logical step is to identify the mineralogy and geochemistry of aquifer material which is done by analysing the core data. The core is highly valuable in knowing the aquifer characteristics, organic activity, captain exchange capacity, mineralogy, redox potential, and potential of plugging. The physical characteristics include permeability, porosity, grain size distribution, and specific gravity. The colour indicates homogeneity in the aquifer, organic activity, and quick reference to oxidation and reduction potential. For instance, High organic activity, reduced iron, and manganese are marked by blue or grey colour. The oxidised iron forms a yellow or red formation that indicates abiotic conditions. To analyse the presence of major phase and clay minerals, optical petrography and X-ray diffraction (XRD) are implemented. The relative abundance and types of clay provide an indication of geochemical reaction or physical plugging. For example, montmorillonite clays are more sensitive to changes in TDS. Similarly, kaolinite is more likely to cause plugging. Another useful parameter is cation exchange capacity which is obtained when the core is flushed with ammonium acetate solution to determine cation concentration that is in an exchangeable position. For instance, if the recharge water has a different chemistry than the subsurface environment, the clay will become unstable and release various cations to achieve equilibrium. Lately, using scanning electron microscopy, it is possible to determine how clay minerals occur in formation pores.

Finally, the interface and interactions between the three reacting components are monitored through observations and monitoring wells and also computer simulations. The advancement in geochemical modelling is proving as a boon in the mixing assessment. These models are user-friendly, highly efficient, feed on large geochemical reactions and processes databases, and can be operated once you have preliminary data. A few common examples are PHREEQC, MINTEQ, and WATEQ. These models can be used to determine the products of the geochemical reactions and the reaction kinematics and pathways that could be possible. The kinematics is the rate of reactions; if the kinematics is slow, it can be ignored. The geochemical processes give rise to a plethora of problems that ultimately lead to decreased ASR feasibility. The immediate mechanisms are physical clogging, bacterial activity, adsorption processes, surface ponding, and ion exchange. The slower reactions like dissolution processes appear after several months of running. Physical clogging is one of the fatal processes for ASR systems. The suspended solids in the recharge water can reduce the hydraulic conductivity of the aquifer matrix and filter, decreasing the recharge rate, storage capacity, and filtration rate. Gas entrapment and biogenic gases can also cause physical clogging. The physical clogging further leads to biological clogging with an accumulation of biomass and the growth of microorganisms. The chemical precipitation of reacting minerals further exacerbates the clogging (Jeong et al., 2018). Pretreatment includes coagulation, sedimentation, filtration, advanced oxidation, and disinfection. However, clogging can still happen in the running phase. At that time the treatment methods that can be used are scrubbing, surging, backwashing, jetting, biociding, acidification, and underreaming. Among all the surface infiltration systems proved to be highly efficient and economical. Stuyfzand and Osma (2019) analyse the biological-chemical-physical clogging mechanisms during pre-feasibility tests due to diatoms, algae, and colloidal or precipitating $Fe(OH)_3$, $Al(OH)_{3,}$ and MnO_2. They first identify the contribution, combination of the membrane filter index (MFI) method, and an amendment of the exponential bacterial growth method to optimise it.

Adsorption can further threaten ASR viability. Although adsorption occurs at every level, from deposition of flocs to ion adsorption, the one stick on the pore is highly dangerous for ASR as it reduces the hydraulic conductivity. Acidification can be used to recover the permeability, and however, if severe adsorption happens, it can restrict the flow of acids from reaching the affected area. Ion exchange is another geochemical process that can significantly affect the ASR system. For instance, sodium on clay minerals is in an exchangeable position in brackish water conditions and remains stable until the TDS isn't lowered. Once freshwater is injected, the exchange between calcium and sodium commences, which convert the clay minerals and mobilise ions to accumulate in pore throats. Similarly, kinetics, oxidation, and dissolution further control the processes.

Arsenic (As) release from ASR sites is the major source of concern worldwide. Many large sites had to be abandoned due to the release of As in initially non-contaminated water. Since the As is present in various hydroxides and sulphide minerals, they remain stable in particular redox conditions. It can be mobilised through the oxidation of sulphides like pyrite when the subsurface has a reducing environment, and surface water is of high oxidation potential. Another release mechanism is the dissolution of hydroxides and releases through other mobile elements like U, Mn, and Fe. Moreover, oxidation-reduction of organic matter can also mobilise As. Appelo and De Vet (2003) reported high As concentration during the removal of in situ iron, where oxygenated water was recharged into anoxic siliciclastic sediments. The geochemical modelling suggested the native groundwater containing phosphate was the main mobilisation mechanism of As. Wallis et al. (2010) investigated the elevated As concentration in the ASTR site in a siliciclastic aquifer. Here, As release was related to oxidation of pyrite due to injection of oxygenated water.

Even after the geochemical modelling prediction and steps taken, in-field water quality problems exist. To tackle them, detailed laboratory analysis of core and aquifer material is required to ensure the water quality standards and simulate the exact field conditions in the lab environment. Such lab testing includes column experiments and batch testing. Rinck-Pfeiffer et al. (2000) conducted column experiments on drill cores to experiment with clogging mechanisms before proceeding to field trials. They observed the above-mentioned interrelation among physical, chemical, and biological clogging mechanisms. Even in low suspended solid conditions, the hydraulic conductivity is maintained between 20% and 50% of the original. In the first 7 days of the experiment, the accumulation of suspended solids and biomass decreased the hydraulic conductivity from 0.78 m/s to 0.068 m/s. However, this significant decrease is countered by the chemical dissolution of calcite at the inflow end, opening the pore spaces. The re-precipitation of calcite at the outflow end is verified from SEM images. Batch testing is another lab experiment. It is inexpensive as compared to column experiments. The sample core materials are mixed together and are subjected to progressive series of leaching tests at steadily increasing pH values to estimate chemical reactions occurring at each step.

6 Case Study: El-Paso Texas

El Paso, Texas, is situated in the Chihuahuan Desert and often experiences prolonged river drought and a heavy burden on groundwater resources (Cliett, 1969). The two major aquifers in the region are Hueco Bolson (Sheng et al., 2001) and the Mesilla Basin, and surface water from the Rio Grande. In the 1980’s El Paso Water Utilities started investigating alternative water resources to substitute for future water supply. They investigated the technical and administrative feasibility of ASR for prolonged water storage. The investigation by the New Mexico-Texas water commission concluded that northeast El Paso has favourable hydrogeological conditions for the implementation of large-scale recharge features. The ASR system is proposed to serve three purposes: reuse of reclaimed freshwater and preservation of the native groundwater, restoration of depleted groundwater levels by artificial recharge; prevention of brackish water intrusion. The treated wastewater up to the level of standard drinking quality is used to recharge the Hueco Bolson aquifer. The aquifer is unconfined to semi-confined within a long sediment-filled trough. The sediments consist of fine- to medium-grained sand with the interbedded lens of clay, silt, gravel, and caliche and have a thickness of 2743 m. The pivot injection test found a horizontal hydraulic conductivity of 8.13 m/day (Heywood & Yager, 2003). The northeast well field site was chosen for storage purposes mainly because of three reasons. First is enough storage space and depth to build up hydraulic heads within recharge wells. Second, injection wells are situated in such a way to allow maximum recovery of freshwater and minimise the cost. Last, adequate residence time will provide enough to further purify the groundwater (Sheng, 2005). The water quality assessment of native groundwater and treated freshwater demonstrate the compatibility between both; the higher sodium and calcium concentration ratios are comparable. The $HCO_3 + CO_3$ ratio of treated water is higher than groundwater, and the sulphate ratio is almost the same. Both are sodium chloride-type water. The system faced one threat: transporting pathogens and microbes in the water system. It is recommended that additional data collection and water testing be conducted to better understand transport mechanisms.

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Declarations The authors declare no conflict of interest.

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