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Review

Management of Seawater Intrusion in Coastal Aquifers: A Review

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Abstract: Seawater intrusion (SWI) is one of the most challenging and widespread environmental problems that threaten the quality and sustainability of fresh groundwater resources in coastal aquifers. The excessive pumping of groundwater, associated with the lack of natural recharge, has exacerbated the SWI problem in arid and semi-arid regions. Therefore, appropriate management strategies should be implemented in coastal aquifers to control the impacts of SWI problems, considering acceptable limits of economic and environmental costs. The management of coastal aquifers involves the identification of an acceptable ultimate landward extent of the saline water body and the calculation of the amount of seaward discharge of freshwater that is necessary to keep the saline–freshwater interface in a seacoast position. This paper presents a comprehensive review of available hydraulic and physical management strategies that can be used to reduce and control SWI in coastal aquifers. Advantages and disadvantages of the different approaches are presented and discussed.

Keywords: costal aquifers; seawater intrusion; physical barriers; hydraulic barriers; artificial recharge

1. Introduction

Under natural conditions, there is a continuous interaction between surface and subsurface water bodies. In humid climates, surface water bodies (e.g., streams, lakes, seas, and oceans) often act as discharge points (outflow boundaries) for groundwater. For example, due to high recharge of groundwater from rainfall events, streams and lakes act as natural drainage systems, and the subsurface flow is mostly towards them. However, in arid and semi-arid regions, as well as in other areas where groundwater pumping is significantly higher than the natural recharge, water moves from surface water bodies to the groundwater systems [1]. Therefore, the salinity and contamination levels of these surface water bodies affects the quality of the groundwater. In coastal regions, the groundwater, as a primary or sole source of freshwater, is continuously subjected to surface–subsurface interaction, as well as salinization due to lateral intrusion of seawater into the aquifer. The rate and degree of the seawater intrusion (SWI) depend on a number of parameters, including variations in the hydrological cycle components and the quality and quantity of the system inflows and outflows. The natural factors associated with the climate change and anthropogenic factors due to coastal urbanization and human activities are the main components that exacerbate the SWI problem. Therefore, remedial measures have to be taken to prevent further degradation of the water quality due to SWI.

Remediation of brackish or saline groundwater using biological, chemical, and physical techniques is a very expensive process and can take a long time, depending on the source and level of salinity. Therefore, sustainable water resources management in coastal areas can be achieved through the use of different arrangements and rates of external sources or sinks of water and physical barriers. To control SWI problems, a seaward hydraulic gradient should be maintained, and, hence, a proportion of the fresh or brackish water should be allowed to flow into the sea. This seaward hydraulic gradient provides a hydraulic barrier against SWI [2–4]. Each of these hydraulic (and physical) approaches has its own advantages and limitations in terms of practical operation and control of SWI. Banks and Richter [5], Bruington [6], Todd [7], van Dam [2], Sherif and Hamza [8], Pool and Carrera [9] and Kallioras et al. [10] listed different methodologies that have attempted to control SWI in coastal aquifers. These methods include reduction of pumping rates, relocation of pumping wells, use of physical surface or subsurface barriers, natural or artificial recharge (pressure or positive barriers), pumping of saline water along the seacoast (abstraction or negative barriers), and combination techniques (mixed barriers). In this paper, the strengths and weaknesses of these methodologies are reviewed and discussed based on recent advances of their theoretical and practical applications. To that end, the available control approaches are categorized into three different groups: (i) conventional methods, (ii) physical barriers, and (iii) hydraulic barriers, as detailed in the following sections.

2. Conventional/Temporary Methods

2.1. Reduction of Pumping

Reduction of abstraction from pumping wells is the simplest, most direct and cost-effective measure to maintain the groundwater balance in aquifers and control SWI problems. However, the possibility of reducing the abstraction can be restricted in some regions in terms of water demand requirement, and of course a supplemental source of water should be provided to substitute the imposed reduction on the groundwater pumping plan [6].

The agriculture sector represents the major water consumer all over the world. In most arid and semi-arid regions, such as the Gulf Cooperation Council (GCC) countries, the water consumption in the agriculture sector represents 88% of the total water consumption [11]. Therefore, a significant reduction in groundwater pumping might be achieved by changing crop patterns and reducing the cultivation of high-demand water crops, such as rice and sugarcane. The use of water-saving irrigation techniques, such as drip and precise irrigation, would also contribute towards the reduction of groundwater pumping.

Increasing the general public awareness in terms of reducing the water losses in water consumption and supply networks in residential, agricultural, and industrial sectors, and encouraging them to use renewable or recycling resources (e.g., reclaimed treated wastewater and desalinated water) can contribute to the success of water conservation plans, and hence minimize groundwater exploration.

However, reduction of water demand may not always be possible due to certain constraints. In addition, the cost of supplying alternative good quality water and making it available in vulnerable areas are other issues that may render this method a temporary measure for protecting aquifers. This is particularly true for areas with high population growth, and thus increasing trends in water demands may not be able to be avoided to achieve the intended objectives [12,13].

The possibility of combining this temporary management approach with other control measures was proposed by Sugio et al. [14] to control the critical conditions of the SWI problem. Reichard and Johnson [15] showed that the application of this methodology could help to reduce the amount (and cost) of in-lieu delivery of surface water for general consumption by local residents or to protect the aquifer against SWI. Based on a sensitivity analysis of SWI versus pumping rate using numerical simulation of the Burdekin Delta aquifer in Australia, Narayan et al. [16] concluded that reducing groundwater abstraction can effectively control SWI. The methodology was also suggested by Tsanis and Song [3] and Don et al. [17]. Sherif et al. [18] showed that a 50% reduction of groundwater pumping in Wadi Ham aquifer, United Arab Emirates, would cause a retardation of the mixing zone in the order of a few kilometers, and would significantly increase the availability of fresh groundwater resources by the year 2020.

Sherif [19] revealed that redistribution of pumping by reducing or switching off the well fields that are less susceptible to intrusion could help mitigate SWI in the Nile delta aquifer. The redistribution of the pumping rates in available wells was also investigated by Zhou et al. [20] in a coastal aquifer in Beihai city in China. It was concluded that the elimination of the wells near the coastline or across the intruded zone with simultaneous reduction of the pumping in wells far from the coast could protect the aquifer. In terms of rescheduling of pumping, Rejani et al. [21] recommended that increasing the pumping rates upstream and reducing the rates in downstream zones could help to retreat SWI in the Balasore coastal groundwater basin in India, especially in the dry years. Lowering of groundwater levels and the associated increase of salinity due to pumping in dry years were the reasons for limiting pumping in this area [21]. Reduction of the total withdrawals from the Akrotiri aquifer in Cyprus during the wet years was one of the possible solutions that was proposed by Koussis et al. [22] to manage SWI. In wet years, the water demand is met fully by surface water, and therefore high water abstraction from aquifers is not necessary. On the other hand, due to the limited surface water resources in dry years, a large fraction of water demand is provided by abstraction from aquifers. Following the same concept, periodic deactivation of most of the pumping wells in the alluvial aquifer of Katapola, Greece, was suggested by Siaka et al. [23] to control the propagation of SWI.

2.2. Relocation of Pumping Wells

In this approach, the pumping wells are commonly relocated further inland away from the coast to provide a proper seaward hydraulic gradient, by keeping the groundwater levels above the sea level in the vicinity of the shoreline and reducing the excessive losses of fresh groundwater by outflow [2–4]. This approach could also be limited in some cases due to unavailability of land or conflicts with other strategic projects in the public sector, or even with private infrastructures that will terminate the process. In some cases, and under high levels of contamination, the size (length) of the aquifer needed to accommodate the new locations of wells far from the intruded seawater wedge is another obstacle to manage with SWI. Moreover, the cost associated with transportation and in-lieu delivery of water from the new pumping wells (far enough from the coastline) to the predeveloped areas near the coastline (susceptible zones) could be another constraint. Therefore, this technique might also be regarded as a temporary solution [24].

The spatial distribution of the new pumping wells in the system should be carefully designed in order to control the problem rather than accelerating it. Datta et al. [25] studied the effects of spatial variations of pumping from a set of five wells and in three different locations in a real study area in India. The locations of this set of wells in two different pumping zones along the coastline showed better results in terms of controlling the intruded body of saline water than their locations in the middle area, which also had the potential to reduce the negative impacts. The problem of finding the optimal pumping patterns (locations and rates of abstraction wells) for controlling SWI has been mainly studied in the literature within simulation optimization frameworks. For example, Mantoglou and Papantoniou [26] studied the optimal design of a pumping network for the management of aquifers using two different schemes of optimization. A genetic algorithm (GA) was used in one of the schemes to optimize both the pumping rates and locations of wells simultaneously, whereas in the second scheme a combination of GA and sequential quadratic programming (SQP) was utilized in two stages. The GA was first used to identify the optimal well locations at any generation point and then SQP was applied to calculate the optimal pumping rates for the new specified well locations. The superior performance of GA than SQP in identification of better optimal solutions was highlighted. A review of the research efforts related to the application of simulation optimization modelling in management of

SWI in coastal aquifers was presented by Werner et al. [27], Ketabchi and Ataie-Ashtiani [28,29], and Singh [30,31]. Planning of the pumping in the middle of the Nile Delta aquifer was suggested by Sherif and Al-Rashed [32] to ensure groundwater sustainability. The management plan for a coastal aquifer by installation of a new well system away from the coastal area was also highlighted by Maimone and Fitzgerald [33] as a reliable technique compared to another approaches that assumed a deeper drilling plan for the old-existing well fields along the coast. The old wells in this system abstracted brackish water that was used (after desalination) for domestic purposes.

3. Physical Barriers

3.1. Physical Subsurface Barriers

In physical subsurface barriers, concrete, grout, bentonite, slurry walls, and sheet piles are commonly designed in front of seawater along the coast (Figure 1). The efficiency of injecting cement grout was examined by Sugio et al. [14] in Okinawa-Jima Island in Japan following experimental and numerical simulations, including experimental sand box tests and finite difference modelling. Moreover, the positive role of these barriers in controlling and delaying the SWI was reported by Galeati et al. [34] through 2D simulation of a case study in southern Italy using an implicit Eulerian–Lagrangian finite element model. Basri [35] performed simulation of a 2D vertical section of a hypothetical aquifer, and Nishikawa et al. [36] simulated a 2D vertical section of Dominguez Gap coastal area of Los Angeles, California, using SUTRA (Saturated-Unsaturated variable-density ground-water flow with solute or energy TRAnsport) code developed by the United States Geological Survey (USGS). The Komesu underground concrete dam (cut-off wall) in Japan, with dimensions of 2320 m × 0.54 m and a depth of 70 m below mean sea level, can be considered as a good example of physical barriers successfully developed at a large scale to protect an aquifer from saltwater intrusion [37]. Through experimental and numerical simulations, Luyun et al. [38] and Abdoulhalik and Ahmed [39] showed that the application of deep physical barriers located closer to the coast and in front of the toe location are more effective.

Numerical models and approximate analytical solutions were used by Kaleris and Ziogas [40] to study the influence of a cut-off wall on progression of SWI in scenarios with and without groundwater extraction. The analytical approximations are based on the inputs and outputs of the SUTRA model. In the absence of abstraction, the physical barrier showed a high protective potential when it was located at greater depths and much closer to the coast. In the second scheme, the ability of this cut-off wall to retard the saline wedge was illustrated in systems with limited number of wells, and in cases where pumping was carried out at smaller distance from the shoreline and at a relatively greater depth. Under this pumping action and in the aquifer systems where the inland boundary was specified with a lower inflow velocity than the intruded velocity of saline water, and also in cases with high anisotropy, the design of physical barrier control was proven to be of immense benefit in the mitigation of SWI.

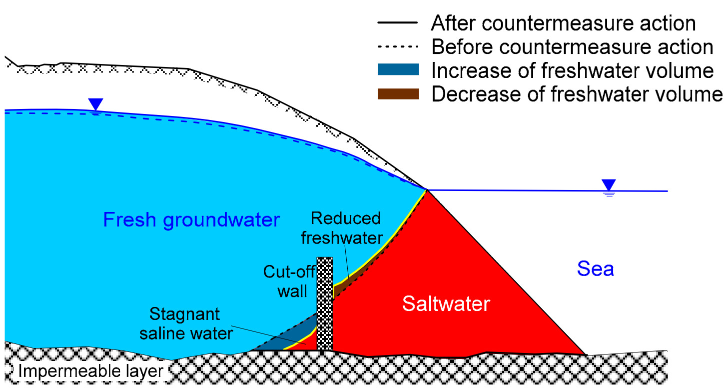

Figure 1. An illustration of a physical subsurface barrier.

Although, the development of such barriers has high initial installation and material costs, they have still been suggested by Allow [41] to be the most cost-effective strategy, since they do not require maintenance and repair activities over their life time. This claim was based on the comparison of the results obtained from two different management options, namely physical barriers and injection wells, where the need to provide the essential source of recharge water and the potentially high future repair costs of the injection process reduced the functionality of the second management option. The two scenarios were applied on the Damsarkho coastal aquifer in Syria and the simulations were conducted in 3D using finite-difference based variable density groundwater flow and transport code (SEAWAT) developed by the USGS.

Generally, the application of a physical subsurface barrier is an expensive process for deep aquifers [42]. Another issue that has been highlighted by Nawa and Miyazaki [37] and Allow [41] is the stagnant condition of the intruded saline water that remains behind the barrier at the time of its construction (Figure 1). According to Nawa and Miyazaki [37], in cases with steep seaward hydraulic gradient, the flow of freshwater can force this residual saltwater to diffuse through the barrier and also to intrude below its foundation toward the sea, increasing the total volume of freshwater. However, under extensive pumping and low hydraulic gradient conditions of the flow system, the reverse diffusion of seawater through the barrier and beneath its base, and hence mixing with this plume of stagnant saltwater, can cause some sort of deficiency in the process.

In a totally different and new technique, James et al. [43] introduced a biological barrier to work against SWI. The methodology was based on the injection of bacteria or nutrient solutions to reduce the hydraulic conductivity of sub surface layers, and hence to reduce the risk of SWI. During the subsequent growth of the bacterial biofilms with time, extracellular polymeric substances (EPS) were produced that tended to clog the pores of the porous matrix and reduce its permeability. It has been projected that the application of biofilm barriers would reduce the economic cost by about 24% compared with the more traditional deep physical barriers, such as injection of recharge water.

3.2. *Physical Surface Barriers (Land Reclamation)*

Coastal land reclamation involves the artificial extension of the coastline towards the sea. In this technique, new land is introduced by artificial filling of the appropriate type of soil at the desired geometry and slope (Figure 2). It is mainly constructed to provide the land area required to meet growing urbanization and population increase. However, from a hydraulic point of view, coastal reclamation creates a foreland that may develop a new zone for a freshwater body, helping to delay the advancement of SWI [42]. In this framework, and in order to maintain the hydraulic equilibrium of the system, the freshwater body starts to penetrate into the newly reclaimed soil, and hence it delays the inflow rates of saline water. Increasing the distance between inland production wells and the coastline, and also providing a larger area to deal with the natural rainfall, are the other beneficial terms of reclamation against SWI [44–46].

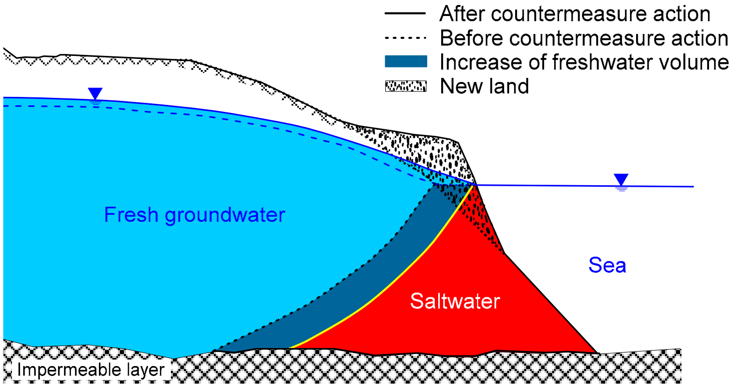

Figure 2. An illustration of coastal land reclamation.

The hydro-geochemical properties of subsurface water of a coastal aquifer in Shenzhen city in China during the rapid urbanization period were studied by Chen and Jiao [44]. The city has undergone massive and large scale land reclamation during the last decades due to its rapid urbanization. In their study, the reduction in the ionic ratios of $rCa/(rHCO_3 + rSO_4)$ and the enrichment of sodium (Na^+) relative to chloride (Cl^-) were considered as two indicators to claim that the system had experienced a significant retardation of SWI over the urbanization and coastal reclamation period. In the first term, r stands for concentration. Accordingly, the monitoring results of the observed groundwater levels in another aquifer located in the same city (Shenzhen) in China showed that during the land reclamation the groundwater level had raised [47]. Furthermore, they conducted a numerical study using FEFLOW (Finite Element subsurface FLOW system) code, in which they emphasized that increasing the seaward recharge (submarine ground discharge) to the newly reclaimed zones of the flow system could offset the impacts of SWI. Uplifting of the groundwater level and the seaward movement of SWI were also proven analytically by Guo and Jiao [45,46], using steady state simulation of the freshwater-saltwater interface movement under the land reclamation conditions.

The cost of equipment and materials for designing such a surface barrier at a large scale is the main limitation to this technique. In addition, the land subsidence that may occur due to the new overburden pressure imposed by the mass of the reclaimed material in the areas that are underlined by soft layers of old soil is another concern. The engineering properties of the filling soil should be reasonably well defined. Also, the environmental impact should be considered as another constraint of this technique, where the reclamation may affect marine life, fishing, and tourism activities in these areas.

4. Hydraulic Barriers

The application of hydraulic barriers to control SWI has gained more popularity than other management strategies. Recharge, abstraction, and combination of abstraction and recharge are the three main types of hydraulic barriers. Treated wastewater (TWW), desalinated seawater, and desalinated brackish water are three possible sources of water that can be used to recharge aquifers. TWW is the reclaimed wastewater that is appropriately treated in treatment plants. All the microbial pathogens, suspended solids, oxygen-depleting organic matters, and nutrients (i.e., nitrogen and phosphorus) from treated effluents produced from sewage treatment plant are significantly reduced through combined mechanical, biological, and chemical treatment processes.

Desalination is a removal process of dissolved minerals (mainly salts) from either seawater or brackish groundwater to produce fresh water of potable water quality. The desalination can be accomplished by different techniques that can be classified under two main processes—thermal (distillation) processes and membrane processes [48]—although other methods (e.g., freezing and solar humidification) have also been developed. A summary of different desalination technologies can be found in Xevgenos et al. [49]. The desalination method can be selected based on three main aspects: technical aspects, environmental aspects, and economic aspects. The challenge in the desalination process is the reduction of the energy used, and thus the total cost of the produced water. Reverse osmosis (RO) is currently one of the fastest-growing techniques in water desalination, which is based on membrane processes. RO consumes less energy, so it is cheaper and has lower carbon emission, requires relatively simple equipment, does not need to be linked to a power plant, and requires small areas of land [50]. RO is a pressure driven technique, wherein dynamic pressure is used to overcome the osmotic pressure of the salt solution. Water is forced to flow through small pores under high pressure through semi-impermeable membranes, while concentrated brine solution is rejected [49]. The pressure difference must be high enough to overcome the natural tendency of water to move from the low salt concentration side of a membrane to the high concentration side, as defined by osmotic pressure. The major energy consumption comes from creating pressure. The quality of the produced water depends on the efficiency of the membranes, the pressure, and the degree of salinity. Sola et al. [51] studied the quality of the feed water at a RO desalination plant, considering the physical, chemical, and microbiological composition of water samples taken from direct seawater intake and others from drilled boreholes over the aquifer shoreline. It was concluded that due to infiltration through the aquifer media, the quality of brackish or saline water abstracted from coastal boreholes is considerably better than direct seawater intakes. Low organic carbon and dissolved oxygen contents, low turbidity, and silt density index are other positive characteristics of the abstracted saline or brackish water, which play a role in the selection of these sources to feed RO desalination units over direct seawater intake [51,52]. According to Miller [53] and Stein et al. [54], the majority the seawater desalination costs using RO re attributed to the high energy consumption. The total cost and energy consumption of brackish water is less than 50% of the seawater desalination method. The contribution of energy (electric power) to the unit cost of seawater desalination is four-fold higher than that of brackish water [53].

4.1. Artificial Recharge

Within the positive or pressure barriers, the aquifer is artificially recharged by high-quality water (e.g., surface water, rainwater, extracted groundwater, treated wastewater, or desalinated water) to maintain the seaward gradient in the system by increasing the inland piezometric heads. Generally, the artificial recharge of water aims to reduce flood flows, store freshwater water in aquifers, raise groundwater levels, relieve over-pumping, and finally, improve water quality and suppress the saline water body [7,55]. This methodology is among the most popular techniques, which have been widely suggested and assessed in the literature. Results of the numerical modelling of SWI in the Burdekin Delta aquifer, Australia [56], show that extensive pumping and lower recharge rates are factors that accelerate the landward encroachment of the seawater wedge. A summary of the more recent works is presented below.

Mahesha and Nagaraja [57] and Narayan et al. [16,56], through a parametric study, concluded that uniform natural rainfall can effectively repulse the saline wedge. Mahesha [58,59] suggested that artificial recharge through injection wells represents an efficient methodology for retardation of SWI in any geological condition of confined or unconfined aquifers, with single or multiple layers (Figure 3). This positive potential of deep recharge barriers in repulsion of SWI has been analyzed by Luyun et al. [38] through experimental, analytical, and numerical modelling. They concluded that the effectiveness of the recharge system is reduced if it is implemented farther and higher from the toe of the saltwater wedge. The methodology has been numerically assessed by Paniconi et al. [60,61], Papadopoulou et al. [62], Narayan et al. [56], and Allow [41] for a range of global real-world case studies.

The benefits of freshwater reinjection through a deep-well system located between the interface toe and the production well was analytically affirmed by Lu et al. [63] through introducing a parallel injection–extraction system to control SWI. By re-injecting part of the freshwater into the coastal aquifer, the net extraction rate of freshwater from the production well was increased up to 50% compared with cases without the injection well (single extraction well system), while at the same time mitigating against the SWI problem. Sun and Semprich [64] compared the efficiency of freshwater injection to that of air injection to manage SWI risks. However, in spite of the lower effectiveness of the deep air injection in providing an efficient pressure gradient against the intruded saltwater wedge, they concluded that relying on the air injection can be a good option (as it readily available) in areas where access to freshwater is limited.

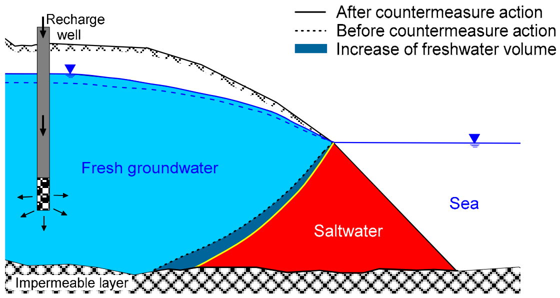

Figure 3. A generalized sketch of a recharge well system.

Surface reservoirs, lakes, canals, and other spreading recharge basins can also be used as recharge systems to recharge (only) the unconfined aquifer systems through infiltration of collected water. Abdalla and Al-Rawahi [65] studied the effects of a large dam (Al Khod dam) in the Sultanate of Oman on retardation of SWI. The dam was purposely constructed to mitigate the depletion of subsurface water during the over-pumping periods and to collect the Wadi flows during intensive rainfall and runoff events. The monitoring of the piezometric head and measuring of the electrical conductivity indicated that the recharge dam was effective and contributed positively toward improving the groundwater quality in the coastal zone. Yuansheng and Zhaohui [66] introduced the artificial recharge of water as an efficient measure to control SWI and elevate the groundwater levels. By transporting river water to inner lakes through a pre-constructed canal, they developed an integrated methodology for future sustainability of the flow system in the coastal city of Haihou, China.

The cost of providing high quality water (e.g., desalinated water) and its in-lieu delivery for recharging purposes is among the main limitations of recharge barriers using desalinated water. In addition, unavailability of such water locally, especially in dry years or in regions that suffer from scarcity of water, constitutes another major restriction [67]. Therefore, in recent years more emphasis has been placed on renewable sources of water, such as treated wastewater, as the sources of recharge for seawater intrusion mitigation (e.g., [13,15,22,68–74]). Application of reclaimed water for common utility sectors or artificial storage in subsurface layers can help to satisfy part of the water demands, resist drought, and also protect the system against SWI in coastal aquifers.

4.2. Abstraction Barriers

In negative barriers, the brackish or saline water is continuously pumped through deep abstraction wells located near the coast (Figure 4). The extracted water can be directly disposed of into the sea or it may be used as a water source for desalination plants. Ray et al. [75] and Hubbs [76] elaborated that subsurface intake systems of desalination plants represent green intake that can be utilized to improve the quality of feed water delivered to reverse osmosis seawater desalination plants. This type of intake is similar in concept to riverbank filtration, wherein the native geological media is used to naturally filter the raw water before entering the treatment facility. Wright and Missimer [77], Schwartz [78,79], and Rachman et al. [80] indicated that subsurface intakes provide physical and biological mechanisms for filtering the feed water by straining and biodegrading organic matter and other particulates, while passing through marine sediments and seabeds similar to the sand filters that are used in freshwater treatment plants.

The extracted groundwater can also be used in industrial activities, for example for cooling purposes, to develop green lands in coastal areas, and for irrigation of certain types of crops [2,8]. The direct disposal of large quantities of extracted saline water (or its waste after industrial use and desalination processing) into the sea could bring other environmental problems that affect the marine life, fishing, and tourism activities [2,12].

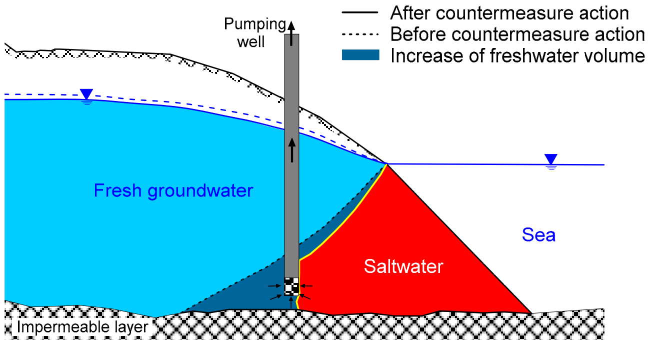

Figure 4. A generalized sketch of an abstraction barrier.

The abstraction of brackish water from the dispersion zone as a measure of SWI control in leaky aquifers was first evaluated by Sherif and Hamza [8] using a two-dimensional finite element model. Their results showed a significant reduction in the width of the mixing zone owing to brackish water pumping. The quality of the pumped water was better in cases where the barriers were screened away from the sea or in the upper horizons of the mixing zone. However, this was associated with the reduction and loss of a portion of freshwater, which was reported as the major drawback of this technique. The same principle of pumping brackish and saline water near the coast was assessed by Mahesha [81] and Kacimov et al. [82] using the sharp interface theory, and by Sherif and Kacimov [83] using the SUTRA code in a 2D vertical section of a hypothetical confined aquifer.

Park et al. [84] used the multidimensional hybrid Lagrangian–Eulerian finite element model [85] to study the effects of different parameters on the quality of the water pumped from another production well. The effects of pumping rates from the barrier well, the horizontal distance of this barrier from the coast and from the production well, the depth of the barrier in the aquifer system, and the number of these barriers were investigated in different cases using a hypothetical model.

In an attempt to reduce the upconing problem that occurs under freshwater production wells, van Dam [2] proposed the application of the scavenger technique for thick aquifers. The new set of installed (scavenger) wells are screened next to, or nearby, the production well, and at some depth below the freshwater–saltwater interface to extract saline water only, and thus reduce the upconing of the interface toward the production well. The protection of the inland wells (for withdrawal of freshwater) using a series of negative barriers was investigated numerically in several research papers within simulation optimization frameworks (e.g., [25,72–74,86–94]).

In general, extraction barriers cause a drop in the piezometric head near the coast, which enhances the seaward hydraulic gradient and protects the aquifer. However, due to this seaward gradient, the process often ends in abstraction of much more freshwater than saline water, which may cause a reduction in the freshwater storage capacity of the aquifer. Therefore, with controlled rates of pumping, the method can be applied as a temporary management strategy in cases where the intrusion is not extensive (i.e. saline water body is far from the pumping wellfield), and also to control salinity in the system before applying other methods [3]. To overcome this problem, Pool and Carrera [9] proposed a new method using double negative barriers in cases where urban aquifers are the only viable option due to space limitation. One of the barriers abstracts the saline water near the coast, while the other pumps freshwater further inland. The idea behind this methodology is to create a low-velocity zone between the two abstraction zones with an almost horizontal hydraulic gradient, which will help to protect and increase the productivity of the inland freshwater well. They showed that this model will have a high efficiency in shallow aquifers, and its efficiency would be even increased in the cases where the seawater well pumps the saline water at higher rates in a zone closer to the sea. It was demonstrated that screening the inland freshwater well at the top and the seawater well at the bottom increases the overall performance of the proposed control measure.

4.3. Combined Barriers

The combination of some of the aforementioned strategies can help to better control SWI by combining the merits of the individual methodologies. For instance, the combination of reduction in the pumping rates and recharge barrier [95] and controlling the pumping rate with artificial recharge [61] has been reported in the literature as a possible solution for SWI. Cherubini and Pastore [96] proposed a solution based on reduction of well density (number of pumping wells per unit area) coupled with artificial recharge for a regional aquifer in Italy. Another possible scheme under this approach is the combination of positive and negative barriers, known as a mixed barrier (Figure 5). This mixed barrier (which is the main focus of this section) uses: (a) application of repeated cycles of recharge and abstraction through the same well system; and (b) injection of freshwater while abstracting saline water. Some variants of the latter scheme have been suggested by a number of research studies as the most effective barrier method (e.g., [3,22,24,69,71–73,81,97,98]).

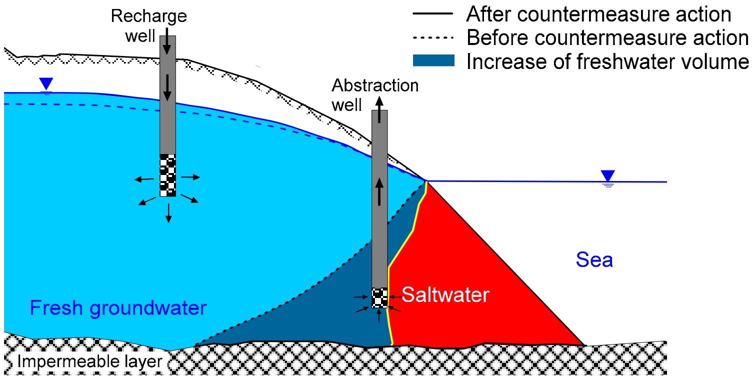

Figure 5. A generalized sketch of an abstraction–recharge barrier system.

4.3.1. Aquifer Storage and Recovery (ASR)

Aquifer storage and recovery (ASR) is a technique introduced by Cederstrom [99] and has been widely used in many countries for management of water resources as an alternative to surface water storage in dams and reservoirs [100]. ASR is one of several techniques used for management of aquifer recharge. The term "management of aquifer recharge" was introduced to describe the "intentional banking and treatment of water in aquifers" [101]. ASR methodology involves continuous storage of excess water by deep injection through recharge wells into deep aquifers or other water-bearing formations, either when water is available or during the wet and low demand season of the year (Figure 6). The stored water is then recovered when needed using the same wells to meet the water demand of the community, and during the next dry or high demand season of the year [102]. Depending on the quality of the native groundwater in the aquifer and also the quality of the recharge water, the recovered water may need to go through a short treatment process before use.

The ASR process is repeated continuously over time, depending on the levels and durations of water scarcity. These repeated cycles of recharge and abstraction also contribute to the improvement of water quality [100,103,104]. Typically, the volume of the extracted water is less than that of the injected water. A buffer zone with marginal water quality is created [105]. The buffer zone basically holds the recoverable fraction of water. Therefore, ASR can be considered as one of the management options to control seawater intrusion, besides its other positive roles in issues related to water production and demand and maintaining the seasonal fluctuation in groundwater storage [106,107]. Misut and Voss [105] investigated the beneficial aspects of ASR in controlling seawater intrusion by defining a series of ASR wells in different confined or unconfined aquifers as a regional case study in the United States. The simulations were conducted in 3D using SUTRA. The positive aspects of ASR system in their results were attributed to the increase in the net storage of the aquifers and continuous seaward movement of the seawater wedge. They concluded that there are several factors that threaten the effectiveness of the hydraulic barrier (using ASR wells). For example, installation of wells in, or in the vicinity of, unconfined areas allows the injected water to leave the aquifer through upward flux and evaporation processes or as coastal outflow. Also, in each of the ASR cycles, application of a long-time storage (or pause) phase between recharge and abstraction allows the injected water to drift beyond the buffer zone. Similarly, mixing and dispersion of injection water with ambient water and application of high rates of injection and abstraction reduces the efficiency of ASR system.

The commonly used measure to evaluate the performance of ASR systems is recovery efficiency, which is defined as the total volume of recovered water as a percentage of the injected volume in each of the operating cycles while satisfying a target water quality criterion in the abstracted water [102]. The impacts of different hydrological factors on recovery efficiency have been assessed by Lowry and Anderson [108] through a set of parametric studies. The enhancement of ASR efficiency with multiple ASR cycles has been reported by Lu et al. [106] and Sherif and Shetty [104] using numerical methods. Lu et al. [106] investigated the efficiency of an ASR system under various hydrogeological and operational conditions, considering the mass transfer parameters of dual-domain aquifers. They concluded that the capacity ratio (ratio of immobile to mobile domain porosity) and the mass transfer time scale (defined as $1/\alpha$, where α is a first-order mass transfer rate coefficient) are among the main variables that affect the recovery efficiency of ASR. The increase of capacity ratio, which is equivalent to the size of the immobile domain in aquifers, causes reduction of the recovery efficiency. This reduction in recovery efficiency is also observed in aquifers with slow mass transfer. ASR, similar to any other management strategy, has some economic cost and quality limitations, and its implementation needs further attention. For instance, the high rates of mixing of injected water with a poor quality native groundwater tend to reduce the total recoverable volume of freshwater (recovery efficiency). In addition to this water–water interaction, the quality of the injected water can also be threatened by water–rock hydrochemical interaction. Numerical simulations were performed by Sherif and Shetty [104] and Hussain et al. [100] to study the effects of an ASR system on inland advancement of saline water in the Wadi Ham aquifer, United Arab Emirates. It was shown that a significant reduction in salinity levels occurred in areas surrounding the system, which was mostly attributed to the application of ASR management scenarios.

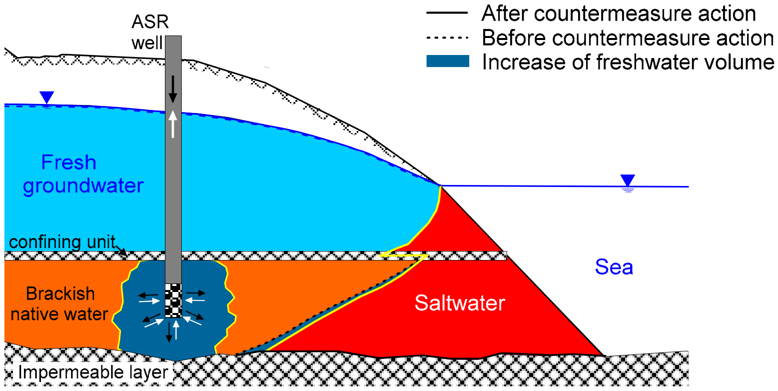

Figure 6. Schematic sketch of aquifer storage and recovery (ASR) system.

4.3.2. Abstraction, Desalination, and Recharge (ADR)

Abd-Elhamid and Javadi [67] and Javadi et al. [109] proposed a combined methodology known as abstraction, desalination, and recharge (ADR) to control SWI. ADR is based on continuous abstraction of brackish water near the coast, desalination of the abstracted brackish water (e.g., using reverse osmosis), and using the excess desalinated water as a source of artificial recharge through injection wells, while the rest of the desalinated water is used to meet some of the water demand (Figure 7). They showed that this method represents an effective and economic method for controlling SWI. Lower energy consumption, lower cost, and lower environmental impact have been characterized as the major advantages of this methodology in controlling SWI. This methodology also led to an increase in the total available freshwater that is produced by desalination of the extracted saline water. In arid or semi-arid regions where the total amount of desalinated water and abstracted freshwater does not satisfy the demand, it would not be possible to use desalinated water as a recharge source for the aquifer system. In addition, desalinated water is a relatively expansive source of water that is produced through an energy-intensive process. In order to address this problem, low-cost effluents reclaimed from municipal wastewater treatment plants can be used to recharge the aquifer. This guided Javadi et al. [73] and Hussain et al. [72,74] to propose a new extension of ADR and a new methodology, called abstraction, desalination, and recharge by treated wastewater (ADRTWW), to control SWI in coastal aquifers.

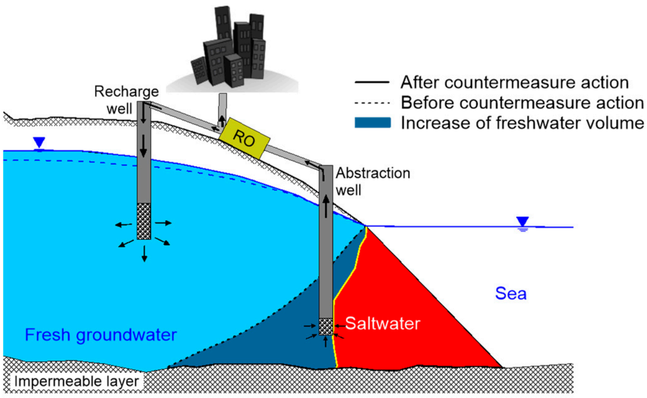

Figure 7. Schematic sketch of ADR system.

4.3.3. ADRTWW

The abstraction, desalination, and recharge by treated wastewater (ADRTWW) methodology concerns the use of more economic sources of water, such as biologically treated wastewater (TWW) and collected rainwater, or transferring good quality water from rivers, canals, lakes, and ponds that exist in the vicinity of the coastal regions. The ADRTWW methodology consists of three steps: (a) abstraction of brackish water from the saline wedge using deep negative barriers (abstraction wells); (b) desalination of the extracted brackish water using a small-scale reverse osmosis (RO) plant and use of the desalinated water as a supplement for an urban water supply system; and finally (c) recharge of the aquifer using an external source of TWW [72,73]. The main concept of this management approach is schematically shown in Figure 8. Treated wastewater (TWW) can provide a continuous and long-term supply of water in developed urban areas. However, the availability of the other sources is dependent upon the pre-existing hydrological features and hydro-environmental formations of the coastal site. Low economic and environmental costs are the two factors that allow the ADRTWW to offer greater potential in controlling SWI than ADR and conventional barriers (either alone or combined). The other inherent difference between ADRTWW and ADR is the total volume of the water that will be offered for use by the population. In ADR, a part of the desalinated water is used for recharge purposes and the rest is offered for urban uses. However, in ADRTWW all of the desalinated water is directly allocated to different sectors of the developed urban area, since the recharge is dependent on reclaimed water [73,110].

One of the main limitations of any hydraulic barrier with deep injection (recharge) wells is the high cost and energy burdens of the water injection process. Therefore, especially for unconfined aquifers, recharge using pond water could be a good alternative (Figure 9). In this approach, the collected TWW is allowed to percolate through the unsaturated zone to the underlying aquifer. Although the TWW contains greater salinity than desalinated water, it helps to retard the saline water by increasing the seaward hydraulic gradient, as shown by Hussain et al. [72,74]. The initial costs of various artificial recharge schemes in an alluvial area in India were reported to be 551, 8, and 1 $/1000 m^3 of recharge structure for recharge wells, spreading channel, and percolation tank (pond) approaches, respectively. Also, the running costs of the recharge through the same structures were 21, 20, and 1 \$/1000 m^3/year, respectively, showing the great economic advantage of surface recharge ponds [111–113].

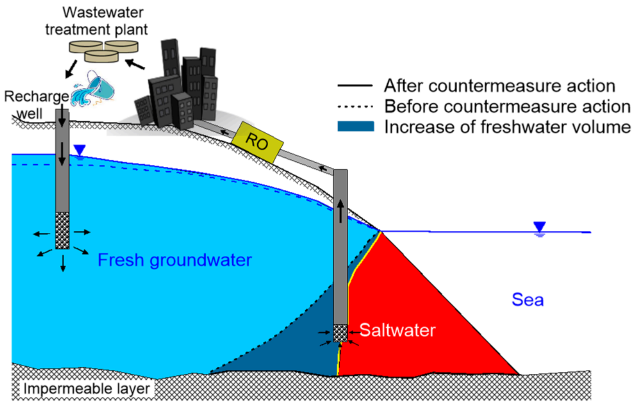

Figure 8. Schematic sketch of abstraction, desalination, and recharge by treated wastewater (ADRTWW) using a recharge well system.

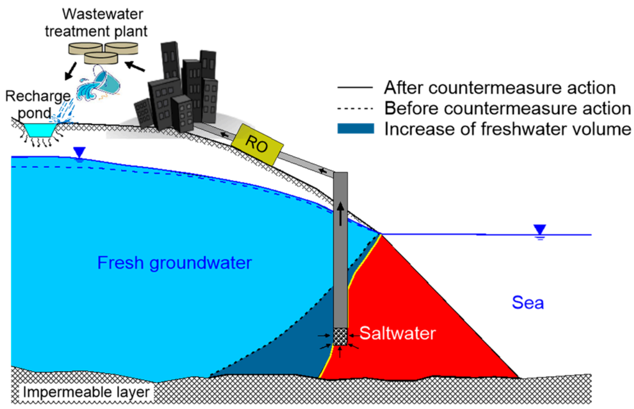

Figure 9. Schematic sketch of ADRTWW using a recharge pond system.

All the positive aspects of TWW make it suitable as a recharge source in coastal areas around the world. The quality of treated effluents produced from the sewage treatment plant should reach the tertiary standards (without chlorination) prior to their use in recharging aquifers. Shammas [69] used a three-dimensional flow and solute advection transport model to assess the future effectiveness of the deep injection of treated water in the Salalah aquifer in Oman. The recharge system was established in the area. The treated wastewater was returned from the available central sewage treatment plant with Total Dissolved Solids (TDS) at 1000 mg/L and was injected into wells in a line parallel to the coast. The enhancement of the piezometric water levels (around recharge wells) and the reduction of inland flow of saline water from the coastline were the main outcomes of this project. Vandenbohede et al. [13] employed an artificial recharge system using two recharge ponds to recharge the dunes of the western Belgian coastal plain and to develop a safe and sustainable water extraction system against seawater intrusion. Tertiary treated wastewater effluent produced from the combination of ultra-filtration and reverse osmosis (TDS = 500 mg/L) was used in these two ponds. Bekele et al. [114] presented the beneficial aspects of passing secondary treated wastewater through a multi-media filtration system (final TDS = 755 mg/L) in recharging groundwater systems using surface basins. Monitoring of the water quality of the percolated TWW in the vadose zone highlighted significant reductions were achieved in the amounts of several constituents (30% reduction for phosphorous, 66% for fluoride, 62% for iron, and 51% for total organic carbon) of the recycled water, implying the general enhancement of the water quality obtained through the filtration of TWW in porous media. Therefore, it is reaffirmed that TWW can be used as a reliable source for subsurface water storage.

5. Conclusions and Future Prospects

This paper presented a comprehensive review of the common methods that can be used to control and mitigate SWI in coastal aquifers. The presented methods include some conventional methods that can be adopted as temporary solutions prior to the application of the main control scheme. Installation of surface and subsurface physical barriers in front of the intruding seawater body constitutes another control methodology. However, due to the costs related to equipment, materials and installation of physical barriers at a large scale, hydraulic barriers have become more popular. Depending on the level of risk of SWI and its impact on the quality of the groundwater in the coastal aquifer, different combinations of these control methods can be used. In order to highlight the environmental impacts of these control methods, an environmental impact assessment should be undertaken during the planning stage. In this study, the advantages and disadvantages of each methodology are highlighted. It is shown that different combinations of control methodologies allow their advantages to be combined to introduce much more efficient control techniques. Effective and efficient control of SWI should be regarded as an important task for any groundwater exploration project in coastal regions. In addition, the limitations in terms of the economic cost and the water demands of growing populations in coastal areas should be taken into account. In order to implement these cost-effective solutions, which satisfy the above conflicting objectives, there is a need for simulation optimization studies. Simulation models should be linked to robust optimization tools in order to provide optimal solutions with a variety of design variables.

For future planning and management of SWI in coastal aquifers, good quality treated wastewater or reclaimed surface water should be used for recharging groundwater systems. Based on the current review, the application of these cost-saving water resources would help mitigate the risks of SWI and flooding simultaneously. In coastal areas, there is a need to develop modern monitoring systems consisting of observation wells with multiple screens at a range of depths, along with sensors and automatic database storage systems to monitor inland advancement of saltwater [115]. Another possible field for future management of SWI is the development of a robust decision support system, encompassing a wide range of hydraulic components of surface–subsurface water interactions (e.g., evaporation, natural recharge, artificial recharge, and groundwater pumping). This decision tool should be integrated with numerical models in order to simulate the aquifer responses to different management scenarios. This integrated tool can be extended to identify the optimal arrangements of each management scenario. The effects of parameter uncertainty on model calibration [116] and the optimal results of each SWI control measure should be studied before implementation.

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