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ESSAY

Challenges and approaches for management of seawater intrusion in coastal aquifers

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Abstract
Coastal aquifers provide water for over one billion people worldwide; however, they face seawater intrusion due to overpumping. The current and future challenges of coastal aquifer management involve issues such as climate change and the control of abstraction and recharge. Different management approaches are being used globally to prevent aquifer salinization. This essay presents the challenges and possible solutions while also discussing the different approaches and their needs for improvement.

Keywords Coastal aquifers · Climate change · Seawater intrusion · Salinization · Water supply

Introduction

Freshwater resources, particularly groundwater, are declining due to overexploitation and climate change. As much of the global population lives in coastal areas, coastal aquifers experience high stress due to extensive pumping of freshwater. This causes seawater intrusion, migration of the fresh–saline water interface (FSI) inland, and salinization of many coastal wells.

Due to the sensitivity of coastal aquifer usage to its salinization by seawater and its importance to coastal communities, appropriate management of coastal aquifers is crucial (Post 2005). The number of studies on seawater intrusion occurrence and mitigation has increased significantly in the past few decades (Mastrocicco and Colombani 2021). Various approaches are used for managing coastal aquifer systems, while their practical contributions are described by Polemio and Zuffianò 2020 and Mastrocicco and Colombani 2021. These approaches can be classified into different practices, measures, and actions that can universally minimize groundwater salinization. Nevertheless, the complexity of managing coastal groundwater due to emerging challenges (e.g., population growth, climate change) is growing, presenting unprecedented conditions for the safe and sustainable supply of freshwater.

This essay describes these challenges and provides suggestions for managing the coastal aquifer in a logical workflow—Fig. S1 at the electronic supplementary material (ESM). Ideas and different directions for dealing with coastal aquifer salinization are provided, alongside a short overview of the different approaches and proposals for future research in this field.

Current and future challenges

The future of water supply for coastal inhabitants looks grim. Throughout the world, water demand exceeds supply as pumping scheme optimization is no longer a viable solution, and other complementary management techniques are needed. This section discusses the expected trends and processes that may affect the current water availability and will be more crucial in the future.

Climate change will cause sea-level rise, which may enhance groundwater salinization, especially in areas of low topography. Moreover, it changes the global pattern of precipitation whereby different areas receive more or less rain gradually. Lower precipitation is expected to enhance seawater intrusion due to lower recharge; however, even in some places that receive greater precipitation, the rainy season can be shortened, which means that for every rainy day there is more runoff and less groundwater recharge. These processes negatively affect the freshwater availability in the coastal zones as seawater ingresses. On the other hand, glacier melting exposes more land, resulting in the creation of new freshwater aquifers. Permafrost thaw creates new connectivity between land and sea, leading to complex dynamics between

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meltwater, freshwater, and seawater. As a result, different submarine groundwater discharge (SGD) patterns occur (Guimond et al. 2022). Understanding how the aforementioned recent and new changes affect coastal hydrology is an important challenge for future coastal aquifer management.

Combined pumping of fresh and saline water, including SGD To manage the coastal aquifer, especially in the vicinity of the shoreline, it is essential to utilize both fresh and saline water pumping together. Such combined pumping may increase both types of water and is indeed suggested in places where saline water is pumped from below the FSI. Pumping of water near the shoreline will decrease the amount of SGD and should be researched in more detail before future large volumes are taken. This process will affect the chemical composition of the coastal seawater and the coastal environment and therefore should be carefully examined.

Improving management of floodwater for increasing recharge Since decreasing recharge due to climate change and decreasing head due to overpumping may enhance seawater intrusion, it is important to find other sources of recharge water. One option is to increase artificial recharge from floods, which otherwise act as a real hazard. Increasing flood recharge, e.g. by building a surface reservoir and possibly infiltration wells, is an engineering challenge; however, this solution can benefit cities where new houses and asphalt roads are built, lowering the natural recharge and increasing the problematic surface flow. Thus, a combined solution is needed that will increase recharge and decrease floods.

Reclaiming new lands from the sea and artificial islands Lack of space has driven planners and engineers towards creative solutions in different parts of the world. Reclaimed land could be an extension of the existing land or completely detached from the previous shoreline, such as artificial islands. This practice is found in several locations (e.g. in the Netherlands and the Arabian Sea) but needs further study and long-term monitoring. Specifically, it is important to understand the rate of flushing of the original seawater and the evolution of the salinity pattern in these new environments. Due to the complicated hydrogeological conditions and higher heterogeneity, it will be more difficult to forecast the rate and direction of the processes.

Using the saline zone of the aquifer for storage Coastal aquifers, in addition to serving as a freshwater reservoir, can or may be used in the future for the storage of energy or contaminants in the saline zone, such as desalination brine (Stein et al. 2021a) or CO_2. The rising number of desalination plants and power plants along the coasts will force engineers and decision-makers to find better solutions for the waste produced by these facilities. The saline zone could be a plausible solution as a repository for the waste if geological conditions allow it. Hydrogeologists must investigate those scenarios soon, since storage is becoming increasingly scarce.

Effect of land subsidence on the salinity pattern The process of land subsidence in coastal aquifers due to overpumping is significant in several areas (El Shinawi et al. 2022). Complex hydrogeological heterogeneity may drive the flow in different directions, creating complicated flow patterns. It is not clear how this phenomenon will affect the salinity pattern and seawater intrusion and thus should also be taken into future consideration.

Listed in the preceding are some future challenges and ideas to deal with those issues globally. However, reality may be more complex, and different regions will experience different effects to which aquifer management approaches should be adapted. The next sections will suggest and discuss approaches for coastal aquifer management that are relevant to different aquifer scenarios.

Aquifer characterization

The most important exercise in coastal aquifer management is to determine the salinity distribution and heterogeneity of the hydrogeological system. There is a huge variety among coastal aquifers but they all share common hydrogeological features—for example, the flow direction is influenced by density gradients, and the salinity distribution is often influenced by long-term processes such as sea-level fluctuations. It is challenging to select the best approach to characterize the aquifer and its salinity distribution. The traditional approach to understanding hydrogeological complexity has involved the drilling of wells and cross-correlating the stratigraphic units. By doing so, conducting profiles for geochemical characterization can enhance understanding of the hydrogeological unit's salinity and water sources and their relation with the sea. Through age dating analysis, radioactive isotopes can be used to distinguish the origin of different water bodies and their velocity. In addition, different low-cost noninvasive geophysical tools are common for characterizing subsurface hydrological systems. Researchers have improved some of these methods while combining several of them and comparing them to in-situ invasive methods (Rey et al. 2020), a practice that should be more widespread for subsurface characterization. However, using these techniques in surface and in-bore applications reveals only a small part of the study area. Airborne electromagnetic methods, which is an emerging field, may close this gap (possibly at a lower resolution) as they can characterize the subsurface at a basin scale up to hundreds of meters deep (Kang et al. 2022). These methods are state-of-the-art and can also characterize the salinity distribution in the aquifer. They may also shed light on the connection of each subaquifer with the sea, which is an important factor in analyzing coastal groundwater systems. Aquifer structure and salinity characterization is the first step in understanding which management tool should be used for mitigating seawater intrusion.

Hydrogeological models

After rigorous characterization of the salinity distribution and heterogeneity structure, flow, and solute transport, hydrogeological models should be used as a predictive tool for different freshwater exploitation scenarios. However, before moving to hydrogeological modeling, the relationship with surface-water systems, hydrological balance, and conceptualization of the system must be obtained. Specifically, the boundary condition at the seashore and each subaquifer connection to the sea must be described accurately. Data acquired from field observations and measurements are used to calibrate and validate the salinity distribution and the different parameters of the hydrogeological models. These models can be used when the data set is still incomplete to help create a conceptual model and fine-tune the data collection effort. Full 3D modeling of the coastal aquifer, which is required in a complicated geological configuration, is still a challenge, mostly due to the vast computational time, and therefore, very few studies exist on a three-dimensional (3D) description of an aquifer. Recent state-of-the-art studies have managed to lower the computational time needed to run flow and transport numerical models using surrogate models with different approaches such as artificial neural networks. This allows the running of simulation-optimization models for different pumping scenarios, resulting in the lowest upconing of saltwater (Christelis and Mantoglou 2019). The hydrogeological model that has been built for a specific aquifer should simulate the scenarios that are considered, and realize the time for the salinization of wells (Figure S1 of the ESM). If, for example, simulations of a certain pumping scenario show that only after 100 years would the wells be salinized, the proposed pumping scheme is probably sufficient. However, if the simulation shows well salinization after 10 years, then different pumping schemes should be adopted. To compare actual results with the predictions and make the necessary adjustments for improving the management of the aquifer, the hydrogeological model should be further used after pumping wells are installed and functioning. In many cases, seawater intrusion will occur even with pumping optimization models; therefore, different management approaches should be adopted. Some of the common and well-studied approaches and strategies are discussed in the following.

Management strategies for mitigating seawater intrusion

Coastal aquifer characteristics and exploitation around the world are very different; thus, different approaches are required for managing each aquifer. For example, California (USA) has implemented an integrated approach for managing the coastal water resources (Kretsinger Grabert and Narasimhan 2006), while two other studies demonstrate the state of seawater intrusion in North (Barlow and Reichard 2010) and South America (Bocanegra et al. 2010) and suggest different classifications for management approaches.

This essay adopts the classification of management approaches proposed by Polemio and Zuffianò (2020), where the different approaches are described along with the relevant references. These approaches have advantages and disadvantages and, thus, it is advised to tackle coastal aquifer management with several of them. The management strategies can be divided into three main classifications that differ by their local, aquifer, and regional extents.

Locally, engineering approaches can deal with small-scale problems of seawater intrusion and specific well-field salinization, e.g., physical subsurface barriers. These underground structures have been notably applied and developed in Japan, China, Ethiopia, and India (Polemio and Zuffianò 2020), and considered in other places. However, they are expensive, require favorable aquifer bottom morphologies and/or aquifer bottom and FSI depth, and require free land to be applied. These disadvantages of physical subsurface barriers can be overcome by using hydraulic barriers that are purposed to change the hydraulic gradient between the fresh and the saline groundwater and minimize seawater intrusion. Recharge of freshwater (positive), abstraction of saline groundwater (SGW; negative), and the combination of both (mixed) are the three main types of hydraulic barriers and they can be achieved in different ways. Tapping SGD is another approach for increasing water availability and reducing the exploitation of groundwater; however, it is difficult to isolate the freshwater from the seawater and the construction of the tapping facility is expensive.

The other approaches involve discharge management which also includes positive/negative hydraulic barriers using injection wells. This set of approaches addresses the aquifer scale and should be handled by the water authorities and municipalities that are responsible for groundwater availability and quality. Cessation of pumping and drilling more wells further inland is the first and obvious approach where pumping wells are being salinized. Well-field optimization should be applied and may include drilling more wells and reducing the pumping rate at each one, which reduces the maximum drawdown. Coastal collectors are a series of shallow pumping wells that intercept the freshwater before flowing to the sea (Dagan and Bear 1968). This way, shallow SGD is lowered which enhances the coastal water supply; however, this practice was introduced only in one country and may not be suitable for other regions.

The simple methods described here may be ineffective when the pumping rates increase. A natural hydrological balance and recharge assessment should be done as it can define the upper limitation of well discharge. Numerical models can help do this by simulating the discharge effect at different rates and locations for a specific hydrological system. Groundwater vulnerability assessment can be done using the GALDIT parametric method (Chachadi et al. 2003), although no practical use of this method was documented.

Another unconventional freshwater source is offshore freshened groundwater, estimated at around 1 million km^3 globally (Post et al. 2013). However, it is not clear if this groundwater is fresh or brackish, as most information about it comes from geophysical methods that cannot distinguish well between fresh and brackish water. New studies should explore these issues and these aquifers' connections to the land.

Another set of management approaches deals with water and land management and affects the region where it is applied. One way to reduce the pumping load is to use different water sources for agriculture in coastal areas, e.g., reclaimed wastewater for crop irrigation. Other water sources, including surface water, runoff water, and saline water, can also be used for crop-specific irrigation.

Seawater reverse osmosis (RO) desalination is a promising technology, which is essential for the resilience of coastal semi-arid areas experiencing a water crisis and has been implemented in coastal regions in the past few decades. That allows less exploitation of surface water and groundwater reservoirs; however, seawater desalination has high energy demands and, therefore, is expensive and not environmentally friendly, and is affordable only in well-established countries. Furthermore, ocean oil spills, ocean storms, and sewage discharge through rivers cause deterioration of the feed water quality for desalination and, in some cases, shutdown of the plants. Using SGW as feed for desalination does not only stabilize the feed water quality, but it is also more energy-efficient and environmentally friendly (Stein et al. 2021b);

the drawbacks are that new infrastructure needs to be built and the FSI dynamics are not clear in a complex hydrogeological setting.

Further desired advancements

Continuous high-quality monitoring of the FSI propagation is an important part of managing a coastal aquifer. Recent studies have improved existing techniques; however, advanced easy-to-use monitoring tools are still missing. There are different invasive and noninvasive approaches for monitoring the FSI movement, including geophysical and geochemical methods. The noninvasive methods can be used at a high temporal frequency and monitor the propagation of saltwater; however, for measurements with a higher vertical resolution, in-bore techniques should be improved and used. Geochemical profiles of salinity, major ions, radioactive and conservative isotopes, dissolved oxygen, nutrients, and trace elements in time can be used to monitor the coastal aquifer dynamics. Nonetheless, the combination of methods from different disciplines strengthens the reliability of the results and increases the ability to monitor and predict seawater intrusion dynamics. As technology advances, different methods should be explored further while creating affordable monitoring systems that could be implemented easily in coastal regions. In particular, cheap and reliable salinity/temperature sensors should be further developed (such as fiber optics) that can be used worldwide and can be inserted into existing monitoring wells.

Concluding remarks

Freshwater demand and thus the pressure on water supplies in coastal areas is high and will increase in the future. It is unclear whether advances in research and technology will provide adequate relief for the global water resources problem or whether even higher water scarcity may force population migration. Further investigation should be done on integrated systems of water treatment and water supply that will create a nexus between these two and with coastal aquifer management while preventing further seawater intrusion. As populations continue to grow, especially in coastal areas, water supply management will need to be optimized. Advances in technology can create a more sustainable state of water supply. Coastal hydrogeology research has advanced remarkably over the past decades. Models have evolved and become easy to use, even for nonmodelers, and more conceptual and case studies have been undertaken. RO desalination research is increasing, resulting in more accessible solutions for developing countries such as cheaper and better membranes or solar-powered facilities. Although some remarkable advances have been made in research, some fields have been neglected and the connection between academic research and assimilation of the knowledge in water organizations is still limited. Emphasized education about climate change and water scarcity must be increased globally to minimize water demand and carbon emissions. It is for us to create and implement a sustainable water supply system for the next generations and for a better world.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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