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Unveiling the factors influencing groundwater resources in a coastal environment – a review

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Abstract. The coastal environment is a dynamic and complex system where the interaction between land and sea gives rise to many challenges and opportunities. Among the critical resources in these regions, groundwater resources in a coastal environment play a vital role in sustaining human communities, ecosystems, and diverse economic endeavors. However, these resources encounter unique challenges due to the complex interaction between freshwater and saltwater interfaces, and the sustainability of coastal groundwater resources is increasingly threatened by various factors. This review highlights the factors that influence these resources to ensure their sustainable management, which sheds light on the intricate dynamics of coastal groundwater systems and for developing effective strategies to safeguard long-term availability.

Key words: coastal groundwater, groundwater resources, islands.

INTRODUCTION

Water is a dynamic resource essential to sustain life on Earth. As an integral part of the hydrological cycle, water intrudes into the soil and is retained in underground reservoirs. The main source of natural recharge of these aquifers is through the infiltration of precipitation into the ground (Roumasset & Wada, 2015). Almost 30% of the freshwater available on the earth is groundwater (Shamsudduha & Panda, 2019). Rising population, urbanization, and industrialization have increased stress on both surface water and groundwater resources (Vo, 2007; Zheng et al., 2020). Large groundwater resources or aquifers are used as additional water sources to meet the water demand. In 2010, a study by Margot and Gun reported that about 982 km^3 $year^{-1}$ of groundwater has been abstracted worldwide for drinking water supply, irrigation, and industrial water supply (Margat & Gun, 2013).

Despite covering just 20% of the Earth's surface, the coastal region is home to 41% of the global population (Martínez et al., 2007). The global average coastal population density is around 80 people per square kilometre (Dugan et al., 2011). Consequently, the water demand in these regions is increasing not only due to the rising population but also due to the increasing standards of living (Dugan et al., 2011; Abarna et al., 2023). Coastal environments are dynamic and captivating terrains where the convergence of land and sea creates a plethora of geological formations and hydrological phenomena, presenting unique challenges and opportunities. Groundwater serves as the primary source of water for rural and coastal water supply systems, often utilized without limitations to meet the growing demand in households, farms, and factories (Foster et al., 2000; Hamed et al., 2018; Prusty & Farooq, 2020).

These resources are significant in coastal environments due to their unique interrelationship between seawater and fresh groundwater. Discharge from coastal aquifers to sea may transport nutrients to support the ecosystem and influence the salinity of the coastal groundwater. Most nutrients, like phosphorus and nitrates, are carried by groundwater to the ocean surfaces (Cabral et al., 2023).

Megacities, which include large population densities, fast urbanization, and intensive human activity, are often found in coastal locations. Factors like transportation and trade options, historical or cultural value, closeness to ports and harbours for commerce, and proximity to other economic and social centres, contribute to the advantageous positioning of many coastal cities. Sufficient water supply is also essential for the effective operation of cities to fulfill their water requirements. Therefore, coastal groundwater resources are crucial to the water supply of coastal cities. However, in big coastal cities, the influence of urban growth on aquifers may be substantial, leading to the depletion of groundwater supplies, the infiltration of saline water, and a decline in water quality (Nlend et al., 2018; Prasad et al., 2021). The coastal aquifer also contributes to tourism activities in the area which help in the socio-economic development of the area. Coastal megacities exert significant pressure on the local groundwater reserves. Researching coastal regions is vital due to the resources and ecological services they offer, along with their crucial role in societal and economic development.

High islands, primarily of rugged volcanic mountains, have water from both surface water as springs and groundwater, whereas in low islands, groundwater is the main source of water (Grover, 2007). In most coastal areas, access to surface water is limited. Therefore, the main source of fresh water to support the needs of the coastal community is groundwater resources. The extent of availability of this source depends on various factors, including geology, climate, and size and shape of the area. Climate change, pollution, and overconsumption affected the groundwater quantity and quality, creating stress in most countries. These have a higher impact on the coastal community, which is already socio-economically and environmentally sensitive (Mastrocicco & Colombani, 2021).

The major reason for the degradation of groundwater is saltwater intrusion due to natural and anthropogenic activities. As sea level rise due to climate change, the water table of coastal aquifers also rises (Chang et al., 2011). This will result in the movement of the mixing zone to the inland and the tidal surges that cause the mixing of saltwater in aquifers. Whereas anthropogenic activities like over-pumping and the adoption of impermeable pavement restricted the percolation of water for the replenishment of the aquifers and degraded the quantity and quality of the aquifers (Chang et al., 2011).

Various factors affect the quality and quantity of the coastal groundwater resources aquifers. Because of the proximity to the ocean and the increase in human habitation in this fragile area, fresh groundwater is more likely to be degraded in coastal regions. Sustainable groundwater extraction is possible because, unlike other natural resources, groundwater is often a renewable resource in some parts of the globe. Identifying groundwater contamination sources and understanding the mechanisms that influence the development of groundwater quality are prerequisites for developing effective management methods whose goal is to conserve groundwater quality. To secure the long-term viability of these resources, insight into the complex dynamics and factors causing these variations in coastal groundwater systems is required (Venkatesh et al., 2021). To guarantee the sustainable availability and management of this unique resource in coastal areas, a comprehensive review of these factors is essential.

GROUNDWATER RESOURCES IN THE COASTAL ENVIRONMENT

The study of coastal groundwater has gained significant attention from researchers due to its vital role in sustaining ecosystems and supporting human activities in these regions. Understanding various formations of groundwater resources in these regions is imperative for several reasons, including sustainable water management, ecosystem preservation, and water supply systems; such understanding will help in developing effective strategies and policies to ensure the long-term availability and resilience of groundwater resources in these dynamic and valuable ecosystems.

In the subsequent session, we will delve into the vital fresh groundwater resources present in the coastal region. These sources play a key role in supplying communities with clean and accessible water by supporting the fragile ecosystems and biodiversity in the coastal areas.

Coastal Aquifer

An aquifer that extends under both land and sea is said to be a coastal aquifer. Specifically, it is in the coastal zone, which stretches between the mainland and the water. Rainfall and ocean water are the two main sources that replenish coastal aquifers, which may be confined or unconfined. Seawater is the primary distinction between coastal and inland aquifers. The composition of the aquifer medium in a region is significantly influenced by the geological formations present. The continual supply of sand from the sea, rivers (especially in river mouth locations), and wind cause most of the world's coastal aquifers to be formed of sedimentary formations (Jayasingha et al., 2014).

The coastal sandy aquifer is a specific type of coastal aquifer. It has distinct ecosystems due to the mixing of terrestrial fresh groundwater with salty groundwater from the sea, resulting in high chemical and physical gradients. Many important ecological functions, such as filtration and purification, nutrient mineralization, storage and outflow of subsurface groundwater, and functional connectivity between land and sea, are provided by sandy beaches. The groundwater in the beach aquifer is divided into three regions: an intertidal saltwater cell, where seawater is pushed through the beach under the influence of waves and tides; a zone of terrestrial freshwater; and a deep saltwater wedge. Subterranean estuaries, like those on the surface, are characterized by steep physical and chemical gradients at the interface between different water types.

Submarine groundwater discharge refers to water outflow from the beach aquifer into the coastal ocean (Archana et al., 2021).

Perched Aquifer

An isolated water body held by an impermeable barrier located above the local water table is referred to as a perched aquifer. Perched aquifers are frequently associated with impermeable strata that serve as a barrier, preventing water from passing below them and retaining it above. In areas with deep regional water tables, they are easily separated. They are mostly found in the vadose zone, the region between the surface earth to the top of the main water table. They are susceptible to contamination, changes in land use, and climatic conditions because of their shallow depth (Hamutoko et al., 2019; Prasad & Ramesh., 2019).

Dyke Impounded Aquifer

Like in the islands of Hawaii, dyke impounded aquifer is the main water source. Dykes are often found in the late phases of the volcanic cycle and are characterized by being almost vertical intrusions. Volcanic dykes have been variously characterized as draining structures or flow barriers, depending on the underlying geology. Low permeability and hard rock conditions are characteristic of where draining features are found. The high degree of dyke weathering, host rock fractures during emplacement, volcanic material contraction, and internal fractures during cooling all contribute to the unusually high permeability in these situations. In contrast, for unweathered dykes implanted in greater permeability and/or weakly consolidated host rocks, barrier features have been identified (Comte et al., 2017). When surrounded by less permeable host rock, dykes may function as preferred flow pathways. Due to their poor permeability, such dykes or dyke swarms may play a significant role in subsurface flow dynamics. Groundwater may be impounded by dykes, resulting in elevated levels like more than 600 m above sea level on the island of Hawaii and limited separation of the aquifer (Houben et al., 2018).

Freshwater Lens or Basal Aquifers

The density of fresh groundwater is typically about 1,000 kg m^{-3}, whereas the density of seawater is between 1,022 kg m^{-3} and 1,028 kg m^{-3} (Holzbecher, 1998). Due to the density differences between freshwater and saltwater, their inability to blend together results in the formation of freshwater lenses above typically saline aquifers in specific regions. These lenses play a crucial role in sustaining both human and environmental activities. Rainfall infiltration forms freshwater lenses above the salty groundwater that originates from the ocean, which may be found in coastal aquifers and on marine islands (Laattoe et al., 2017).

Coastal Karst Aquifer

One kind of coastal aquifer is the karst aquifer, which may be recognized by its location in karst landscapes, commonly in the Mediterranean basin (Bakalowicz, 2018). In many coastal areas, coastal karst aquifers are the primary or sole supply of drinking water. Karst topography is distinguished by the dissolved rocks like limestone and dolomite. Consequently, a subterranean system of caverns, channels, and fissures is formed, facilitating the smooth passage of water through the rock. Limestone has a high porosity, which facilitates the infiltration of precipitation into the underlying subsurface (González-Herrera et al., 2022). Coastal karst aquifers are key water sources, valued for their ability to naturally prevent saltwater intrusion and discharge freshwater to the communities and ecosystems, particularly in the Mediterranean basin and its surrounding regions (Larson & Mylroie, 2018a).

FACTORS INFLUENCING THE COASTAL GROUNDWATER

Understanding the factors that influence the groundwater is essential for effectively managing and conserving this valuable resource. Various factors, ranging from natural to anthropogenic as shown in Fig 1, can significantly impact groundwater behaviour and availability.

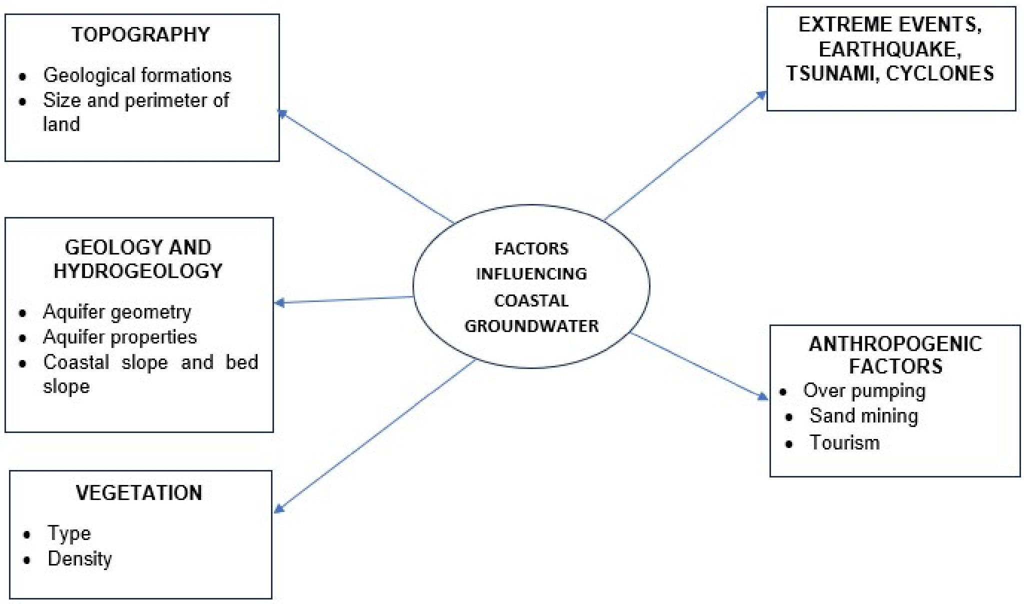

Figure 1. Factors influencing coastal groundwater.

Topography

Topography plays an important role in groundwater dynamics. In coastal areas, topography has significance in groundwater recharge, groundwater flow, and salinity. The geological formations of coastal areas determine the topographical features which helps in the groundwater flow and storage. Coastal formations like sand dunes, barriers, and karstic formations influence the groundwater storage, recharge as well as flow in a coastal aquifer.

Because of climate change-induced sea level rise, low-lying coastal communities face an increased risk of flooding. Saltwater may seep into groundwater reserves when the water table rises due to rising sea levels (Abd-Elhamid et al., 2023). There is a potential for damage to coastal groundwater resources from lateral saltwater intrusion and vertical infiltration during high tides and ocean surge inundation. The quantity of infiltrating seawater is greatly increased by depressions with ponded saltwater, and the time taken to flush the area is significantly lengthened (Yu et al., 2016).

The configuration of the flow system that forms within a freshwater lens is significantly influenced by the size of the islands present. Diffuse flow easily transports caught meteoric water from the freshwater lens to the sea if the island is small and the underlying geology contains carbonates. The area of the island responsible for meteoric catchment expands exponentially, whereas the perimeter responsible for discharging the lens expands only in a linear manner, as predicted by Mylroie and Vacher (Larson & Mylroie, 2018b).

Geology and Hydrogeology

The movement, quality, and sustainability of coastal groundwater are significantly impacted by the geological composition of the area. This can be volcanic, limestone, sedimentary, or various other types of rock in nature. Water movement along the beach and the interactions between saltwater and groundwater may be affected by the complicated groundwater flow patterns caused by geologic variability in coastal aquifers (Zamrsky et al., 2020). Submarine groundwater discharge is influenced by geology and may alter coastal water quality and geochemical cycles via passing heat, nutrients, and pollutants.

The chemical constituents of coastal groundwater are affected by both natural and anthropogenic chemical inputs, as well as the composition of the aquifer media at the time of formation and subsequent geochemical processes. The geological formation of a region largely dictates the components of the aquifer medium. The continual supply of sand from the sea, rivers, and wind causes the vast majority of the world's coastal aquifers to be formed of sedimentary formations, which tend to be shallow and unconfined (Jayasingha et al., 2014). Aquifer geometry is directly related to the aquifer width, the distance from the circle centre to the no-flow boundary, and the aquifer shape, i.e., whether the aquifer is convergent or divergent, and thus impacts the freshwater-seawater interface and water table elevation. Aquifers with a convergent shape have the least amount of seawater intrusion, while those with a divergent shape are the most susceptible. Correspondingly, the water table elevation is the lowest in divergent aquifers and highest in convergent aquifers (Luo et al., 2021).

The aquifer's permeability and storage capacity affect groundwater near the coast. The permeability and percolation of water in the system depend on the pore size of the soil. Several forms of pollutants may impair groundwater if they make their way into the surrounding aquifer from the water table or the land surface above. Because of frictional losses associated with the aquifer's permeability and poroelastic storage capacity, the pressure signal of groundwater flow is often reduced (Oberle et al., 2017). Thus, the aquifer's permeability and storage affect groundwater's response to climate and sea-level changes. Slope also affects the groundwater quality, saltwater intrusion rises with increasing coastal slope, and the length of saltwater intrusion decreases with increasing bed slope towards the land (Abd-Elhamid et al., 2019; Abd-Elaty & Polemio, 2023). Precipitation and groundwater are interconnected as rainfall is the major source for the recharge of the groundwater in coastal areas. The supply of freshwater for coastal populations is threatened by changes in precipitation patterns brought on by climate change, which may lead to extended periods of droughts and floods. In addition to seawater intrusion, rising sea levels may also push the freshwater/saltwater boundary closer to land (Bar et al., 2021).

Vegetation

The interaction between vegetation and groundwater is complex and has a significant impact on the overall health and stability of the environment. One way in which plants influence groundwater is through evapotranspiration. Evapotranspiration is the combined process of water vapour loss from the soil and transpiration from the plants. This process can reduce the amount of water available for the recharge of the aquifer. Studies have shown that evapotranspiration accounts for about 50% of water loss in coastal environments (Fahle & Dietrich, 2014).

However, vegetation can also help to maintain groundwater levels by acting as a sponge for absorbing the rainfall. It decelerates water flow towards water bodies, extending the duration of water within the soil and facilitating water percolation for recharging groundwater. Plant roots aid in stabilizing the soil, contributing to the prevention of soil erosion and supporting infiltration. The type and density of vegetation also affect the groundwater level. Coastal wetlands and mangroves help in coastal zone protection as well as in water purification (Kayalvizhi & Kathiresan, 2019). Protecting and retaining sediments from erosive processes like tides, waves, and storms, coastal vegetation, including mangroves, salt marshes, seagrasses, macroalgae, and coastal strands and dunes, are essential. These ecosystems perform vital environmental roles by filtering water and absorbing nutrients (Dugan et al., 2011).

Extreme Events

Extreme events, earthquakes, cyclones, and tsunamis affect the coastal groundwater system. These events have a long-term effect on the groundwater and need a larger recovery time to reach the before-event condition. Variations in groundwater levels can occur due to earthquakes and the ground displacements caused by the seismic activity can produce fissures in the aquifer. This may result in water entering or leaving the aquifer via such fissures. When an earthquake occurs, it may induce a pressure difference between the freshwater aquifer and the saltwater ocean below. As a result of the pressure difference, saltwater may seep into the freshwater aquifer. A study conducted in Korea by Lee reported the rise in water level and change in physical and chemical characteristics in Seacheon, due to the M5.8 earthquake and aftershock in Gyeongju, which is 241 km away (Lee et al., 2020).

Similar to earthquake, tsunami changes the aquifer characteristics. Changes in the groundwater level primarily stem from the post-event flash flood, which results in the intrusion of saltwater into the groundwater aquifer and changes the characteristics by introducing contaminants and saltwater. Following the Tohoku earthquake in March 2011 in Japan, more than 400 square kilometres of land were flooded, and both groundwater and river water were tainted by the tsunami. Although the tsunami did not cause any significant shifts in the groundwater table, but there was an increase in Cl, Na, Ca, Mg, and electric conductivity in the months after the disaster. However, the levels of Cl^- and electric conductivity experienced a sharp decline after June 2011. Additionally in June 2011, elevated concentration of Pb and Cu were detected in the regions' wells, likely transported from the seafloor of the Pacific Ocean by tsunami waves (Kaihotsu et al., 2017). While some preliminary research has been conducted on the topic of tsunami-caused groundwater contamination, no comprehensive scientific and dynamic studies spanning long periods have yet to be conducted.

Cyclones and storm surges threaten coastal groundwater resources because the precipitation and high tides they bring may cause flooding, pollution from surface runoff, and vertical saltwater intrusion (Van Biersel et al., 2007). The frequency, intensity, and duration of surges affect the groundwater. The movement of groundwater can be impacted by floods triggered by storm surges. Medium-intensity storm surges, for instance, might disrupt groundwater dynamics, hindering complete restoration even after the surge has receded. It takes time for the soil to drain and recover to its initial state after a storm. The drainage process can vary from one to ten days in the absence of such incidents. Similar to the effects of stronger tropical cyclones, moderate and more common storm surges may devastate coastal ecosystems. Plants and animals that depend on groundwater may not thrive or survive if the salinity and water table are altered (Nordio et al., 2023).

Anthropogenic factors

The rise in human settlement in the coastal region, influences the coastal aquifer, with changes in the surface and increased pumping rates. The over-pumping of coastal aquifers for agriculture, industrial use, and drinking water supply can lead to saltwater intrusion, which lowers the water table resulting in infiltration of saltwater from the ocean to the aquifer, thereby deteriorating water quality. Excessive pumping can occasionally lead to the subsidence of coastal land, allowing seawater to infiltrate the aquifer, mainly depending on the aquifer's properties such as permeability. Northern China's Yang-Dai River plain is a vital agricultural area that depends significantly on groundwater. According to studies undertaken in this area, excessive groundwater pumping has caused saltwater to seep underground, contaminating coastal groundwater and rendering it unfit for human use. Anthropogenic activities like the intensive usage of fertilizers and the construction of an anti-tide dam were found to be the primary causes of the coastal groundwater salinization in the Yang-Dai River plain (He et al., 2020; Prasad et al., 2022).

Another anthropogenic activity is coastal sand mining for heavy minerals sand comprising ores like ilmenite and iron that serves as sources of metals such as titanium, zircon, iron, monazite, and garnet. These metals find application in our day-to-day products like ceramics, paint, etc (Bisht & Martinez-Alier, 2023). Loss of land due to coastal erosion, lower water levels, and reduced sediment supply are some of the negative effects of the current rate of sand extraction, which is having a ripple effect on economic and social development in coastal and marine areas (Leal Filho et al., 2021).

Many coastal regions rely heavily on tourism, which may have serious consequences for groundwater supplies. Overexploitation of groundwater resources due to tourism-related water consumption has resulted in a drop in the water table, land subsidence, decline in groundwater quality, and potential intrusion of saltwater (Gössling, 2001). Soil subsidence and saline intrusion, caused by the overuse of water resources, pose threats to the health of coastal ecosystems and the livelihoods of both coastal residents and tourists.

The effects of tourism on coastal groundwater resources have been the subject of several studies, which have offered suggestions for more environmentally friendly approaches to industry. Land use change, global warming, rising sea levels, and abundant tourist infrastructure are all problems that demand attention. The sustainable preservation of coastal groundwater resources necessitates the adoption of practices like water preservation, efficient wastewater management, and the utilization of alternative water sources (Gössling, 2001; Pérez et al., 2020; Prasad et al., 2020).

CONCLUSIONS

In coastal areas, groundwater is a vital asset for human well-being and environmental health. However, both natural and anthropogenic activities pose significant threats to these resources, including saltwater intrusion and over-exploitation. The factors that govern the groundwater are interconnected, for instance, reduced vegetation and steeper slopes lead to increased runoff, and reduced infiltration of precipitation, thereby reducing the recharge of the aquifer followed by inland movement of saltwater.

To prevent the pressure on the groundwater resources, suitable sustainable management practices need to be adopted, and proper documentation is also needed. Significant temporal variability in water quality parameters has been observed in recent decades, especially in coastal settings; therefore, documenting the dominant scales of variation of these parameters and identifying the underlying factors causing these variations is essential for ensuring sustainable management. The ideas like coastal reservoirs also help in the beneficial use of these resources. The man-made wetlands may operate as a pollution barrier, charge aquifers, conserve water, and provide a home for species when flood water flows through them on its way to coastal reservoirs. This can aid in purifying and storing freshwater, mitigating flooding, replenishing groundwater tables, provision of nurseries for freshwater and marine fish, safeguarding coastlines, retention of sediment, establishing harbours, preserving ecological diversity, and reduction of the impacts of climate change. Lack of data, limited accessibility, and outdated information are the few factors that make the groundwater monitoring and development policy difficult. A single model governance is unfeasible, whereas various levels of operating from local to international governance are needed for successfully implementing policies. The development of new methods with more accuracy, simplicity, and less cost is needed to assess the challenges faced by groundwater resources and should be able to predict the future as the climate is changing abruptly. Suitable policies and sustainable management practices are needed to monitor and reduce the stress on these vulnerable resources ensuing their conservation for the future generations.

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