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Desalinization and Salinization: A Review of Major Challenges for Coastal Reservoirs

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ABSTRACT

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Coastal reservoirs are a possible solution to water supply and management issues in coastal zones. However, salinization can degrade the utility of such reservoirs. Two related major challenges affecting the operation of a coastal reservoir are desalinization and seawater intrusion. The former arises mainly during the period following reservoir construction, while the latter is ongoing. This review discusses the salt dynamics of coastal reservoirs under the influence of surface-water flows, river inflows, reservoir water level, and tides. Various salt transport processes are examined in relation to water salinity changes in coastal reservoirs. The methods and limitations of existing numerical models for coastal reservoirs are also discussed. Given the difficulty in reproducing realistic boundary conditions for laboratory experiments, further research needs to focus on investigations that consider salinization in real coastal reservoirs. More broadly, there remains a need to unravel the impacts of coastal reservoirs on the surrounding environment, as they can significantly change the hydrodynamics and chemical transport pathways in coastal waters. A comprehensive understanding of coastal reservoir salinization will improve water management and thus contribute to alleviating overexploitation of water resources in coastal zones.

ADDITIONAL INDEX WORDS: *Desalinization, seawater intrusion, salt transport, reservoir water dynamics.*

INTRODUCTION

In recent years, rapid economic development has exacerbated the problem of water shortages, especially in coastal plains (Herrera-León *et al.*, 2018), where meeting demands for freshwater can be a challenge (Phan *et al.*, 2018). This situation is made more complex by the irregular spatial and temporal distributions of freshwater resources in these areas. The amount of runoff (or flood water) flowing across coastal plains is typically large, but the river network has little capacity to retain this freshwater resource (Ge, 2012). An obvious benefit of coastal reservoirs is the provision of additional storage capacity of freshwater for water supply

networks (Xu, 2001). In stressed regions, coastal reservoirs can contribute to the alleviation of water shortages, which often underpins local economic development (Li and Chen, 2005).

Many coastal reservoirs have been constructed in China, South Korea, Hong Kong, and Singapore (Yuan, Yang, and Zhuang, 2007). Even so, there is no consistent definition of coastal reservoirs. In the literature, the term refers to any reservoir built on the coast, seashore, bay, beach, or river estuary. Here, a coastal reservoir is defined as a comprehensive water conservancy structure constructed within a river estuary or in other coastal areas for the storage of freshwater and control of water resources.

Despite the importance of coastal reservoirs, there is a dearth of research on this topic, with many problems yet to be resolved, the most important of which is salinization—the focus of this review.

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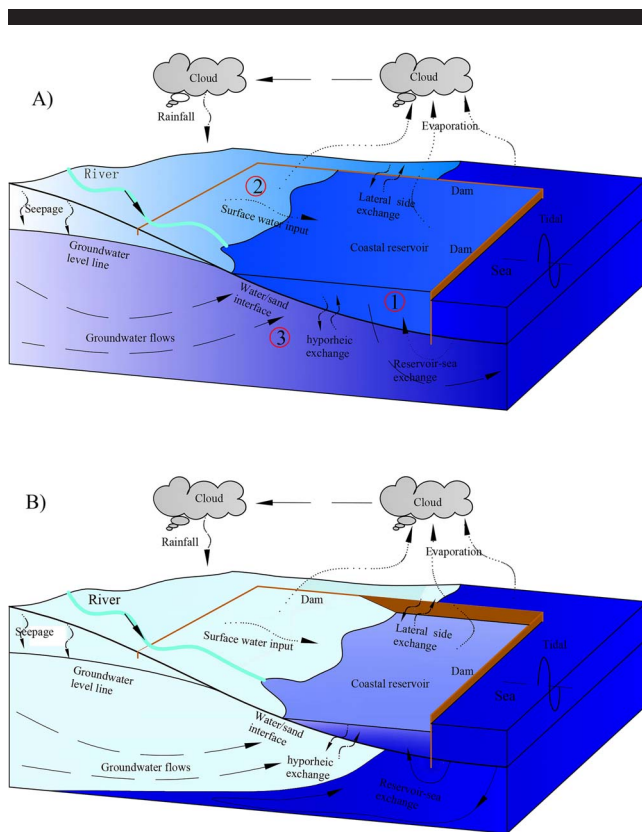


Figure 1. Coastal reservoirs in the (a) early operation stage, when reservoir water and surrounding soils/sediments contain saltwater with a relatively high salt concentration: (1) reservoir water; (2) reservoir intertidal zone; and (3) reservoir bottom sediment; and (b) during dry periods, when the reservoir water level is low, resulting in intensified seawater intrusion. The darker the blue color, the higher is the salinity. (Color for this figure is available in the online version of this paper.)

MAJOR CHALLENGES FACED BY COASTAL RESERVOIRS

In coastal reservoirs, salt transport processes vary over the different operational stages of the reservoirs' whole life cycle. In general, there are two major stages: (1) In the initial stage following the construction, desalinization dominates, as shown in Figure 1a. (2) During normal operations, seawater intrusion presents a serious threat, as shown in Figures 1b and 2. Both desalinization and saltwater intrusion, if not properly resolved, can impose a significant impact on the performance of the coastal reservoir.

Desalinization

In the context of coastal reservoirs, the definition of desalinization is the replacement of saltwater (in the reservoir or sediments) with freshwater. Desalinization is an important process in the early operational stage of a coastal reservoir. Coastal reservoirs are often constructed in a lagoon, on low-lying land, or adjacent to estuaries, separated from the seawater by a dam along the seashore. Once completed, a coastal reservoir tends to contain a small quantity of seawater, especially if the construction is through damming an area within the intertidal zone. Moreover, the sediment around the reservoir can have high salinity (Jiang and Pei, 2007). When the reservoir water level is low, the water trapped in the sediment of the intertidal zone will evaporate, leaving salt to accumulate in the sediment (Shokri-Kuehni *et al.*, 2017). In the early operation stage of a coastal reservoir, the accumulated salt can be rapidly released from the sediment to the reservoir, resulting in a significant increase in the salinity of the reservoir water, as shown in Figure 1a.

The most commonly used method for desalinization of coastal reservoirs is to drain high-concentration saline water via pumping (Mao *et al.*, 2005; Pan *et al.*, 2004; Zhu, 2002). To reduce the salinity of surrounding sediments, the method is to establish subsurface drainage systems (Chen *et al.*, 2015). In general, desalinization can significantly reduce the salinity of the reservoir water and restrict the later release of salt from

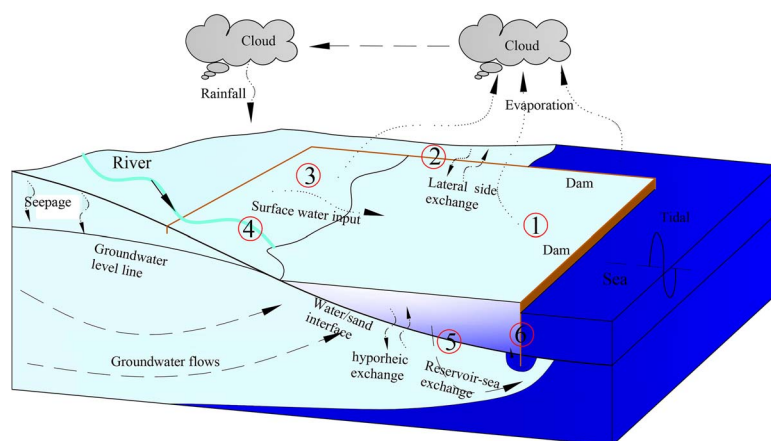


Figure 2. Schematic diagram of a typical coast reservoir: (1) water surface, (2) lateral side, (3) intertidal zone, (4) inflow rivers, (5) bottom, and (6) dam. (Color for this figure is available in the online version of this paper.)

sediments, thus improving the water quality of coastal reservoirs.

Salinization/Seawater Intrusion

It is expected that after several years of operation, most salts in the sediment have been released into the reservoir, as shown in Figure 2. Water recharge and drainage are the most important drivers for the exchange of reservoir water (Jin, Sun, and Xia, 2013). The reservoir water is in a relatively static state under normal operating conditions, resulting in a stable salinity stratification of the reservoir water. However, the exchange of reservoir water with seawater occurs not only at the bottom of the reservoir, but also at the sluices that open to the sea from time to time. In addition, overexploitation of groundwater can lead to a reduction in the groundwater level and consequently a lower hydraulic head in the (fresh) groundwater relative to that of the seawater, which may induce the intrusion of seawater into the groundwater and coastal reservoir (Wang and Zhu, 2014; Yang, Zhou, and Liu, 2004). More generally, any process leading to the aforementioned imbalance in hydraulic heads will result in intrusion of seawater into the reservoir and thus increased salinity of the reservoir water. Along with exploitation of groundwater, seawater intrusion can occur due to changes of land utilization and associated water use, climate change, and sea-level fluctuations (Svensson and Theander, 2013; Vu, Yamada, and Ishidaira, 2018; Zhou *et al.*, 2017). Seawater intrusion tends to intensify during dry periods when the reservoir water level is low, as shown in Figure 1b.

DYNAMICS OF COASTAL RESERVOIRS AND FACTORS INFLUENCING SALT TRANSPORT

As mentioned above, the reduction and control of high-salinity reservoir water are the major challenges in coastal reservoirs. The dynamics of coastal reservoirs are typically complex and may have significant impacts on the salt transport pathways. Various processes underlying coastal reservoir dynamics are presented in this section, with a focus on major factors that influence salt transport.

Dynamics of Coastal Reservoirs

The dynamic processes of coastal reservoirs are illustrated in Figure 2. Coastal reservoirs contribute significantly to alleviating water shortages in coastal areas, and they provide substantial socioeconomic and environmental benefits (Yang, 2018). Many related problems remain to be explored and resolved. In particular, the high salinity of the reservoir water occurring during dry periods reduces water availability for industry, agriculture, and domestic use (Mao *et al.*, 2004). Typically, coastal reservoirs are confined by six boundaries, with each boundary affected by factors such as: (1) water surface, where the dominant factors affecting salinity include precipitation and evaporation; and (2) lateral boundaries, influenced mainly by differences between the reservoir water and groundwater levels. These differences are influenced by terrestrial groundwater fluxes, tides, precipitation, and evaporation. In undisturbed systems, the (inland) terrestrial groundwater level is higher than sea level (accounting for density differences), leading to the discharge of terrestrial groundwater into the sea. (3) The intertidal is

zone influenced by precipitation, evaporation, and the terrestrial groundwater and reservoir water levels. The salts in the intertidal zone can be carried into the reservoir by runoff; (4) riverine inflows and variations therein; and (5) exchanges across the reservoir bed, which are influenced mainly by discharge, the water-table elevation, and reservoir levels. The salt transport in the reservoir bed on the seaward boundary is also influenced by waves and tides via circulating flow and exchange. (6) A coastal or estuary dam is influenced mainly by tides and the reservoir water level. From time to time, the reservoir water can be discharged into the sea through the dam.

It is evident that the boundary conditions of coastal reservoirs are potentially very complex and affected by a variety of factors, including the aforementioned precipitation, evaporation, river flow, terrestrial groundwater level, reservoir water level, waves, and tides. As a consequence, the resulting hydrodynamic and salt transport processes in the reservoir are also complex. This underscores the need for a better understanding of the hydrodynamic processes of the coastal reservoirs and factors influencing salt transport.

Factors Influencing the Hydrodynamics and Salt Transport in Coastal Reservoirs

Salinity is among the most important factors in determining the water quality of coastal reservoirs. Custodio (1987a,b) summarized in a qualitative manner the factors influencing seawater intrusion, including dispersive mixing, tides, density differences, and human factors. Only some of these factors have been investigated previously, and much remains to be examined, both experimentally and theoretically, for a better understanding of salt transport in coastal reservoirs. Various dynamic factors have been implicated in water/salt exchange across different boundaries, as shown in Figure 1 and discussed in the following.

Meteorological Conditions

Meteorological conditions have a considerable influence on the salinity of the reservoir water. Precipitation and evaporation affect the amount of water flowing into or out of the reservoir (Berghuijs *et al.*, 2017), which in turn influences the salinity of the reservoir water. Recharge of the reservoir by precipitation leads to a reduction in the salinity of the reservoir water, whereas evaporation leads to a salinity increase (Pan *et al.*, 2004). In addition, the salt in the bare intertidal zone of the reservoir can be dissolved and then brought into the reservoir by runoff, increasing the reservoir water salinity.

Sediment and Intertidal Zone

The reservoir bed usually contains sediments with high salt concentrations (Zhang *et al.*, 2014), which can contribute to salinization of the reservoir water mainly at the early (postconstruction) stage rather than in the normal operational stage (Mao *et al.*, 2005). External influences can drive exchanges of water between sediments and overlying water, leading to release of salt from the sediment to the reservoir (Zhu, 2002). The intertidal zone around the reservoir may also have a high salt concentration, potentially producing salt loads to the reservoir and causing salinization of the reservoir water.

Upstream Rivers

The water quantity and quality of the upstream rivers, as the main water source of the reservoir, play a critical role in controlling the salinity of the reservoir water. River flow may also bring a large quantity of sediment into the reservoir. Moreover, coastal reservoirs, which typically receive waters from long distances upstream, can be susceptible to pollution, associated with inputs of industrial and domestic wastewater containing high loads of saline and contaminated materials (Li and Chen, 2005).

Saltwater-Freshwater Mixing Rate

Water exchanges are the norm in coastal reservoirs, the rates of which vary considerably depending on the incoming water, wind, and reservoir depth. In general, high-velocity inflows, high wind speeds, and shallow water depths are conducive to complete mixing within the reservoir, and possibly exchanges between the reservoir water and underlying sediments (Liu and Jeng, 2007). In deeper lakes, full mixing across the water column is limited by stable thermal stratification (especially during summer) and salinity-controlled stratification (Yeates and Imberger, 2003), which limits vertical mixing and exchanges (Li and Chen, 2005). Coastal reservoirs will typically have long-lasting high-salinity pools at the reservoir bed, particularly in bed depressions (Pan *et al.*, 2004).

Seawater Leakage

Seawater leakage depends to a large extent on engineering design and quality of the reservoir dam construction (Lee *et al.*, 2005). For instance, at a coastal reservoir with an earth dam, tidal loading imposes a pressure on the dam, causing seawater leakage and consequently high salinity of the reservoir water (Yu, 1996).

Exchange between Coastal Reservoir and Groundwater

Water/salt exchange occurs mainly at the lateral sides, bed, and sea side of the reservoir (Figure 1). The exchange between coastal reservoir and groundwater has not been studied adequately. However, previous studies on exchange between coastal lagoons and groundwater provide insights into coastal reservoir and groundwater interactions because of the similarity in boundary conditions between the two cases (Moran *et al.*, 2014).

Coastal Reservoir and Lateral Side Groundwater

The aquifer(s) adjacent to a coastal reservoir can discharge groundwater into the reservoir or receive water from it, depending on the head difference across the reservoir-aquifer boundary. The aquifer water quality is irrelevant when the reservoir discharges to the aquifer, although leakage of reservoir water may be undesirable. Generally speaking, the aquifer hydraulic head fluctuates less than the reservoir head; the latter responds to oscillations of reservoir inflow and outflow. During periods when the reservoir water level is reduced, and aquifer water flows into the reservoir, the salinity of the inflow affects the reservoir water quality, depending on the amount of the inflow (Wu, Li, and Li, 2010). In practice, the exchange capacity (lateral side groundwater fluxes into and out of the reservoir) depends largely on the relative position of the reservoir and the season. Cheng and Anderson (1994) showed

that a lower position of the reservoir leads to a higher and more stable exchange capacity between the reservoir and lateral side groundwater. As the season changes, the exchange capacity also varies.

Coastal Reservoir and Underlying Groundwater

Exchange between coastal reservoir (overlying) water and underlying groundwater can also occur. A pressure gradient may be induced at the water-sediment interface by waves (Boano, Revelli, and Ridolfi, 2011; Hsu and Jeng, 1994), and by interactions between reservoir water flow and reservoir bed forms, producing circulating flow and advective solute transport across the interface (Jin *et al.*, 2010). In addition, when the salinity/density of the coastal reservoir water is higher than that of underlying groundwater, density gradients drive flow, which in turn leads to the exchange (Jin *et al.*, 2011). Evaporative losses can increase the surface salinity of the coastal reservoir water (Sumner and Belaineh, 2005), resulting in downward convection to the bottom of the coastal reservoir, and further to the underlying groundwater. This has been observed to dramatically increase the groundwater salinity (Yang and Ferguson, 2010). Density-driven flow accelerates the transport of salinity from the sediment into the underlying groundwater and impedes the release of salt into the coastal reservoir water (Jin *et al.*, 2015).

Coastal Reservoir and Submarine Groundwater

Submarine groundwater is rich in salt, and thus it is a major source of the salinity for a coastal reservoir. Although the dam can prevent seawater flow into the reservoir directly, exchange between the coastal reservoir and submarine groundwater can occur, which affects salinization of the reservoir water (Xie, 2015). For a better understanding of field-scale interactions between submarine groundwater and reservoir/lagoon water, Ji *et al.* (2013) studied a lagoon located in Hainan, China, and found that the exchange between submarine groundwater and the lagoon also contributed to the high levels of nutrients in the reservoir/lagoon water.

In conclusion, the exchange between coastal reservoirs and groundwater plays an important role in salt transport, and thus it can greatly affect the desalinization and salinization of coastal reservoirs.

Subsidiary Functions of Coastal Reservoirs

Coastal reservoirs have been utilized for a variety of purposes other than water supply, such as aquaculture, shipping, irrigation, and drainage (Parthasarathy, Sitharam, and Kola-thayar, 2018), which may lead to an increase in the salinity of the reservoir water (Ge, 2012). For instance, the feed for aquaculture often contains a large quantity of nutrients. The sluices will be opened to the ocean, resulting in an influx of seawater into the reservoir.

PREVIOUS STUDIES ON SALT TRANSPORT IN COASTAL RESERVOIRS

Salinity is the key factor that influences the quality of reservoir water. In the following section, discussions regarding the salt transport in coastal reservoirs/lagoons are presented in three parts: (1) desalinization; (2) salinization/seawater intrusion; and (3) numerical simulation.

Desalinization

It is necessary to consider the desalinization of not only reservoir water, but also surrounding sediment, as salt contained in the sediment and intertidal zone can be transported into the reservoir.

Salt-rich sediments in the reservoir bed have been considered as the main cause of salinization of reservoir water. In the early operation stage, the surface water of the reservoir can be desalinized to produce freshwater suitable for human consumption, irrigation, industrial use, and a variety of other uses (salinity < 0.45‰) in rainy seasons. Mao *et al.* (2004) simulated the desalinization process in a coastal reservoir. The simulation results showed that the influx of freshwater runoff led to a rapid decrease in the surface-water salinity during the impounding period, whereas the salinity remained high at the bottom of the reservoir, especially in the deep pools, where water was hardly desalinated. Due to the stable density profile, the deep pools, if not disturbed, have no effect on the salinity of the upper water layer. However, when the reservoir water level is low, and the reservoir water may be easily disturbed, the high-concentration saltwater at the bottom will flow upward to the upper water layer, leading to the salinization of the surface water and consequently an adverse effect on water quality and availability for industry, agriculture, and domestic uses (Mao *et al.*, 2004). For instance, salinity in the Datanggang and Huchengang Reservoirs in Zhejiang Province, China, has been declining since the reservoir construction 20 years ago (Jin and Xiang, 2015; Wang and Zhu, 1998; Zhu, 2002). However, the salinity in these reservoirs remains at a relatively high level and fluctuates significantly over time. The amount of salt released from the bottom sediment is affected by various factors, including wind, pH, overlying water level, and temperature (Zhang, Zhu, and Zheng, 2010). Zhao *et al.* (2006) showed from a hydrodynamic perspective that wind-induced vertical and horizontal circulation enhanced the diffusion of salinity from sediments into the reservoir water.

In coastal areas, salt can accumulate in the intertidal zone due to the combined influence of high groundwater level, capillarity, and evaporation (Hughes, Binning, and Willgoose, 1998). Wang *et al.* (2007) found that factors such as evapotranspiration, temperature, hydraulic conductivity, tides, and seawater salinity lead to the formation of salt barrens/flats. In addition, the mean high tide sea level (Stumpf and Haines, 1998) and tidal range control the maximum salinity location and hypersaline zone width, respectively, in salt marshes (Yuchping *et al.*, 2004). Zhang *et al.* (2014) showed that the degree of salinization of reservoir sediment decreased vertically with depth up to 1 m due to evaporation, remained largely unchanged between 1 m and 4 m, and then increased with depth due to saline groundwater. This phenomenon has also been observed in newly reclaimed areas (Lin, 2009). Sediment salinity data from the Xuanmen coastal reservoir showed that the desalinization rate (ratio of measured salinity to original salinity) reached 45% in the 3 years after construction and 80% 20 years later. In conclusion, desalinization is particularly evident in the early operational stage of a reservoir.

The exchange between sediment and overlying water resulting from external disturbance may enhance the release of salt. Yue *et al.* (2013) investigated the mechanism of abrupt

salinization in estuary reservoirs by evaluating the changes of salt concentration and amount in the water column during rapid disruption of stratified water. The results showed that the mixing of saltwater in the benthic boundary layer with freshwater in the top layer led to salinization, while the solutes released from the shallow sediments under the disruption conditions provided additional sources of salt. Through laboratory experiments, Xiang *et al.* (2008) showed that the amount of salt released from sediment was relatively high at the initial stage and decreased with time. An exponential relationship was found between the salt release rate and sediment salinity.

The variations and stratification of salinity have also been investigated through soil column and tank tests. Gao, Zheng, and Wu (2006) found a saline zone of 7.5 cm thickness above the water-sediment interface due to diffusion, and they found that the salt concentration in this area was relatively low and constant. However, the salinity increased gradually over time, resulting in the stratification of salinity over the water-sediment interface. The tank tests showed an abrupt change in the salinity concentration in the water 3 cm above the water-sediment interface (110–114 g/L below the interface and much lower above the interface). The release of salt decayed exponentially, and it decreased in order of silty clay, medium-fine sand, and pelitic silt. Li *et al.* (2014) showed a salinity variation zone (diffusion boundary layer) in the water 10 cm above the sediment-water interface.

After the construction of coastal reservoirs, the desalinization rate, which on average scales with the reservoir flushing time, controls the earliest time for the coastal reservoir to be put into use. Li (2016) found that the tidal period has an effect on the desalinization process in a coastal reservoir. Longer periods lead to increased water salinity, as well as greater saltwater intrusion through the reservoir bed, which subsequently reduces the rate of desalinization. There have been few empirical studies on the salinity transport under complex hydrodynamic conditions, and so the timescale for reservoir flushing is probably unknown with any precision in practice.

Salinization/Seawater Intrusion of Coastal Reservoirs

Despite considerable progress in understanding of seawater intrusion, many questions remain to be answered. Previous studies in this field focused on the rational and sustainable utilization of coastal groundwater (Ge, 2012). At the same time, understanding and quantification of relevant processes, measurements, and coastal reservoir simulations need to be improved (Svensson and Theander, 2013).

The occurrence of the seawater intrusion depends on the estuarine hydrogeological conditions of the coastal reservoir (Lin and Liu, 2014). Reservoir water level, inflow flux, groundwater flow, and seasonal changes affect seawater intrusion (Pham and Lee, 2015; Sappa *et al.*, 2015; Xie, 2015). Seawater intrusion into the reservoir is more likely to occur when the reservoir water level is low during dry periods (Song, 2014). Sun *et al.* (2008) showed that the seawater intrusion into the Qingcaosha coastal reservoir (Yangtze River estuary) could be alleviated with large volumes of freshwater discharged from the Three Gorges Dam. Overexploitation of groundwater led to an increase in the zone of groundwater depression, and thus an

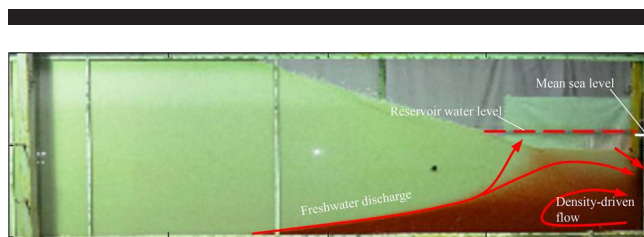


Figure 3. Schematic diagram of seawater intrusion into coastal reservoirs, showing tidal influence on seawater-freshwater mixing. (Color for this figure is available in the online version of this paper.)

increase in the extent of seawater intrusion due to the hydraulic gradient. Rimmer (2003) found that coastal aquifer seawater intrusion produces input of saline water to Lake Kinneret (Israel) through the bed. Seawater intrusion increases with rising sea level and/or decreasing reservoir water level (Fujinawa *et al.*, 2009; Yuan *et al.*, 2011). In a modeling study, Hong and Shen (2012) investigated the effect of potential sea-level rise in Chesapeake Bay, the largest estuary in North America. They found that salt content, salt intrusion length, and stratification all showed an increasing trend with sea-level rise. Moreover, the stratification is more prominent in spring (following high-flow periods) and in wet years than in autumn (following low-flow periods) and in dry years. Vanek (1993) showed that the water quality of a coastal pond was affected by occasional upwelling of underground saltwater through its bottom. Franco *et al.* (2009) found that there was a seasonal change in seawater intrusion in the southern Venice Lagoon. In autumn-winter, the intrusion front was landward biased, and in spring-summer season, it moved seawards. Hussain and Javadi (2016) showed that the extent of seawater intrusion in flat-bottomed sloped aquifers is greater than that in steep-bottomed sloped aquifers. Furthermore, flat-bottomed sloped aquifers need shorter durations to reach steady state than steep-bottomed sloped aquifers. This occurs because the seawater-freshwater circulation and terrestrial groundwater-level fluctuations are more stable in such aquifers than that in steeply sloped aquifers. Mahmoodzadeh and Karamouz (2017) indicated that the extent of seawater intrusion was significantly intensified due to coastal storms, and that the extent of seawater intrusion could be enhanced by the topographic depressions.

The intrusion of seawater into coastal reservoirs is relatively simple if the effects of tides are not considered (Zhang, Volker, and Lockington, 2001). Recent experiments showed that the saltwater wedge in a coastal reservoir's surrounding sediment can be described analytically using catastrophe interface theory (Koussis, Mazi, and Destouni, 2012). For instance, the saltwater wedge in the absence or presence of a coastal reservoir can be well described by the analytical solution of Glover (1959) or Anwar (1983), respectively. However, the sea surface fluctuates periodically under the effect of tides (Robinson, Li, and Barry, 2007) (low-frequency waves) and waves (Xin *et al.*, 2010) (high-frequency waves), resulting in complex hydraulic and salt concentration fields in the aquifer (Mulligan, Langevin, and Post, 2011). Xie (2015) found that seawater intrusion occurs at the base of the aquifer under the

reservoir bed, where an upper salt wedge is formed. Seawater intrusion at these locations varies with tidal amplitude. Higher amplitudes increase the extent of seawater intrusion and the size of the upper salt wedge. Kuan *et al.* (2012) showed by experiments that tidal oscillations caused: (1) groundwater-level fluctuations in the nearshore aquifer; (2) intrusion of the saltwater wedge; and (3) mixing of seawater with groundwater. They interacted with each other and constituted a complex saltwater-freshwater interface known as a "subterranean estuary" (a mixing zone between the terrestrial groundwater and seawater in analogy to a "surface estuary") (Moore, 1999). Chen, Zhu, and Wang (2013) showed that there was a significant difference in the intensity of seawater intrusion between summer and winter, which could be a result of the seasonal change in the runoff, whereas the tidal effects caused changes in the salinity. In addition, a statistical model was established to predict the reservoir water salinity. Jin, Xie, and Kuan (2015) also showed experimentally that tides promoted the formation of high-salinity areas, and as the groundwater flow increased, the extent of seawater intrusion decreased, as shown in Figure 3 (Xie, 2015).

Numerical Simulations

Mao *et al.* (2004) simulated the water desalination process in a coastal reservoir using Delft3D. Although there has been no attempt to simulate the coupled problem of coastal reservoir surface water-groundwater, corresponding coupled models have been developed for salt marshes (Allen, 2004; Moffett *et al.*, 2012). Xin *et al.* (2009) simulated tidally driven pore-water flows as influenced by crab burrows in salt marshes. The results indicated that the presence of an underlying sand layer with a high permeability leads to the lowering of the water table in the upper mud layer during the ebb tide. Chen (2014) analyzed the residence time of saltwater intrusion in the Qingcaosha reservoir in the Yangtze River estuary using a three-dimensional (3-D) numerical model. The reservoir was divided into six regions because of significant spatial differences in the residence time. The results indicated that the flow in the reservoir was controlled mainly by the wind-driven current, and to a lesser extent by the inlet/outlet current.

There is a mismatch between surface-water and groundwater models in terms of timescales. The timescale of groundwater models is inversely proportional to the transmissibility coefficient of the aquifer, and it is typically several orders of magnitude greater than that of surface-water models. Existing integrated surface-water-groundwater models can be distinguished based on the spatial dimensions (one, two, or three dimensions) used to describe the surface-water and groundwater flows. Surface-water flow is often described by one-dimensional (1-D) equations for channel flow (Spanoudaki, Stamou, and Nanougiannarou, 2009), and sometimes by two-dimensional 2-D equations for overland flow (*e.g.*, MOD-HMS; Panday and Huyakorn, 2004). Liang, Falconer, and Lin (2007) simulated the variations of lagoons by simultaneously solving surface-water and groundwater equations. Because the time step was controlled by the surface-water model, the simulation was very time-consuming. Spanoudaki, Stamou, and Nanougiannarou (2009) proposed a new surface-water-groundwater

model, combining the 3-D saturated groundwater flow equation and the Navier-Stokes equations for surface-water flow. Simultaneous solution was achieved by integrating governing equations at the interface between the surface water and groundwater, with improved computational efficiency. However, a finite-difference method was used for the solution of the governing equations, and thus the selection of computational grids and time steps was limited. In addition, salt transport was not considered in this integrated model, making it difficult to use for the analysis of salt transport associated with the hydrodynamics in the coastal reservoirs.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Coastal reservoirs are a new type of water storage and management project around the world that can significantly alleviate the freshwater shortage problem in coastal zones. This review pointed out two major challenges faced by coastal reservoirs (desalinization and salinization), discussed the various coastal reservoir dynamics and factors influencing salt transport, and presented the knowledge gaps on salinization, desalinization, and numerical simulation. Research on coastal reservoirs remains in its infancy; to improve understanding and utilization of coastal reservoirs, much work remains to be done, including the following:

The hydrodynamics of the reservoir surface water and groundwater require further investigation, especially the hydrodynamics near the six boundaries as discussed in this review. Knowledge of hydrodynamics is essential for better understanding of the salinity transport process in coastal reservoirs.

Future research should explore the mechanism and processes underlying salt transport that lead to the desalinization of the reservoir water and surrounding soils or seawater intrusion. These mechanisms and processes determine to a large extent the water quality of the reservoir.

The 3-D coupled models of reservoir water, seawater, and groundwater under complex dynamic conditions (*i.e.* seasonal changes or storm surges) should be developed for integrated simulation of the behavior of coastal reservoirs.

The impacts of coastal reservoirs on the surrounding environment need to be investigated. The impoundment of a reservoir may reduce saltwater intrusion into coastal aquifers. At the same time, pollutants produced by, for example, aquaculture in coastal reservoirs may enter the surrounding groundwater and affect the water environment of the coastal zone.

The influence of coastal reservoirs on aquatic ecology remains unknown and requires much research. Aquatic organisms, especially those living on the beach, can be significantly affected due to the presence of a coastal reservoir. In addition, the desalinization of the groundwater may also affect the growth of these aquatic organisms.

Laboratory experimental results may not be generalizable for real-world settings. It is necessary to undertake both laboratory and field experiments to investigate the problems and possible solutions.

The influence of sluices and dams needs further research. Seawater leakage may occur at the sluices and dams of the

reservoir and thus lead to changes in the salinity of the reservoir water.

Coastal reservoirs need to be rationally utilized. The following aspects may be important for seawater intrusion: (1) the depth of the dam, (2) the maximum and minimum operation water level of the reservoir, both of which, although irrelevant to the safety of the reservoir, affect the water quality of the reservoir; and (3) control of effects of desalinization based on hydrodynamic processes.

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