Journal of Coastal Research | 35 | 3 | 664–672 | Coconut Creek, Florida | May 2019

www.JCRonline.org

www.cerf-jcr.org

REVIEW ARTICLES

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

Guangqiu Jin[†‡], Yuming Mo[†‡], Mengdi Li[§], Hongwu Tang[†‡*], Yongzheng Qi[†††], Ling Li[‡‡], and D.A. Barry[§§]

[†]Hydrology and Water Resources and Hydropower Engineering
State Key Laboratory
Hohai University
Nanjing 210000, China

[‡]College of Water Conservancy and Hydropower
Engineering
Hohai University
Nanjing 210029, China

[§]Minhang District Drainage Management Office
Shanghai 201100, China

[††]Faculty of Civil Engineering and Architecture
Jiangsu University of Science and Technology
Zhenjiang 212000, China

[‡‡]National Center for Groundwater Research and Training
School of Civil Engineering
University of Queensland
St. Lucia 4000, QLD, Australia

[§§]Laboratoire de Technologie Ecologique (ECOL), Institut
d'Ingénierie de l'Environnement (IIE), Faculté de
l'Environnement Naturel, Architectural et Construit (ENAC),
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Lausanne 1015, Switzerland

ABSTRACT

Jin, G.; Mo, Y.; Li, M.; Tang, H.; Qi, Y.; Li, L., and Barry, D.A., 2019. Desalinization and salinization: A review of major challenges for coastal reservoirs. *Journal of Coastal Research,* 35(3), 664–672. Coconut Creek (Florida), ISSN 0749-0208.

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.

DOI: 10.2112/JCOASTRES-D-18-00067.1 received 4 May 2018; accepted in revision 1 October 2018; corrected proofs received 20 December 2018; published pre-print online 30 January 2019.

*Corresponding author: hwtang@hhu.edu.cn

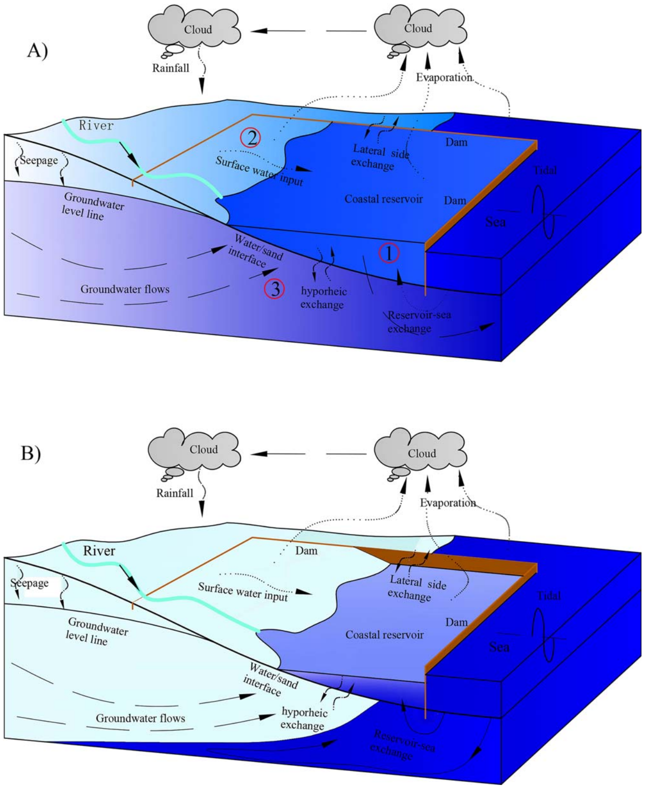

Figure 1. Coastal reservoirs in the (a) early operation stage, when reservoir water and surrounding soils/sediments contain saltwater with a relatively high salt concentration: (1) reservoir water; (2) reservoir intertidal zone; and (3) reservoir bottom sediment; and (b) during dry periods, when the 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

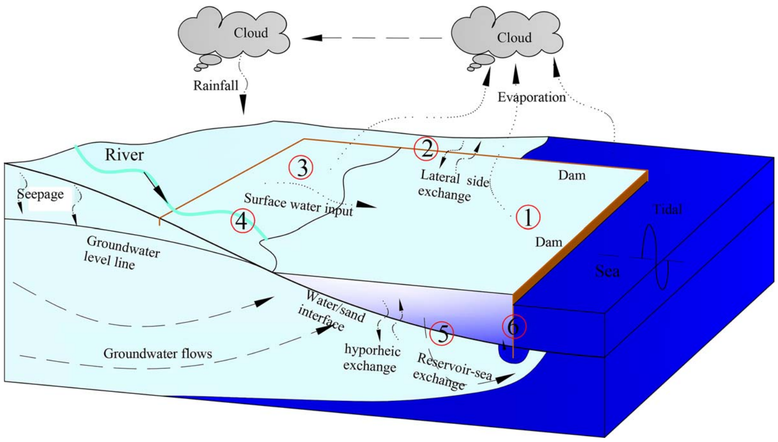

Figure 2. Schematic diagram of a typical coast reservoir: (1) water surface, (2) lateral side, (3) intertidal zone, (4) inflow rivers, (5) bottom, and (6) dam. (Color for this figure is available in the online version of this paper.)

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 Kolathayar, 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

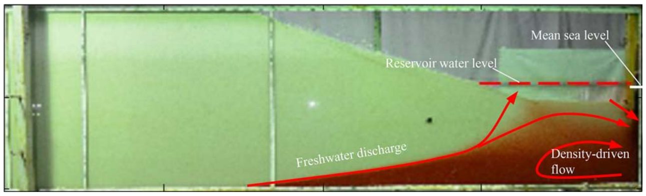

Figure 3. Schematic diagram of seawater intrusion into coastal reservoirs, showing tidal influence on seawater-freshwater mixing. (Color for this figure is available in the online version of this paper.)

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 desalinization 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.

ACKNOWLEDGMENTS

This research was supported by the Natural Science Foundation of China (51421006, 51479069, 51279056) and the 111 Project (B17015), Ministry of Education and State Administration of Foreign Experts Affairs, P.R. China.

LITERATURE CITED

Allen, J.R.L., 2004. Salt marsh morphodynamics: An investigation of tidal flows and marsh channel equilibrium. *Journal of Coastal Research,* 20(1), 301–316. doi:10.2112/1551-5036(2004)20[301:SMMAIO]2.0.CO;2

Anwar, H.O., 1983. The effect of a subsurface barrier on the conservation of freshwater in coastal aquifers. *Water Research,* 17(10), 1257–1265. doi:10.1016/0043-1354(83)90250-6

Berghuijs, W.R.; Larsen, J.R.; Van Emmerik, T.H.M., and Woods, R.A., 2017. A global assessment of runoff sensitivity to changes in precipitation, potential evaporation, and other factors. *Water Resources Research,* 53(10), 8475–8486. doi:10.1002/2017WR021593

Boano, F.; Revelli, R., and Ridolfi, L., 2011. Water and solute exchange through flat streambeds induced by large turbulent eddies. *Journal of Hydrology,* 402(3–4), 290–296. doi:10.1016/j.jhydrol.2011.03.023

Chen, J., 2014. Current Field, Residence Time and Sources of Saltwater Intrusion at the Water Intake of Qingcaosha Reservoir. Shanghai, China: East China Normal University, Master's thesis, 128p.

Chen, L.; Yang, X.; Guo, X.P., and Huang, D., 2015. The design and application of subsurface drainage pipe system for coastal zones. *Jiangsu Agricultural Sciences,* 43(9), 464–467. doi:10.15889/j.issn.1002-1302.2015.09.146

Chen, L.; Zhu, J.R., and Wang, B., 2013. Study on statistical model of saltwater invasion in Chenhang Reservoir, Changjiang Estuary. *Water & Wastewater Engineering,* 39(7), 162–165. doi:10.13789/j.cnki.wwe1964.2013.07.003

Cheng, X. and Anderson, M.P., 1994. Simulating the influence of lake position on groundwater fluxes. *Water Resources Research,* 30(7), 2041–2049. doi:10.1029/93WR03510

Custodio, E., 1987a. Salt–fresh water interrelationships under natural conditions. *In*: Custodio, E. and Bruggeman, G.A. (eds.), *Ground Problems in Coastal Areas*. Paris: UNESCO, pp. 14–96.

Custodio, E., 1987b. Effects of human activities on salt–fresh water relationships in coastal aquifers. *In*: Custodio, E. and Bruggeman, G.A. (eds.), *Ground Problems in Coastal Areas*. Paris: UNESCO, pp. 97–117.

Franco, R.D.; Biella, G.; Tosi, L.; Teatini, P.; Lozej, A.; Chiozzotto, B.; Giada, M.; Rizzetto, F.; Claude, C., and Mayer, A., 2009. Monitoring the saltwater intrusion by time lapse electrical resistivity tomography: The Chioggia test site (Venice Lagoon, Italy). *Journal of Applied Geophysics,* 69(3), 117–130. doi:10.1016/j.jappgeo.2009.08.004

Fujinawa, K.; Iba, T.; Fujihara, Y., and Watanabe, T., 2009. Modeling interaction of fluid and salt in an aquifer/lagoon system. *Ground Water,* 47(1), 35–48. doi:10.1111/j.1745-6584.2008.00482.x

Gao, Z.W.; Zheng, X.L., and Wu, J.W., 2006. Experimental studies on salt exchange between freshwater and sediments in a polder reservoir. *Advances in Water Science,* 17(2), 170–175. doi:10.14042/j.cnki.32.1309.2006.02.004

Ge, X.P., 2012. Layout optimization of freshwater-storage projects in coastal reclamation areas. *Journal of Economics of Water Resources,* 03(8), 51–53. doi:10.3969/j.issn.1003-9511.2012.03.013

Glover, R.E., 1959. The pattern of fresh-water flow in a coastal aquifer. *Journal of Geophysical Research,* 64(4), 457–459. doi:10.1029/JZ064i004p00457

Herrera-León, S.; Lucay, F.; Kraslawski, A.; Cisternas, L.A., and Gálvez, E.D., 2018. Optimization approach to designing water supply systems in non-coastal areas suffering from water scarcity. *Water Resources Management,* 32(7), 2457–2473. doi:10.1007/s11269-018-1939-z.

Hong, B. and Shen, J., 2012. Responses of estuarine salinity and transport processes to potential future sea-level rise in the Chesapeake Bay. *Estuarine Coastal & Shelf Science*, 104–105, 33–45. doi:10.1016/j.ecss.2012.03.014

Hsu, J.R.C. and Jeng, D.S., 1994. Wave-induced soil response in an unsaturated anisotropic seabed of finite thickness. *International Journal for Numerical and Analytical Methods in Geomechanics*, 18(11), 785–807. doi:10.1002/nag.1610181104

Hughes, C.E.; Binning, P., and Willgoose, G.R., 1998. Characterisation of the hydrology of an estuarine wetland. *Journal of Hydrology,* 211(1–4), 34–49. doi:10.1016/S0022-1694(98)00194-2

Hussain, M.S. and Javadi, A.A., 2016. Assessing impacts of sea level rise on seawater intrusion in a coastal aquifer with sloped shoreline boundary. *Journal of Hydro-environment Research,* 11, 29–41. doi:10.1016/j.jher.2016.01.003

Ji, T.; Du, J.; Moore, W.S.; Zhang, G.; Su, N., and Zhang, J., 2013. Nutrient inputs to a lagoon through submarine groundwater discharge: The case of Laoye Lagoon, Hainan, China. *Journal of Marine Systems,* 111–112(2), 253–262. doi:10.1016/j.jmarsys.2012.11.007

Jiang, C.L. and Pei, H.F., 2007. Reasons of water salinization and its prevention measures in Beitang Reservoir, Tianjin City. *Journal of Lake Sciences,* 19(4), 428–433.

Jin, D.G.; Sun, Y., and Xia, S.S., 2013. Study on the accelerating desalinization methods in coastal reservoir. *Zhejiang Hydrotechnics,* 41(1), 17–19. doi:10.13641/j.cnki.33-1162/tv.2013.01.008

Jin, G.Q.; Tang, H.W.; Gibbes, B.; Li, L., and Barry, D.A., 2010. Transport of nonsorbing solutes in a streambed with periodic bedforms. *Advances in Water Resources,* 33(11), 1402–1416. doi:10.1016/j.advwatres.2010.09.003

Jin, G.Q.; Tang, H.W.; Li, L., and Barry, D.A., 2011. Hyporheic flow under periodic bed forms influenced by low-density gradients. *Geophysical Research Letters,* 38(22), L22401.1–L22401.6. doi:10.1029/2011GL049694

Jin, G.Q.; Tang, H.W.; Li, L., and Barry, D.A., 2015. Prolonged river water pollution due to variable-density flow and solute transport in the riverbed. *Water Resources Research,* 51(4), 1898–1915. doi:10.1002/2014WR016369

Jin, R.H. and Xiang, Q.F., 2015. Design of the pump stations in Huchenggang reservoirs. *China Water Transport,* 15(01), 311–312.

Jin, G.Q.; Xie, T.Y., and Kuan, W., 2015. Effects of tide on salt intrusion: Experimental setup and methods. *Research and Exploration in Laboratory,* 34(02), 57–61. doi:10.3969/j.issn.1006-7167.2015.02.015

Koussis, A.D.; Mazi, K., and Destouni, G., 2012. Analytical single-potential, sharp-interface solutions for regional seawater intrusion in sloping unconfined coastal aquifers, with pumping and recharge. *Journal of Hydrology,* 416(2), 1–11. doi:10.1016/j.jhydrol.2011.11.012

Kuan, W.K.; Jin, G.Q.; Xin, P.; Robinson, C.; Gibbes, B., and Li, L., 2012. Tidal influence on seawater intrusion in unconfined coastal aquifers. *Water Resources Research,* 48(2), 136–149. doi:10.1029/2011WR010678

Lee, J.Y.; Choi, Y.K.; Kim, H.S., and Yun, S.T., 2005. Hydrologic characteristics of a large rockfill dam: Implications for water leakage. *Engineering Geology,* 80(1–2), 43–59. doi:10.1016/j.enggeo.2005.03.002

Li, M.D., 2016. Influence of Desalinization in the Coastal Reservoir Bottom Under Land Groundwater. Nanjing, China: Hohai University, Master's thesis, 79p.

Li, H.N. and Chen, F.X., 2005. Analysis of water desalting influence factor in tidal land reservoir. *Water Resource & Hydropower of Northeast China,* 23(10), 42–44. doi:10.3969/j.issn.1002-0624.2005.10.020

Li, H.M.; Chen, J.J.; Li, Y., and Li, Q., 2014. Law of salt release at soil-water interface in Beidagang reservoir. *South-to-North Water Transfers and Water Science & Technology,* 12(3), 47–50. doi:10.13476/j.cnki.nsbdqk.2014.03.010

Liang, D.F.; Falconer, R.A., and Lin, B.L., 2007. Coupling surface and subsurface flows in a depth averaged flood wave model. *Journal of Hydrology,* 337(1), 147–158. doi:10.1016/j.jhydrol.2007.01.045

Lin, Y., 2009. The forecast analysis of the rate of soil desalinization and groundwater desalting. *Ground Water,* 31(2), 38–39. doi:10.3969/j.issn.1004-1184.2009.02.013

Lin, G.H. and Liu, J.P., 2014. Present situation and treatment of seawater intrusion in Dalian City. *Water Resources and Hydropower of Northeast China,* 32(07), 32–34. doi:10.14124/j.cnki.dbslsd22-1097.2014.07.031

Liu, H. and Jeng, D.S., 2007. A semi-analytical solution for random wave-induced soil response and seabed liquefaction in marine sediments. *Ocean Engineering,* 34(08), 1211–1224. doi:10.1016/j.oceaneng.2006.07.004

Mahmoodzadeh, D. and Karamouz, M., 2017. Influence of coastal flooding on seawater intrusion in coastal aquifers. *In*: Dunn, C.N. and Van Weele, B. (eds.), *World Environmental and Water Resources Congress*. Sacramento, California. pp. 66–79. doi:10.1061/9780784480618.007.

Mao, X.Z.; Chen, F.Y.; Yu, Q.W., and Zhu, X.A., 2004. Numerical prediction of water desalinization in a polder reservoir. *Journal of Hydraulic Engineering,* 35(7), 79–84. doi:10.13243/j.cnki.slxb.2004.07.014

Mao, X.Z.; Zhu, X.A.; Chen, F.Y.; Yu, Q.W., and Weng, B.Z., 2005. Study on accelerating water desalinization in a polder reservoir for storage of fresh water along the coast. *Advances in Water Science,* 16(6), 773–776. doi:10.3321/j.issn:1001-6791.2005.06.003

Moffett, K.B.; Gorelick, S.M.; Mclaren, R.G., and Sudicky, E.A., 2012. Salt marsh ecohydrological zonation due to heterogeneous vegetation–groundwater–surface water interactions. *Water Resources Research,* 48(2), 350–361. doi:10.1029/2011WR010874

Moore, W.S., 1999. The subterranean estuary: A reaction zone of ground water and sea water. *Marine Chemistry,* 65(1–2), 111–125. doi:10.1016/S0304-4203(99)00014-6

Moran, S.B.; Stachelhaus, S.L.; Kelly, R.P., and Brush, M.J., 2014. Submarine groundwater discharge as a source of dissolved inorganic nitrogen and phosphorus to coastal ponds of southern Rhode Island. *Estuaries & Coasts,* 37(1), 104–118. doi:10.1007/s12237-013-9663-7

Mulligan, A.E.; Langevin, C., and Post, V.E., 2011. Tidal boundary conditions in SEAWAT. *Ground Water,* 49(6), 866. doi:10.1111/j.1745-6584.2010.00788.x

Pan, G.E.; Huang, L.C.; Jin, L.J., and Zhu, X.A., 2004. Study on technology of fresh water storage of reservoirs on coastal areas. *Water Conservancy Planning and Design,* 2, 51–55. doi:10.3969/j.issn.1672-2469.2004.02.014

Panday, S. and Huyakorn, P.S., 2004. A fully coupled physically-based spatially-distributed model for evaluating surface/subsurface flow. *Advances in Water Resources,* 27(4), 361–382. doi:10.1016/j.advwatres.2004.02.016

Parthasarathy, C.R.; Sitharam, T.G., and Kolathayar, S., 2018. Geotechnical considerations for the concept of coastal reservoir at Mangaluru to impound the flood waters of Netravati River. *Marine Georesources & Geotechnology,* 2, 1–9. doi:10.1080/1064119X.2018.1430194

Pham, H.V. and Lee, S.I., 2015. Assessment of seawater intrusion potential from sea-level rise and groundwater extraction in a coastal aquifer. *Desalination and Water Treatment,* 53(9), 2324–2338. doi:10.1080/19443994.2014.971617

Phan, T.D.; Smart, J.C.R.; Sahin, O.; Capon, S.J., and Hadwen, W.L., 2018. Assessment of the vulnerability of coastal freshwater system to climatic and non-climatic changes: A system dynamics approach. *Journal of Cleaner Production,* 183, 940–955. doi:10.1016/j.jclepro.2018.02.169

Rimmer, A., 2003. The mechanism of Lake Kinneret salinization as a linear reservoir. *Journal of Hydrology,* 281(3), 173–186. doi:10.1016/S0022-1694(03)00238-5

Robinson, C.; Li, L., and Barry, D.A., 2007. Effect of tidal forcing on a subterranean estuary. *Advances in Water Resources,* 30(4), 851–865. doi:10.1016/j.advwatres.2006.07.006

Sappa, G.; Ergul, S.; Ferranti, F.; Sweya, L.N., and Luciani, G., 2015. Effects of seasonal change and seawater intrusion on water quality for drinking and irrigation purposes, in coastal aquifers of Dar es Salaam, Tanzania. *Journal of African Earth Sciences,* 105, 64–84. doi:10.1016/j.jafrearsci.2015.02.007

Shokri-Kuehni, S.M.S.; Vetter, T.; Webb, C., and Shokri, N., 2017. New insights into saline water evaporation from porous media: Complex interaction between evaporation rates, precipitation, and surface temperature. *Geophysical Research Letters,* 44(11), 5504–5510. doi:10.1002/2017GL073337

Song, Q., 2014. Groundwater resources protection and sea water intrusion in Ganjingzi District of Dalian City. *Groundwater,* 36(1), 98–100.

Spanoudaki, K.; Stamou, A.I., and Nanougiannarou, A., 2009. Development and verification of a 3-D integrated surface water-groundwater model. *Journal of Hydrology,* 375(3–4), 410–427. doi:10.1016/j.jhydrol.2009.06.041

Stumpf, R.P. and Haines, J.W., 1998. Variations in tidal level in the Gulf of Mexico and implications for tidal wetlands. *Estuarine, Coastal and Shelf Science,* 46(2), 165–173. doi:10.1006/ecss.1997.0276

Sumner, D.M. and Belaineh, G., 2005. Evaporation, precipitation, and associated salinity changes at a humid, subtropical estuary. *Estuaries and Coasts,* 28(6), 844–855. doi:10.1007/BF02696014

Sun, B.; Liu, S.G.; Gu, J.; Kuang, C.P., and Yu, W.W., 2008. Numerical study on impact of water regulation of TGP and South-to-North Water Diversion Project on water source area of the Yangtze Estuary. *Yangtze River,* 39(16), 4–6. doi:10.16232/j.cnki.1001-4179.2008.16.009

Svensson, A. and Theander, J., 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources,* 51(1), 3–26. doi:10.1016/j.advwatres.2012.03.004

Vanek, V., 1993. Groundwater regime of a tidally influenced coastal pond. *Journal of Hydrology,* 151(2–4), 317–342. doi:10.1016/0022-1694(93)90241-Z

Vu, D.T.; Yamada, T., and Ishidaira, H., 2018. Assessing the impact of sea level rise due to climate change on seawater intrusion in Mekong Delta, Vietnam. *Water Science & Technology,* 77(6), 1632–1639. doi:10.2166/wst.2018.038

Wang, H.; Hsieh, Y.P.; Harwell, M.A., and Huang, W., 2007. Modeling soil salinity distribution along topographic gradients in tidal salt marshes in Atlantic and Gulf coastal regions. *Ecological Modelling,* 201(3–4), 429–439. doi:10.1016/j.ecolmodel.2006.10.013

Wang, G.Z. and Zhu, J.P., 1998. Mechanical technology for pumping saltwater in Datanggang Reservoir. *Advances in Science and Technology of Water Resources,* 18(4), 44–46.

Wang, L.Q. and Zhu, M., 2014. Seawater intrusion in the eastern coastal area of Changli County and the prevention measures. *Journal of Hebei Engineering & Technical College,* 3, 30–32. doi:10.16046/j.cnki.issn1008-3782.2014.03.038

Wu, G.H.; Li, J.Z., and Li, X.J., 2010. Cause and prevention countermeasures of water salinization of city water supply reservoir in the coastal region of Tianjin. *Water Resources Protection,* 26(1), 29–31. doi:10.3969/j.issn.1004-6933.2010.01.008

Xiang, J.; Peng, J.P.; Pang, Y.; Zhou, B.L., and Chen, G.J., 2008. Study on sediment salinity release in estuaries and loughs. *Journal of China Hydrology,* 28(4), 12–15. doi:10.3969/j.issn.1000-0852.2008.04.004

Xie, T.Y., 2015. The Effects of Tide and Freshwater on the Saltwater Intrusion of Coastal Reservoir. Nanjing, China: Hohai University, Master's thesis, 77p.

Xin, P.; Jin, G.Q.; Li, L., and Barry, D.A., 2009. Effects of crab burrows on pore water flows in salt marshes. *Advances in Water Resources,* 32(3), 439–449. doi:10.1016/j.advwatres.2008.12.008

Xin, P.; Robinson, C.; Li, L.; Barry, D.A., and Bakhtyar, R., 2010. Effects of wave forcing on a subterranean estuary. *Water Resources Research,* 46(12), 439–445. doi:10.1029/2010WR009632

Xu, L.Z., 2001. Discussion about the struction of coastal reservoir in Northern Jiangsu Province. *Jiangsu Water Resources,* 11, 34–35. doi:10.16310/j.cnki.jssl.2001.11.017

Yang, S.Q., 2018. Coastal reservoir—How to develop freshwater from the sea without desalination. *In*: Singh, V.P.; Yadav, S., and Yadava, R.N. (eds.), *Water Resources Management*. Singapore: Springer, pp. 121–139. doi:10.1007/978-981-10-5711-3_9

Yang, S.Q. and Ferguson, S., 2010. Coastal reservoirs can harness stormwater. *Water Engineering Australia,* 8, 25–27.

Yang, Y.X.; Zhou, Z.X., and Liu, S.T., 2004. Study on dynamic monitoring of seawater intrusion in the coastal plain of Qinhuangdao, Hebei, China. *Geological and Mineral Information in Hebei,* 2, 14–19.

Yeates, P.S. and Imberger, J., 2003. Pseudo two-dimensional simulations of internal and boundary fluxes in stratified lakes and reservoirs. *International Journal of River Basin Management,* 1(4), 297–319. doi:10.1080/15715124.2003.9635214

Yu, K., 1996. Analysis and prediction of water desalination in Zhejiang Haitu reservoir. *Environmental Pollution and Prevention,* 8(2), 27–29. doi:10.15985/j.cnki.1001-3865.1996.02.009

Yuan, L.R.; Xin, P.; Kong, J.; Li, L., and Lockington, D., 2011. A coupled model for simulating surface water and groundwater interactions in coastal wetlands. *Hydrological Processes,* 25(23), 3533–3546. doi:10.1002/hyp.8079

Yuan, W.X.; Yang, S.T., and Zhuang, M., 2007. Arguments of the coastal reservoir in RuDong JiangSu Province. *Yangtze River,* 38(6), 35–37. doi:10.16232/j.cnki.1001-4179.2007.06.015

Yuchping, H.; Fagherazzi, S.; Marani, M., and Blum, L.K., 2004. Dynamics of tidal salt barren formation and the record of present-day sea level change. *In*: Fagherazzi, S.; Marani, M., and Blum, L.K. (eds.), *Ground Problems in Coastal Areas*. Washington, D.C.: American Geophysical Union, pp. 231–245.

Yue, D.W.; Gao, Z.W.; Zhao, Q.S., and Peng, Y.C., 2013. Experimental study of abrupt salinization in estuary reservoirs. *Water Resources Protection,* 29(4), 40–44. doi:10.3969/j.issn.10046933.2013.04.008

Zhang, P.; Jiang, C.L.; Zhu, X.Q.; Li, D.M.; Cao, C.; Zhu, L.Q.; Xing, X.G., and Shen, X.J., 2014. Analysis of sediment salinization degree of the proposed reservoir in the coastal area of Tianjin. *Yellow River,* 36(1), 67–70. doi:10.3969/j.issn.1000-1379.2014.01.023

Zhang, Q.; Volker, R.E., and Lockington, D.A., 2001. Influence of seaward boundary condition on contaminant transport in unconfined coastal aquifers. *Journal of Contaminant Hydrology,* 49(3), 201–215. doi:10.1016/S0169-7722(00)00194-7

Zhang, X.L.; Zhu, M.H., and Zheng, X.L., 2010. Test investigation for salt release from sediments in a polder reservoir under effects of environmental factors. *Marine Science Bulletin,* 29(2), 135–142. doi:10.3969/j.issn.1001-6392.2010.02.003

Zhao, W.Y.; Wang, Q.S.; Ting, W.U.; Li-Bo, W.U.; Wang, X.Y., and Zhang, Y., 2006. Reservoir water salinization and mechanism analysis in Tianjin Binhai area. *Haihe Water Resources,* 3, 33–35. doi:10.3969/j.issn.1004-7328.2006.03.013

Zhou, X.; Yang, T.; Shi, P.; Yu, Z.; Wang, X., and Li, Z., 2017. Prospective scenarios of the saltwater intrusion in an estuary under climate change context using Bayesian neural networks. *Stochastic Environmental Research & Risk Assessment,* 31(4), 981–991. doi:10.1007/s00477-017-1399-7

Zhu, J., 2002. Analysis on the causes of salty water quality in Huchengang Reservoir and its control measures. *Zhejiang Water Conservancy Science and Technology,* 4, 50–51. doi: 10.3969/j.issn.1008-701X.2002.04.023