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CHINA COASTAL WETLANDS

Interactions Between Surface Water and Groundwater: Key Processes in Ecological Restoration of Degraded Coastal Wetlands Caused by Reclamation

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Abstract Interactions between surface water and groundwater (SW-GW), composed of complex hydrological networks, maintain a dynamic balance between water regimes and salinity in coastal wetlands. Impacted by reclamation activity, however, changes in water regimes and salinity have resulted in wetland degradation. To mitigate such reclamation impacts on coastal wetlands, it is vital to understand the role of SW-GW interactions involved in maintaining the integrity of coastal wetlands. The objectives of this review were to: (*i*) outlining SW-GW interactions; (*ii*) addressing ecological responses to changes in water regimes and salinity; and (*iii*) exploring modeling techniques used to ascertain interactions between groundwater and coastal wetlands. Key findings are as follows: SW-GW interactions control water regimes and salinity while maintaining the integrity of coastal wetlands; the combined effects of water and salinity have an impact on ecological processes and patterns disturbed by hydrological pulses; and the distribution of physically-based models is an approach that can provide a profound means by which to understand the vital role in maintaining hydrological connectivity. Further research is required to fully reveal SW-GW interactions in maintaining coastal wetlands integrity and the mitigating effects reclamation has on coastal wetlands.

Keywords Coastal wetland · Groundwater · Surface water · Ecological response · Reclamation

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Introduction

Coastal wetlands are defined as ecosystems that are found within an elevation gradient that ranges between subtidal depths to which light penetrates to support photosynthesis of benthic plants and the landward edge where the sea transfers its hydrologic influence to groundwater and atmospheric processes (Perillo et al. 2009). Coastal wetlands where land and sea are linked are one such ecosystem, characterized by complex hydrological processes that are prone to degradation (Mitsch and Gosselink 2000; Howes et al. 2010; Dawson et al. 2011). Along with hydrological gradients, coastal wetlands include seagrasses, tidal flats, tidal salt and freshwater marshes, and mangrove and tidal freshwater forests (Perillo et al. 2009). Due to the unique characteristics in its structure, coastal wetlands provide a significant amount of ecosystem services: (*i*) supporting fish and other such wildlife by providing habitat; (*ii*) improving water quality by filtering runoff; and (*iii*) protecting coastal regions from erosion and flooding, particularly during strong storm events (Costanza et al. 1997; Chen and Zhang 2000; Zedler and Kercher 2005; Howes et al. 2010).

With rapid societal and economical development, coastal wetlands have suffered great losses and degradation from wetland reclamation, population pressures, and misguided policies over past decades (Yang et al. 2011) in many regions of the world, e.g., China (Xie et al. 2010; Yang et al. 2011), America (Turner and Lewis 1997; Perillo et al. 2009) and Europe (Airoldi and Beck 2007; Almeida et al. 2014). When excluding shallow coastal waters (depths between 0 and −5 m), for example, roughly 16 % of China's coastal wetlands have been lost between the 1970s and 2007 (Zuo et al. 2013).

Besides inhabited land, reclamation activity (e.g., that which was converted into land for agricultural and residential use, port construction, and industrial estates) have altered hydrological processes, resulting in river, wetland, and groundwater fragmentation (Brunner et al. 2009b), which is likely a key reason behind coastal wetlands degradation seen today.

Mitsch and Gosselink (2000) noted that, “hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetland,” In order to mitigate reclamation impacts, hydrological networks have been incorporated into wetland restoration goals (Lei and Zhang 2005; Cui et al. 2012). According to Simenstad et al. (2006), depredated wetland restoration involves processes and not structures. Under such changes in hydrological connectivity outlook, a recent development in hydrological research has combined SW-GW together, treating them as a single system, and groundwater-dependent ecosystems have even been proposed (Winter et al. 1999; Euliss et al. 2004; Eamus et al. 2006; Jolly et al. 2008). Available surface water is declining while the extraction of groundwater beyond natural recharge rates is taking place, lowering the water table and causing the degradation of groundwater-dependent ecosystem (Jolly et al. 2008; Brunner et al. 2009a, b; Raulings et al. 2010; Lamontagne et al. 2014). Freshwater wetlands within coastal regions are also prone to salinization. This is due to reclamation-induced changes in hydrological cycling, resulting in recharge increases that in turn lead to increases in saline groundwater or seawater intrusion (Jolly et al. 2008; Blum and Roberts 2009; Neubauer 2013). As ecological processes and patterns have changed as a consequence of altered hydrological conditions, a great deal of effort has been focused on restoring more natural water regimes to reinstate healthy plant communities in hydrologically modified wetlands (Lewis 1990a, b; Wilcox and Whillans 1999; Smith et al. 2007; Raulings et al. 2010) Fig. 1.

This review is comprised of three sections: (*i*) establishing controls that impact interactions between SW-GW in coastal wetlands; (*ii*) addressing such ecological responses that derive from the combined effects of water regimes and salinity; and (*iii*) summarizing modeling techniques used when determining interactions between groundwater and coastal wetlands as well as key modeling processes.

SW-GW Interactions in Coastal Wetlands

Wetland SW-GW Controls

Potential gradient changes under different temporal and spatial scales control groundwater movements and alter interactions between SW-GW in wetlands (Boulton et al. 1998). Flow regime types typically depend upon water table structure between wetlands and upland areas (Hayashi and Rosenberry 2002; Fan et al. 2012). Specifically, groundwater flow direction is governed by the slope of the water table (Jolly et al. 2008; Baalousha 2012). As summarized by Sophocleous (2002), larger scale hydrologic SW-GW exchanges are controlled by: (*i*) the distribution and magnitude of hydraulic conductivity, both within channels and associated alluvial plain sediments; (*ii*) the relationship between stream stage and adjacent groundwater levels; and (*iii*) the geometry and position of stream channels within alluvial plains. Jolly et al. (2008) indicated that SW-GW interactions in wetlands can be broadly classified into four flow regimes: (*i*) connected losing wetland—where wetland surface water is lost (i.e., recharged) to the underlying aquifer; (*ii*) disconnected losing wetland—similar to (*i*) except that wetland surface water seepage is slow enough that an unsaturated zone underneath the wetland remains; (*iii*) flow-through wetland—where water is gained (i.e., receives discharge) from groundwater in certain areas of the wetland and where water is lost (i.e., recharged) in other

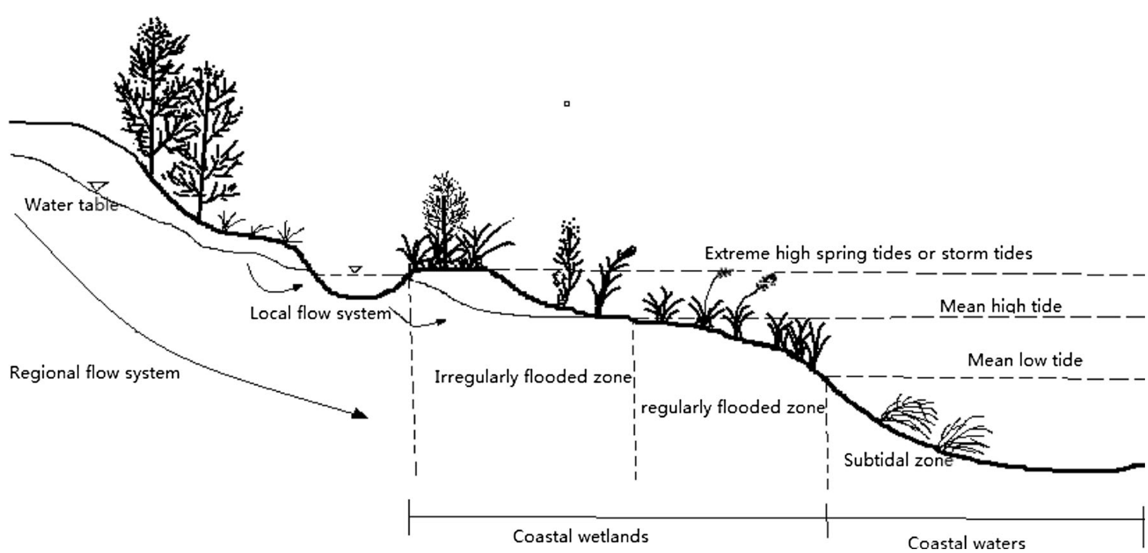

Fig. 1 An illustration of a typical coastal wetland (derived from an illustration provided in Tiner (1993))

areas; and (*iv*) gaining wetland—where water is gained (i.e., receives discharge) from the underlying aquifer. Interactions between SW-GW, affected by groundwater discharge from regional flow systems and from local flow systems associated with scarps and terraces, evapotranspiration, and tidal flooding, is highly variable (Winter et al. 1999; Sánchez-Martos et al. 2014). In this context, under the effect of variations in climate, tidal flooding as well as other related factors, individual wetlands may temporally change from one type to another depending upon how surface water levels in wetlands and their corresponding underlying groundwater levels change over time even in groundwater dependent ecosystems (Jolly et al. 2008; Sánchez-Martos et al. 2014). Subject to precipitation events and seasonal patterns (Sena and Teresa Condesso de Melo 2012), changes in flow direction (affluence or effluence) take place when the hydraulic head is altered whereas flow itself depends upon sediment hydraulic conductivity. Owor et al. (2011) pointed out that hydraulic gradients are highest during periods of monsoonal rainfall when direct recharge elevates groundwater levels. On the other hand, variable flow regimes could alter hydraulic conductivity of sediment via erosion and deposition processes and thus affect SW-GW interaction intensity (Sophocleous 2002; Elsawwaf et al. 2012). Hydrological interactions are inherently complex, being subject to periodic water-level changes caused by periodic tidal events (Winter et al. 1999; Yuan and Lin 2009; Gao et al. 2010; Carol et al. 2012; Moffett et al. 2012; Zapata-Rios and Price 2012) Fig. 2.

Vital Roles of SW-GW Interactions in Coastal Wetlands

Vertical and lateral flow exchanges are composed of complex water networks that maintain the ecological integrity of coastal wetlands (Euliss et al. 2004; Cook and Richard Hauer 2007; Acworth 2009; Cui et al. 2012; Raab and Bayley 2012). On the one hand, water networks composed of interactions between SW-GW provide freshwater while preventing seawater intrusion (Harvey and Nuttle 1995; Nuttle and Harvey 1995). In an ecological context, connectivity is defined as the transfer of material between different locations via wind and water as well as via human and animal activity (Peters 2008). Reclamation activities (e.g., dam construction, farming, etc.) impede connectivity, restricting the input of freshwater for wetland function (McFalls et al. 2010; Zhang et al. 2012), which can even result in the creation of geographically isolated wetlands (Winter and LaBaugh 2003; Golden et al. 2014). As an example, wetland loss has primarily been driven by the construction of flood control levees in the Louisiana coastal zone along the Mississippi River (Blum and Roberts 2009; McFalls et al. 2010). In China, connectivity impediment and water regime alteration resulting from reclamation also have caused coastal wetland degradation in the Pearl River and Yellow River deltas (Cui et al. 2009a, b; Zhang et al. 2012). On the other hand, SW-GW interactions allow for organic matter and mineral transport, especially in terms of controlling salinity and interactions that lead to diversity in wetland type. With the help of connectivity (e.g., vertical and lateral flow), material and resources can be transported within and among different wetland types, altering salinity (Winter 2001; McFalls et al. 2010; Álvarez-Romero et al. 2011), which influences surface water chemistry, water depth, hydrologic regimes, soil morphology, and plant species composition (LaBaugh et al. 1998; Euliss et al. 2004). Flood events can cause temporal changes in streambed elevation and particle size composition, which can influence hydraulic properties

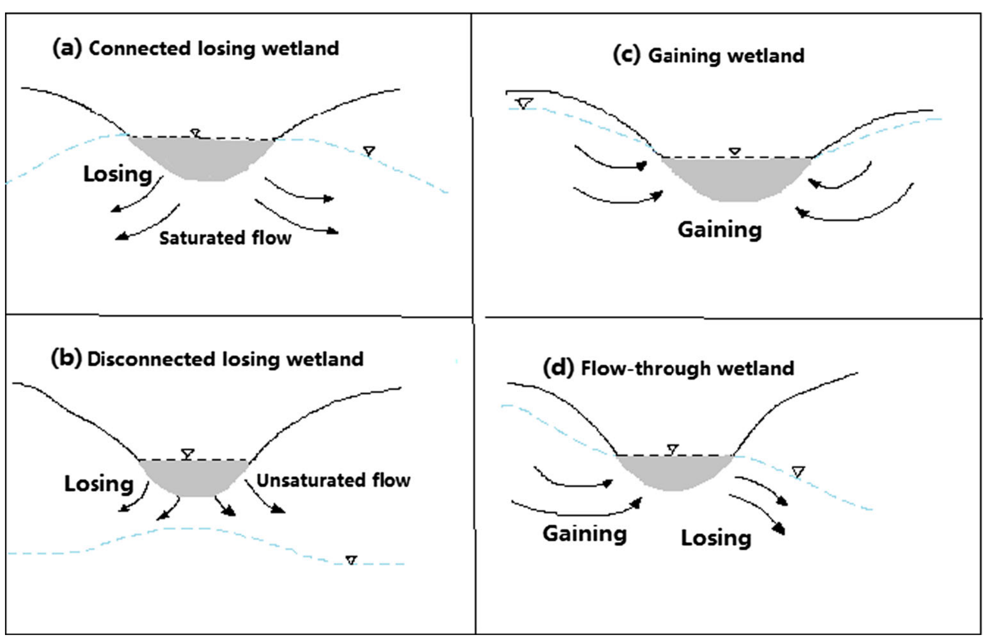

Fig. 2 Conceptual groundwater flow paths to and from **a** connected losing; **b** disconnected losing; **c** gaining; and **d** flow-through wetland regimes (after Jolly et al. 2008)

and stream-aquifer fluxes in beds during and after an event (Simpson and Meixner 2012). Furthermore, due to complex interactions between surface water and groundwater, it remains difficult to establish particular reference conditions used to define "good" surface water quality and to understand the influence that groundwater has on such coastal wetlands (Sánchez-Martos et al. 2014).

Response of Ecological Patterns and Processes to SW-GW Changes

Combined Effects of Water and Salinity

Changes in hydrological processes and salinity are the key drivers for ecological patterns and processes as well as the control of ecological evolution (McCarthy 2006; Jolly et al. 2008). A number of studies targeted water regime impacts on morphological characteristics, density, biomass, and spatial patterns of plant species (Horton and Clark 2001; Langford et al. 2009; Froend and Sommer 2010; Xie et al. 2011; Yuan et al. 2011), exploring tolerance levels and outlining suitable water regimes for different plant species (James et al. 2003; Eamus et al. 2006; Merritt et al. 2009; Raulings et al. 2010). Both temporary and permanent salinity conditions resulting from water regime changes to coastal wetlands has led to complex physiological and ecological responses (Jin 2008; Antonellini and Mollema 2010; Yu et al. 2012; Johns et al. 2014). In other words, combined effects of water regimes and salinity will control ecological patterns and processes (Slama et al. 2008; Antonellini and Mollema 2010; Cui et al. 2010; Gorai et al. 2010). Tolerances of different plant species to the combined effects of salinity and water have been previously investigated, such as *Suaeda maritima* (e.g., Alhdad et al. 2013), *Phragmites australi*s (e.g., Gorai et al. 2010; Yang et al. 2012), and *Sesuvium portulacastrum* (e.g., Slama et al. 2008). Although many emergent wetland plant species may readily tolerate rapid changes in flooding and drying under freshwater conditions, their tolerance to dynamic water regimes may be compromised by salinity (Salter et al. 2010). For example, increases in salinity can reduce growth rates and above-ground biomass production in non-halophytic macrophytes, which may reduce inundation tolerance (Johns et al. 2014). Furthermore, salinity resulting from variations in water regimes also can impact biodiversity in coastal wetlands (Amores et al. 2013).

Hydrological Events and Water Pulses in Addition to Salinity Tolerance

Hydrological event pulses, such as flood pulses and tides, maintain a freshwater and salinity balance in coastal wetlands. Certain studies have shown that wetlands that undergo pulsing hydrology experience higher carbon (C) productivity and retention in soils than wetlands that are continuously flooded (Middleton 2002; Neubauer 2013; Marín-Muñiz et al. 2014). For example, soil microbial communities respond quickly to changes in salinity, altering the rate of soil organic carbon (SOC) loss and associated biogeochemical processes (Chambers et al. 2013). The interconnection of river channels and floodplains is critical because ecological functions such as production, decomposition, and consumption are driven by flood pulses, and water fluctuation drives succession (Middleton 2002). Hydrological event pulses can maintain a dynamical balance in coastal wetlands with respect to variation in salinity tolerance between different plant species and life stages (Brock and Casanova 1997; Kefford et al. 2007; Raulings et al. 2010). *P. australis* is generally considered to be less salt-tolerant than *Spartina alterniflora*. It has been proposed that recent *P. australis* invasions are related to a reduction in salinity associated with anthropogenic alterations of habitat, such as storm runoff being redirected to the rear of marshes (Silliman and Bertness 2004; Cui et al. 2010). Although controversial, juvenile plants are considered more sensitive to water regimes and salinity than adult plants, and the reproductive capacity of adults may be impaired by elevated, albeit sublethal, salinity levels (Jolly et al. 2008). Mismatched tolerance levels to water regimes and salinity can unquestionably alter plant species and populations in coastal wetlands by such means as flood pulses or seawater intrusion via over pumping of aquifers, and even alter wetland integrity (Spalding and Hester 2007; Amores et al. 2013; Hopfensperger et al. 2014; Johns et al. 2014).

Modeling Interactions Between SW-GW

Modeling Groundwater and Coastal Wetlands Together

Modeling interactions between groundwater and coastal wetlands can provide a profound means by which to understand the vital role in maintaining the connectivity of hydrological processes (Kazezyılmaz-Alhan et al. 2007; Fleckenstein et al. 2010; Yang et al. 2010; Guay et al. 2013; Haines 2013). Jolly et al. (2008) reviewed modeling approaches between groundwater and wetlands in arid and semi-arid regions. They found that researchers have paid more attention in site-specific and developing generic relationships between water body geometry and lake/wetland-aquifer interactions. As a result, they focused on site-specific transient studies using traditional numerical modeling approaches and newer analytic element techniques and link-node approaches. Realizing such shortcomings of earlier studies, more attention is starting to be paid to the movement of both water bodies and sea salt. This is especially important considering unsaturated zone processes within and around wetlands, which are critical in terms of ecological responses, particularly in relation to vegetation growth, decomposition, and nutrient release (Kazezyelmaz-Alhan and Medina 2008; Yuan et al. 2011). Due to a lack of a specific wetland model, distributed parameter physically-based models have been applied to reflect complex hydrological processes in wetlands, such as MIKE SHE (Graham and Refsgaard 2001), InHM (VanderKwaak and Loague 2001), and MODHMS (Panday and Huyakorn 2004). Most integrated models are also based on the assumption of a constant fluid density, and thus their applicability to coastal regions is questionable unless it can be somehow shown that model results are insensitive to density variation (Langevin et al. 2005). Numerical models are increasingly used to explore hypotheses and to develop new conceptual models related to SW-GW interactions (Xu et al. 2009). New technologies such as distributed temperature sensing (DTS) allow for an assessment of process dynamics at unprecedented spatial and temporal resolutions (Fleckenstein et al. 2010; Rau et al. 2012). Although integrated models provide a good means by which to understand interactions between groundwater and coastal wetlands, owing to the large number of contributing hydrological processes, shallow hydraulic gradients, and variable density flow conditions, there remains much to do to improve model performance in this regard (Yuan and Lin 2009; Haines 2013).

Key Processes Involved in Modeling Groundwater in Coastal Wetlands

Due to the complex ecohydrological characteristics of coastal wetlands, more attention should be paid to model interactions between groundwater and coastal wetlands, such as (*i*) variability in changes of evapotranspiration (*ET*) alongside wetland ecological patterns. On the one hand, *ET* will be altered alongside ratio changes between open water and vegetation coverage that results from changes in water levels (Sánchez-Carrillo et al. 2004; Huckelbridge et al. 2007; Headley et al. 2012). On the other hand, plant species communities, owing to specific physiological and ecological characteristics, are subject to high *ET* rates (Xu et al. 2010; Zhou et al. 2010; Białowiec et al. 2012). Owing to the difficulty in distinguishing between vegetation *ET* and water evaporation, how plants enhance or reduce *ET* remains controversial, which increases water budget uncertainty in modeling interactions between SW-GW. (*ii*) High pulses in hydrological events can result from floods, tides, and reclamation. Being influenced by climatic changes and anthropogenic activity, coastal wetlands (especially in estuaries) are easily affected by high hydrological pulsing events, such as floods, tides, and water-sediment regulation (Day et al. 2007; Cui et al. 2009a; Moffett et al. 2012). High hydrological pulsing events can alter the steady state of water regimes that result from physiological and ecological characteristics, even leading to changes in plant species distribution or ecosystem evolution (Day et al. 2007; Moffett et al. 2012; Temmerman et al. 2012). Furthermore, due to the influence of high hydrological pulsing events, especially tides, the transport of seawater to wetlands is inherently complex. Conversely, changes in salinity can also impact ecological processes and alter hydrological processes (Gómez-Sapiens et al. 2013; Webb et al. 2013). All of the above factors can alter boundaries in integrated models and increase difficulties in modeling interactions between SW-GW.

Conclusion

Interactions between SW-GW control water regimes and salinity, preventing seawater intrusion in coastal wetlands. Complex hydrological networks, maintained via vertical and lateral water interactions, play a vital role in maintaining diverse habitats and forming wetland networks. The combined effect of water and salinity results in a complex mechanism related to plant species tolerance, controlling the spatial distribution of vegetation. Hydrological event pulses (e.g., flood and tidal pulses), and, in particular, inundation, drought, and seawater intrusion promoted by reclamation, have altered morphological characteristics of plant species, density, biomass, and spatial patterns, resulting in wetland degradation. The distribution of physically-based models provides a profound means by which to understand the vital role in maintaining hydrological connectivity. More attention should be paid to key processes within integrated models, such as variability in *ET* changes alongside ecological patterns of wetlands as well as high hydrological event pulses resulting from floods, tides, and reclamation.

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