Chapter 18

Coastal Wetland Hydrologic Resilience to Climatic Disturbances: Concept, Quantification, and Threshold Response

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Abstract Climate change, the rising air temperature and changes in the intensity and frequency of rainfall, and sea level rise (SLR), represents one of the most important threats to coastal wetlands that have numerous ecosystem services from erosion and water quality control to wildlife habitat. Climate change-induced disturbances affect the sustainability of coastal wetland ecosystems mainly through altering their hydrologic functions. However, how to assess wetland hydrological resilience, the ability of wetland hydrology to recover from climate disturbances remain challenging. This chapter first summarizes current knowledge of the coastal hydrologic cycle and the influence of climate change on the coastal hydrologic cycle. Then, we define hydrologic resilience, identify the hydrologic conditions, and quantify the hydrologic resilience. Last, we present a case study on bottomland hardwood forests along the Atlantic coast. We applied a physically based watershed-scale wetland hydrological model (PIHM-Wetland) to the coastal wetland system and quantified the hydrologic resilience in response to climate extreme events during the recent 20 years using a distributed-system approach. The case study shows that the metrics to quantify hydrologic resilience to drought, extreme rainfall events, and sea level rise are effective and may be appliable to other similar regions.

Keywords Wetland · Hydrologic resilience · Climatic disturbances · Threshold response · Climate change

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1 Introduction

Coastal wetlands link the terrestrial landscapes and ocean providing important ecosystem services to attenuate flood, store water and carbon, stabilize the shoreline, and provide habitats for wildlife (Roulet, 1990; Tiner, 2013). However, the wetland benefits to people and wildlife are rapidly diminishing due to the serious threats from climate change in terms of the significant changes in temperature regimes and precipitation variability (Poff et al., 2002), as well as the short-term sea level variations due to hurricane, storm surge, and long-term sea level rise (SLR) (Park et al., 1989). These climatic changes disturb the coastal wetland ecosystem functions (e.g., biogeochemical and geomorphological functions) mainly through affecting the wetland hydrologic functions, the capability of coastal wetlands in storing and releasing the water through the wetland surface and subsurface (Zhang et al., 2019). For example, the changes in precipitation, temperature, and sea level affect the wetland surface and aquifer storage, thereby impacting the surface and subsurface hydrologic interactions, freshwater-saltwater balance, and groundwater level. Consequently, these hydrologic changes would influence soil organic carbon storage and vegetation productivity (Silvestri & Marani, 2004). Also, climate change impacts the capability of coastal wetlands in absorbing and releasing water through wetland surface and subsurface, therefore altering surface and subsurface flow rate and direction, which are critical drivers for coastal erosion and nutrient transport (FitzGerald & Hughes, 2019). Thus, a complete understanding of how the coastal ecosystems respond to climate change may not be achieved without a comprehensive understanding of their hydrologic responses to climate change.

Hydrologic resilience (HR) is a measure of how the hydrological processes of coastal wetlands respond to climate change because HR describes the capability of a wetland ecosystem in resisting disturbances, recovering and rerunning to its prior-disturbance hydrologic conditions (Peterson et al., 2012; Ridolfi et al., 2006; Zhang et al., 2019). Although the concept of hydrologic resilience has been accepted in the science community, its definition is still vague. For example, to what extent can one say that a disturbance is absorbed? to what extent can one say that a system goes back to its prior-disturbance condition? In addition, the method for quantifying HR is still not well developed. A lacking quantitative definition can result in an inaccurate understanding of coastal wetland resilience.

The objective of this chapter is to discuss the basic elements required for quantifying the hydrologic resilience of coastal wetlands, providing a predictive understanding of the response of coastal wetlands to climatic change. The first part of this chapter focuses on the description of hydrological processes of the coastal wetlands to provide a framework for assessing coastal hydrological response to climatic disturbances. The second part of the chapter introduces the concept of coastal hydrologic resilience and quantitative methods. The last part of the chapter presents a case study for understanding the coastal hydrologic resilience to climatic variability. The coastal wetlands are excluded in the high latitude region, like Arctic coastal wetlands, in this chapter.

2 Coastal Hydrologic Processes and Their Responses to Climatic Disturbances

Similar to the hydrologic cycle in other terrestrial landscapes, the dynamics of coastal wetland hydrology is controlled by precipitation, surface and subsurface water flow, plant transpiration, canopy interception, soil evaporation, and possibly snow in the winter season. However, unlike the inland wetlands that are dominated by precipitation and local runoff as water inputs and influenced by high topographic gradient (Fan & Miguez-Macho, 2011), coastal wetlands are located at the low gradient flood plains with relatively shallow groundwater table. Thus, the coastal wetlands are more surface water-fed but groundwater-supported wetlands (Fan & Miguez-Macho, 2011). Since the topographic gradient is small, the drainage divides of coastal catchments are not strictly defined based on their topography. Therefore, the coastal wetlands are not topographically isolated, and regional hydrologic connectivity between the upland terrestrial landscape and coastal wetlands is important to the wetlands' hydrology (Zhang et al., 2018). In addition, coastal wetlands interact with coastal processes, such as tide, sea level rise, hurricane, and storm surge, which affects the surface water flow and water storage, subsurface saturation condition, groundwater flow, and saltwater intrusion in a coastal aquifer.

Climate-induced disturbances are expected to increase in frequency and intensity and affect the hydrologic cycle of a coastal wetland ecosystem in various ways. For example, the warming climate will increase evapotranspiration. Climate change also causes a change in the intensity and frequency of precipitation. The deficit between the precipitation and evapotranspiration defines the water availability, which determines the local water supply to coastal wetlands. If climate change results in a decrease in water availability, surface water, soil moisture, and groundwater table will decline. In contrast, with an increase in water availability, soil moisture and groundwater table may rise and flooding is more likely to occur. Zhu et al. (2017) suggested that the groundwater table depth of five coastal forested wetlands along the southeast coast will drop by 4–22 cm in response to the decrease in water availability (precipitation minus evapotranspiration) in the future based on 20 general circulation model (GCM) predictions. Besides precipitation and temperature, the sea level rise (SLR) is another consequence of climate change in coastal regions. The rising sea level will intensify coastal flooding (the storage of surface water). For example, Kirshen et al. (2008) estimated that the present-day 1%-occurrence flood level was projected to become the 26%-occurrence flood level by 2100 under SLR. SLR will also break the balance of freshwater-saltwater interaction in a coastal aquifer. A large amount of saltwater will intrude into coastal wetlands and push fresh groundwater landward, thereby changing the coastal subsurface groundwater flow and soil salinity.

3 Coastal Hydrologic Resilience: Definition and Quantification

3.1 The Concept of Hydrologic Resilience

The term “hydrological resilience” can be traced back to the concept of “ecological resilience” introduced by Holling (1973), who suggested a new way to help understand the nonlinear dynamics of ecosystems under disturbances. After decades of the introduction of this concept, the definition of ecological resilience was still ambiguous. Folke et al. (2002) summarized the previous definitions into one comprehensive definition: “the capacity of a social-ecological ecosystem to absorb perturbations and to sustain and develop its fundamental function, structure, identity, and feedbacks through either recovery of the original state or reorganization in a new context, still maintaining original functions.” Following this definition, coastal wetland hydrologic resilience describes the capacity of coastal wetlands in (1) absorbing the disturbances without significant change in its hydrologic regime and (2) recovering to its prior conditions before the disturbances (Peterson et al., 2012; Zhang et al., 2019).

3.2 Definition of Hydrologic Regime

From the description of hydrologic resilience above, an important part of its definition is to define/identify the hydrologic regime and the “significant change” of the regime after disturbances. First of all, the hydrologic regime refers to the variations in the state and fluxes of a water body which are regularly repeated in time. The hydrologic states include the states of water storage in the coastal wetland system, such as surface water height, soil moisture content, and groundwater table depth. The hydrologic fluxes include the release of water in a coastal wetland system, such as surface overland flow, channel flow, infiltration, groundwater flow, and saltwater intrusion. Since the coastal wetland hydrologic system is a nonlinear dynamic system, its hydrologic states and fluxes vary through time and space driven by regular external climatic forcing. Thus, the definition of a hydrologic regime should reflect the nature of the system’s average trend, as well as the hydrologic variation. The approach for quantifying hydrologic regime varies with the different research intents. Some previous studies quantified the hydrologic regime by investigating the long-term or steady-state of a hydrologic system under an averaged external forcing (Peterson et al., 2012; Richter et al., 1996). Richter et al. (1996) examined the tipping point of a climate condition passing which the monthly and yearly stream flows were altered. This method can detect the long-term response of a hydrologic system to external disturbances, such as the dam and long-term groundwater pumping conditions. However, a short-term response of the system to disturbances cannot be captured and examined. Peterson et al. (2012) focused more on the shorter time scale analysis of a hydrologic system by looking at the shift of a steady-state groundwater condition under different short-term disturbances. However, most of the real-world systems are not reaching or even close to their steady-state due to the stochastic features of external forcing. Thus, some other studies quantified the hydrologic regime by estimating the averaged hydrologic states and fluxes over a certain period. For example, Zhang et al. (2019) quantified the coastal wetland hydrologic states by computing their daily-, seasonally-, and yearly-averaged values by considering the temporal variation of external climate forcing.

It is critical to define to what extent a change in hydrologic regime is "significant." The "significant" used in describing the change in hydrologic regime is not the same as the "significant" in statistics that helps quantify whether a result is likely due to the chance or some factor of interest (Montgomery et al., 2009). Statistically, when a finding is significant, it simply means one can feel confident that it is real, not only got lucky in choosing the sample. Here, the "significant" focuses more on describing the "big" change of a hydrologic regime that may temporally change the current hydrologic cycle of a system, or permanently alter the hydrologic functions of the system. There is still no consensus on what magnitude of change is a "significant" change because different coastal systems are different. A small change in one system may mean a big change in another system. Zhang et al. (2019) defined a "significant" change as the change of a hydrologic regime exceeded one standard deviation below or above its climatological mean. In addition, some other thresholds from practical or theoretical purposes are also applicable as the indicators for "significant" changes. For example, Tiner (2013) defined wetland as a landscape with a groundwater table within 0.3 m from the ground surface for at least 2 weeks in its growing season; it is thus reasonable to define the "significant" change of the groundwater table as the groundwater table is below 0.3 m from the ground surface in the growing season. The "significant" change could be also defined as the condition when the hydrologic change causes dysfunction of a coastal wetland ecosystem. For example, a "significant" change of surface water can be the condition when the ponded water causes the mortality of wetland vegetation, the damage of infrastructure, and the flooding of a coastal city within or near a coastal wetland domain.

3.3 *The Quantification of Hydrologic Resilience*

According to the definition of hydrologic resilience above, hydrologic resilience quantification should focus on: (1) the threshold intensity of climate disturbances that coastal wetland system could withstand without significant change in their hydrological functions, and (2) the rate of recovering their hydrological functions from disturbances to the pre-disturbance conditions. Due to the nonlinearity of the complex wetland system, one or several thresholds of climate disturbances/forcing may exist (Peterson et al., 2012), the hydrologic resilience of coastal wetlands may not be easily examined under a short-time series analysis. The characteristics of the hydrologic cycle of coastal wetland may not be captured under a short time period, thus a long time series analysis of the hydrological cycle (e.g., decades) is needed, such as years or decades (Zhang et al., 2019). All the components in the hydrologic cycle of coastal wetland, such as evapotranspiration, surface water depth, overland flow, channelized flow, soil moisture, groundwater level, and groundwater flow, should be able to indicate a part of the hydrologic resilience of coastal wetlands to climate disturbances because these components reflect the wetland hydrologic functions (storing and releasing water). As introduced above, the quantification of hydrologic resilience is the process of investigating (1) at what climate disturbance, the hydrologic cycle component/components can still vary within their regular variation range without "significant" change (e.g., one standard deviation deviates from their climatological mean) and (2) if a "significant" change occurs, how long does it take for the hydrologic component/components return to its prior-disturbance variation range? Depending on the different research purposes, a coastal wetland can be treated as a lumped system and quantify a systematic hydrologic response of this lumped system to climatic disturbances. In the meantime the spatial variation of hydrologic resilience can be also quantified, instead of having a hydrologic resilience for the whole system, if the spatial heterogeneity is an important to factor controlling the overall resilience of the system.

4 Case Study: Hydrologic Resilience of a Real-World Distributed Coastal Wetland System

4.1 Study Area

The case study presented in this chapter focuses on using a distributed-system approach to understand the hydrologic resilience of a coastal wetland system based on a 20-year hydrologic model simulation and in-situ observations of groundwater level, soil moisture, and evapotranspiration. The study site is located at the Albemarle-Pamlico peninsula of North Carolina with an area of 2784 km^2 managed as a wildlife reserve (35°24′48″ N, 76°40′15″ W—36°5′11″ N, 75°40′33″ W) (Fig. 18.1). The wetland consists of 78% forested wetland and 3% emergent herbaceous wetland (Fig. 18.1). An eddy flux observation station was set up to measure energy, water, and carbon fluxes and associated meteorology (Aguilos et al., 2020). Several subsurface sensors were installed to measure the groundwater table dynamics and soil water content. Annual mean precipitation is about 1300–1400 mm, mean annual temperature is around 16.9 °C (1971–2000) (Aguilos et al., 2020; Miao et al., 2013), and annual actual evapotranspiration is about 700–800 mm (Aguilos et al., 2020), and the mean sea level increased by 0.083 m from 1995 to 2014 (NOAA, 2017). The groundwater table (GWT) of the forested wetland varied between 0.3 m below the ground surface and 0.3 m above the ground surface from 2009 to 2011 (Miao et al., 2013). The averaged summer and winter GWT of the herbaceous wetland is about 0.1 m higher and 0.02 m lower than those in the forested wetland, respectively (Zhang et al., 2018).

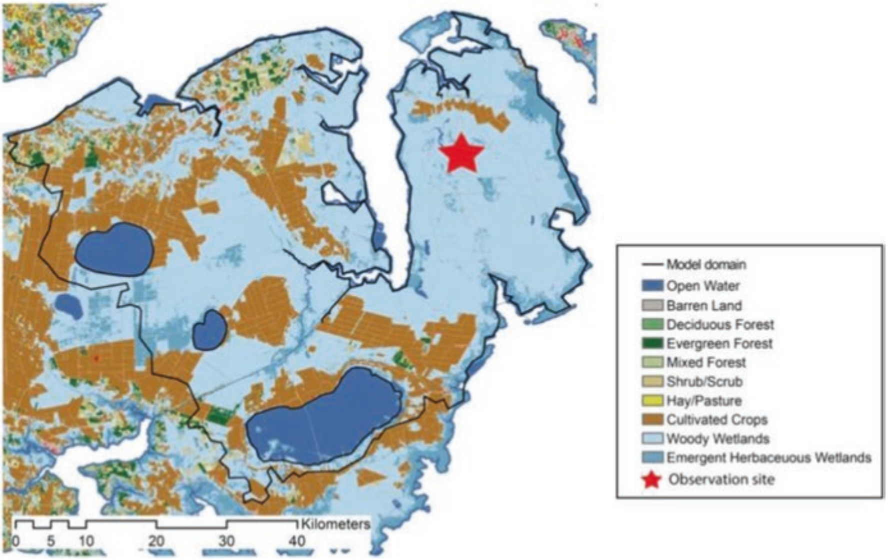

Fig. 18.1 The study area at the Alligator River coastal wetland in North Carolina, USA. The red star indicates the observation site (35°46′34″ N, 75°54′12″ W). The black lines indicate the model boundary (adapted from Zhang et al. (2019))

4.2 Model and Data

To capture the spatial heterogeneity of the coastal wetland in responding to climate disturbances, Zhang et al. (2019) implemented a physically based distributed hydrologic model, PIHM-Wetland, to simulate the change of surface water, unsaturated and saturated soil water, saltwater, and canopy water by simulating water exchange through canopy interception, infiltration, overland flow, channel flow, unsaturated water flow, saturated water flow, saltwater lateral flow, and evapotranspiration. PIHM-Wetland considers the hydrologic interaction between the upland river basins, coastal wetlands, and the ocean. The model was driven by the meteorological forcing from 1995 to 2014 from Phase 2 of the National Land Data Assimilation System (NLDAS-2) (Xia et al., 2012) and tide and sea level change from the same period from NOAA (National Oceanic and Atmospheric Association) tide and current observation (the Oregon Inlet Marina station, Station ID: 8652587). The soil and land cover parameters were derived from the national Gridded Soil Survey Geographic (gSSURGO) database (Soil Survey Staff, 2016) and the National Land Cover Dataset (NLCD) (Fry et al., 2011), respectively.

4.3 Quantification of Wetland Hydrologic Resilience

To characterize wetland hydrologic resilience, Zhang et al. (2019) used the following method: (1) the threshold intensity of climate disturbances that coastal wetland system could withstand without significant change in their hydrological function, and (2) the capability of recovering their hydrological function from disturbances to the pre-disturbance state. They also identified the change of the hydrological conditions as statistically significant when the change was at least one standard deviation above or below the climatological mean.

The proposed method in Zhang et al. (2019) emphasized the hydrological interactions among upland, coastal forested wetlands, coastal herbaceous wetlands, and the ocean, which together determine the hydrodynamics of coastal wetlands. They chose the groundwater table (GWT), overland flow rate (OFR), and water table of saltwater (ST) as indicators of wetland hydrologic resilience. Zhang et al. (2019) first identified climate variability and extremes (e.g., dry and wet years, large rainfall events, and droughts). Then, they quantified the hydrologic resilience by investigating the responses of GWT, OFR, and ST to climatic disturbances, such as drought, heavy rainfall, and sea level rise.

4.4 *Identification of Long-Term Climate Disturbances*

To better understand hydrological responses to climate disturbances, Zhang et al. (2019) classified the 20-year period into three dry years (1997, 2001, and 2007) and three wet years (1996, 2003, and 2009), where the annual precipitation anomaly is lower and higher than one standard deviation of the climatological mean precipitation (see Fig. 18.3). The remaining 14 years were the normal years. They also identified the heavy-rainfall events with a precipitation rate at the 75th percentile of the entire precipitation distribution, which is higher than 13 mm/day. There is no big variation of temperature, compared with the precipitation. The seasonal and annual variation of sea level was also analyzed. The seasonal sea level variation is relatively small (within 0.05 m). The annual sea level decreases in the first 7 years from 1996 to 2002, and then it gradually increased from 2003 to 2006. A clear drop in sea level was also observed in 2007 followed by a large increase in sea level from 2008 to 2014 (see Fig. 18.2).

4.5 *Hydrologic Resilience to the Climate Variabilities*

Zhang et al. (2019) analyzed the response of GWT to drought events with different durations at a daily scale. Figure 18.3 shows the lowest daily GWT of the forested and herbaceous wetlands within the continuous days of no rainfall for the wet and dry years, respectively. They found that the GWT of the forested wetland stays at a similar level in the wet years even when the duration of no rainfall reaches the maximum (9 days) (blue bars in Fig. 18.3a), which indicates that the forested wetland can absorb all of the drought disturbances in the wet years. Similarly, in the dry years, the forested wetland can absorb the drought disturbances when the duration of no rainfall is less than 6 days (orange bars in Fig. 18.3a). However, the GWT

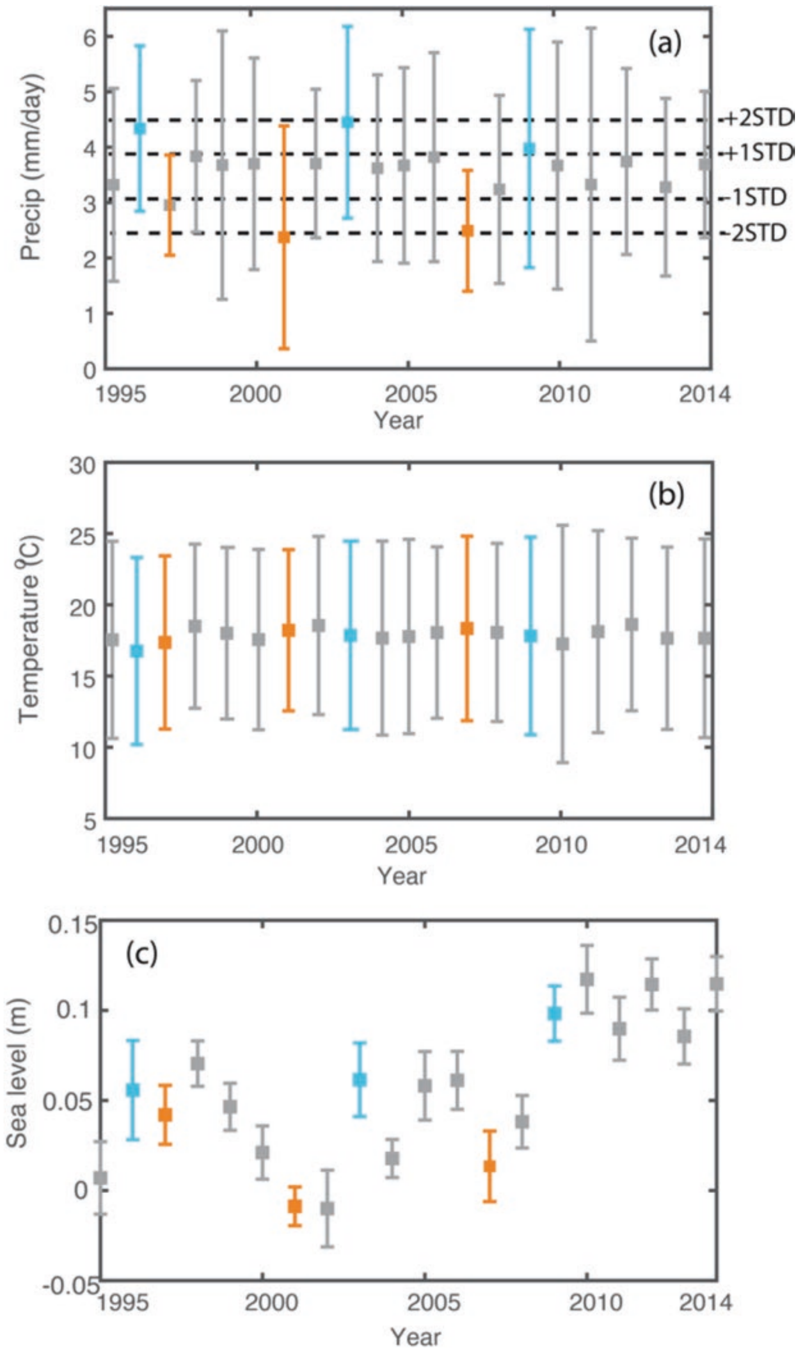

Fig. 18.2 Climate variability in annual (**a**) precipitation, (**b**) temperature, and (**c**) sea level. The orange bars indicate the dry years and the light blue bars are the wet years. (adapted from Zhang et al. (2019))

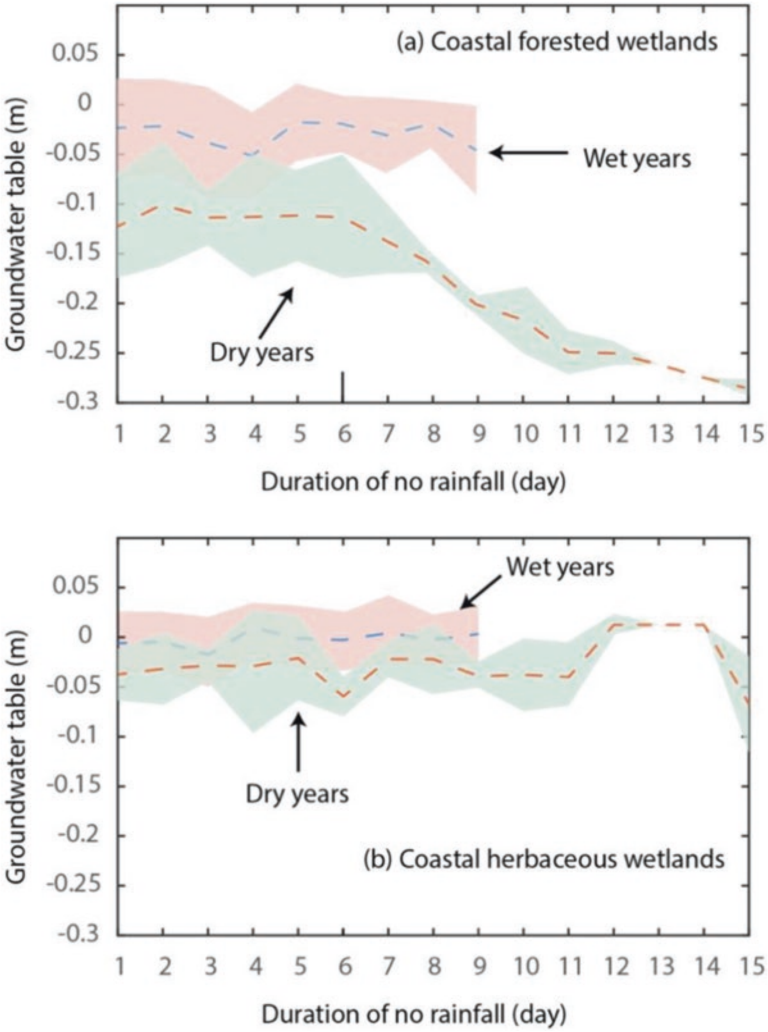

Fig. 18.3 The lowest daily GWT under drought events for (**a**) the forested wetlands and (**b**) the herbaceous wetlands. The blue and orange bars indicate the mean GWT and its one standard deviation for the wetland and dry years, respectively (adapted from Zhang et al. (2019))

dramatically decreases when the duration of no rainfall is greater than 6 days, which implies that the groundwater system of the forested wetland is not able to absorb those drought disturbances. Therefore, the resilience of the forested wetland to drought decreases after 6 days of no rainfall. For the GWT of the herbaceous wetlands (Fig. 18.3b), supported by the sea level, the GWT variations under drought events are small. No big drop of GWT is observed even when the duration of no rainfall reaches its maximum. Therefore, the herbaceous wetland is more resilient to drought, compared with the forested wetlands.

Zhang et al. (2019) also investigated the threshold response of overland flow to individual rainfall events on a daily scale (Fig. 18.4). In the dry years (Fig. 18.4b), almost no large overland flow occurred when rainfall was less than 30 mm/day because of sufficient soil water storage room for infiltration. However, a relatively large overland flow was observed in winter when GWT rose and soil water storage room decreased. In contrast, during the wet years, the overland flow rates were doubled or tripled, compared with the rates in the dry years in all seasons (Fig. 18.4b) due to limited soil water storage year-round. Therefore, for both the forested and herbaceous wetlands, the system is less resilient to rainfall in the wet years, while it is more resilient to rainfall in the dry years.

Last, Zhang et al. (2019) analyzed the saltwater table variation under sea level rise at the seasonal and interannual scales. The seasonal saltwater table variation was small (within 0.025 m) due to the slow response of the saltwater diffusion process to sea level change. Inter-annually, saltwater table variation was also small from 1995 to 2007, after which the saltwater table was elevated from 2008 to 2014. Therefore, coastal wetlands are more resilient to short-term sea level variation. However, a long-term sea level change has a dominant control on saltwater intrusion (Fig. 18.5).

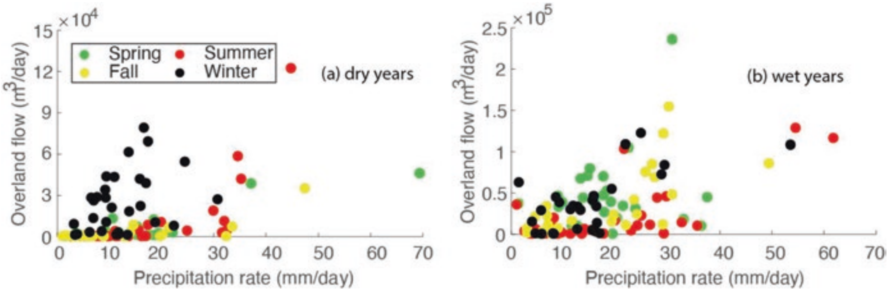

Fig. 18.4 Daily averaged overland flow rate as a function of precipitation rate for (**a**) the dry years and (**b**) the wet years. Dots of different colors indicate different seasons (adapted from Zhang et al., 2019)

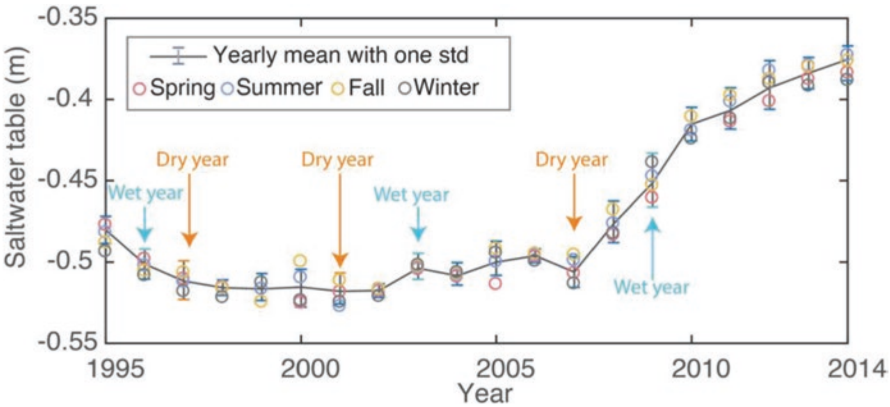

Fig. 18.5 Seasonal and yearly variation of the saltwater table from 1995 to 2014 (adapted from Zhang et al. (2019))

5 Conclusions

This chapter introduced the concept of coastal wetland hydrologic resilience: its definition, quantification method, related hydrologic processes, and climate impacts. Several key components have been highlighted that have not been well studied, such as the definition of hydrologic resilience, the identification of hydrologic conditions, the quantification method, and real-world applications. The case study described how to use a modeling approach to understand the spatial variation of hydrologic resilience in a real-world coastal wetland ecosystem. The selected metrics for quantifying hydrologic resilience to climate variabilities may apply to similar coastal wetlands in other regions.

This study identified several challenges in assessing coastal wetland hydrologic resilience: (1) identifying the tipping point of hydrologic states, passing which the hydrologic functions are significantly altered, (2) transforming hydrologic information (e.g., hydrograph) into resilience characteristics, and (3) quantifying the co-evolution of a system to better understand its hydrologic response. Future studies should focus on better integration of models and data to compile and extract information from different aspects of the hydrologic cycle at different scales. The development of high-resolution remote sensing data and machine learning techniques may be applied in the hydrologic resilience studies. Explicit integration of multi-scale, multi-process, co-evolving coastal hydro-eco-geomorphologic models for more accurate quantification of coastal wetland resilience is also important.

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