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A Comprehensive Review of Compound Inundation Models in Low-Gradient Coastal Watersheds

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Abstract

Extreme coastal flooding poses a major threat to human life and infrastructure. Low-gradient coastal watersheds can be vulnerable to flooding from both intense rainfall and storm surge. Here we present a comprehensive review of the most recent studies that quantify extreme flooding using variations of a compound inundation model. A compound inundation model may consist of different numerical models, observed data, and/or a combination of these. The definitions, advantages, and limitations of each joining technique are discussed with the goal of enabling and focusing subsequent research. Future investigation should focus on the development of a tight-coupling procedure that can accurately represent the complex physical interactions between storm surge and rainfall-runoff. A more accurate compound flood forecast tool can help decision-makers, stakeholders and authorities converge on better coastal resiliency measures that can potentially save human lives, aid in the design of structures and communities, and decrease property damage.

Keywords: storm surge; rainfall-runoff; compound flood; flood transition zone; tropical cyclone; inundation model.

1. Introduction

Coastal regions are vital for the advancement of society by supporting capital flows for tourism, industrialization, transportation, and urban development. Current projections for the United States (US) population that resides in low-gradient coastal zones indicates an increase of 145% by 2030 with respect to 2000 (Neumann et al., 2015). In addition, the US has 17 port cities with a population greater than 1 million (Wahl et al., 2015). Extreme coastal flooding is one of the hazardous elements that pose a major threat to human life and infrastructure (Bates et al., 2005; Bhaskaran et al., 2014; Moussa and Bocquillon, 2009; Padgett et al., 2008). Low-gradient coastal watersheds are vulnerable to flooding hazards from both intense rainfall and coastal storm surge penetration, which are produced from extreme meteorological events (e.g. tropical cyclones, low-pressure systems) (Bilskie and Hagen, 2018; Comer et al., 2017; McInnes et al., 2002; Moftakhari et al., 2017; Ray et al., 2011; Silva-Araya et al., 2018). Hurricanes were responsible for 40% of the global total deaths for all weather-related disasters from 1995 to 2015 (UNISDR and CRED, 2015). Also, three of the five costliest hurricanes that have impacted the US mainland and its territories occurred in the 2017 hurricane season (NOAA, 2018). Hurricanes Harvey, Irma, and Maria affected the Texas and Louisiana coasts, the Florida peninsula, and Puerto Rico and the U.S. Virgin Islands, respectively, in less than a month. These three hurricanes produced a total damage of $265,000 million (2017 USD) and were directly responsible for the loss of 183 human lives (Blake and Zelinsky, 2018; Cangialosi et al., 2018; NOAA, 2018; Pasch et al., 2018; Ward et al., 2018; Zscheischler et al., 2018). These natural hazards can be devastating with wide-ranging social (Comer et al., 2017; Karamouz et al., 2017a; Olbert et al., 2017), economic (Chen and Liu, 2014; Karamouz et al., 2015; Lian et al., 2013; Wang et al., 2015) and environmental (Costabile et al., 2013; Park et al., 2011; Stamey et al., 2007) consequences in low-gradient coastal watersheds around the world.

Floods can emerge from several mechanisms or driving forces (Bacopoulos et al., 2017; Serafin et al., 2019). Here, we limit focus on the flooding mechanisms produced by a tropical cyclone and extreme precipitation events, in which subsurface flow and storm-water systems are typically negligible. These flooding mechanisms can occur due to a single meteorological event (e.g. tropical cyclone that includes extreme precipitation) or by a combination of separate events that occur in close succession or simultaneously, such as when an intense and prolongated precipitation event occurs before any extreme wind event (e.g. tropical cyclone, prevalent strong onshore winds, low-pressure system). Figure 1 illustrates the flooding mechanisms typically considered during a cyclonic event in a coastal watershed. These mechanisms can produce flooding via:

i. Precipitation (rainfall): Intense or prolonged precipitation can induce surface runoff. Runoff moves from overland areas to a stream, increasing the streamflow rate to a point that exceeds the channel capacity and producing an out-of-bank flow (i.e. overbank flow) that inundates the floodplain (Figure 2).

ii. Storm surge: Storm surge is produced by high winds and low atmospheric pressure that drives oceanic waters to interact with the local coastal geometry. The total water level is temporarily raised and can penetrate inland to inundate the floodplain.

iii. Compound Flood: A combination of both mechanisms (i.e. rainfall-runoff and storm surge) that can occur simultaneously or in close succession, commonly referred as compound flooding (Bilskie and Hagen, 2018; Ikeuchi et al., 2017; Kumbier et al., 2018a; Paprotny et al., 2018; Saleh et al., 2017; Wahl et al., 2015; Ward et al., 2018; Zscheischler et al., 2018). Also, a compound flood can be produced by other flooding mechanisms that are not considered here, such as waves and tides (Blanton et al., 2018; Buschman et al., 2009; Comer et al., 2017; Olbert et al., 2017; Orton et al., 2018). For example, when both mechanisms (i.e. rainfall-runoff and storm surge) occur simultaneously, there is an increase in the flood hazard due to the combined effects of high river flow rates and elevated sea levels at the river outlet (e.g. estuarine or tidal river) (Erikson et al., 2018; Hubbert and McInnes, 1999; Ikeuchi et al., 2017; Maskell et al., 2014; Svensson and Jones, 2004; Tromble et al., 2010; Wahl et al., 2015). Therefore, storm surge and rainfall-runoff in coastal watersheds are not necessarily mutually exclusive hazards (Christian et al., 2015; Karamouz et al., 2017b; Torres et al., 2015).

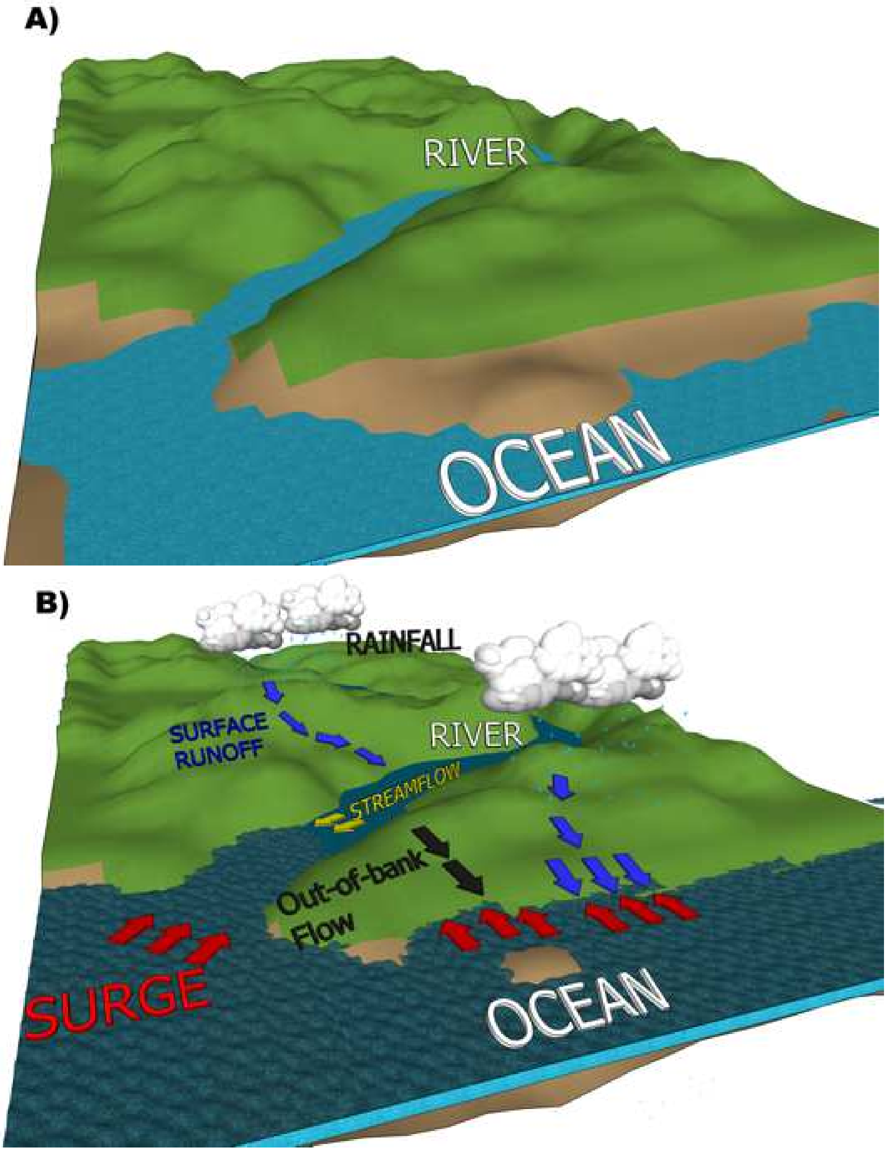

Figure 1. Flooding mechanisms generated by a tropical cyclone event in a coastal watershed. **A**) Illustration of the initial conditions and **B**) illustration of the conditions during the tropical cyclone-driven flooding. The initial condition serves as a reference for visualizing the inundated area along the coastline due to the tropical cyclone. Each colored arrow represents a different flooding mechanism. *(Use color figure for printed version) [This Figure will be a 2-column fitting image]*

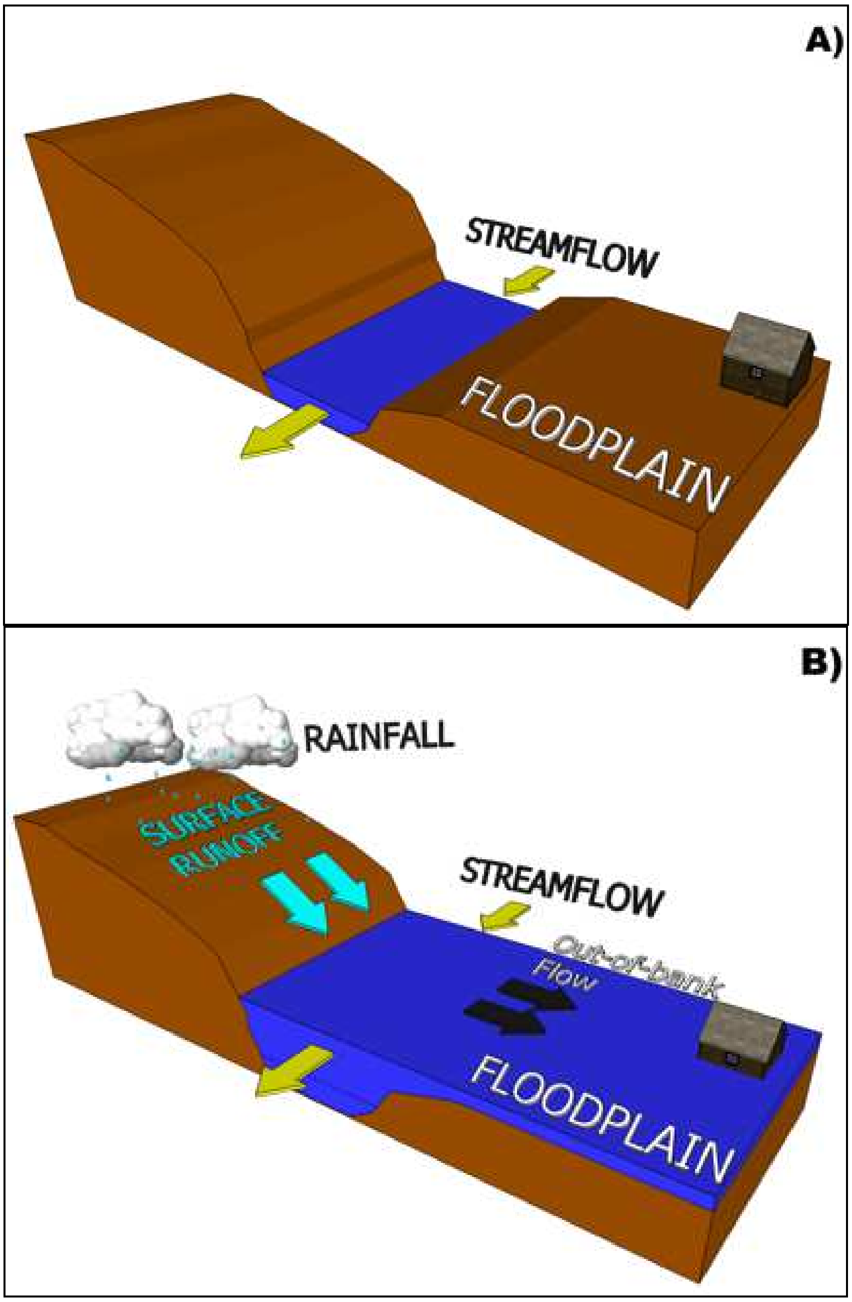

Figure 2. Flooding mechanism produced by an extreme precipitation event at a riverine floodplain. **A**) Illustration of the initial conditions and **B**) illustration of the conditions during the extreme precipitation event. The initial condition serves as a reference for visualizing the inundated area along the floodplain due to the out-of-bank flow. Each colored arrow represents a different flooding mechanism. *(Use color figure for printed version) [This Figure will be a 1.5-column fitting image]*

Since the early 2000s, studies have investigated the probability of storm surge and rainfall-runoff occurring simultaneously or in close succession. These studies highlight that these flooding mechanisms are present over different length scales, such as local scale (Kew et al., 2013; Klerk et al., 2015; Svensson and Jones, 2004; Thompson and Frazier, 2014; Zheng et al., 2014), continental scale (Moftakhari et al., 2017; Paprotny et al., 2018; Wahl et al., 2015; Zheng et al., 2013) and global scale (Ward et al., 2018). They depend on watershed properties, such as location and size. For example, Hurricane Florence (2018) produced a catastrophic flood in North Carolina (US), which was induced by intense and prolonged precipitation and high levels of storm surge that blocked the streamflow towards the estuaries (Almasy et al., 2018; Elliott, 2018). Therefore, it is critical to quantify the dependence between the flooding mechanisms (Bilskie and Hagen, 2018; Zheng et al., 2014).

As the effects of carbon emissions shape the Earth’s climate it is possible that extreme weather events and their compound effects will become more severe and frequent through increased sea levels (Bhaskaran et al., 2014; Bilskie et al., 2019; Ge et al., 2014; Karamouz et al., 2017a; Passeri et al., 2015b; Smith et al., 2012; Sweet and Park, 2014), river discharges (Paprotny et al., 2018; Zscheischler et al., 2018), and extreme precipitation (Chen et al., 2013; Feng and Brubaker, 2016; Karamouz et al., 2015; Wang et al., 2013). Observations indicate that hurricanes are expected to become stronger and more frequent, with the number of major storms (e.g. categories IV and V based on the Saffir-Simpson scale) increasing over the past 35 years along with ocean temperature (Anthes et al., 2006; Bender et al., 2010; Elsner, 2008; Emanuel, 2005, 1987; Holland and Bruyère, 2014; Lal, 2001; Lynn et al., 2009; Tang et al., 2013; van Aalst, 2006). In addition, projections of future climate indicate potential shifts in rainfall patterns toward stronger and more intense storms (Feng and Brubaker, 2016; Karamouz et al., 2015; Risser and Wehner, 2017; Trenberth et al., 2018; Wang et al., 2013). Understanding the hazard posed by the combination of extreme events under present and future sea levels is crucial for the successful management of coastal communities by means of effective coastal resilient measures. These measures may include a comprehensive understanding and the capability of modeling effectively both mechanisms (i.e. storm surge and rainfall-runoff) that produce these extreme flooding (Bacopoulos et al., 2017; Bhaskaran et al., 2014; Bilskie and Hagen, 2018; Dresback et al., 2013; Passeri et al., 2015b).

Flood inundation maps, useful for planning and management of riverine and coastal floodplains, are another important consideration regarding compound flooding. These maps are used to delineate no-build zones, flood insurance rates, identify evacuation routes for communities, issue early warning advisories, and as aid in the development of safe and cost-effective design criteria for hydraulic structures (e.g. bridges, culverts, levees, seawalls, flood gates, etc.) (Christian et al., 2015; Moftakhari et al., 2017; Silva-Araya et al., 2018; Torres et al., 2015). Common flood hazard assessment practices typically account for one mechanism at a time (e.g. rainfall-runoff or storm surge) and not their combination, whereas coastal cities are exposed to multiple flooding mechanisms(Bilskie and Hagen, 2018; Erikson et al., 2018; Klerk et al., 2015; Moftakhari et al., 2017; Orton et al., 2015; Serafin et al., 2019; Torres et al., 2015; Ward et al., 2018; Zscheischler et al., 2018). For example, the standard assumption with the Federal Emergency Management Agency (FEMA) flood zone mapping, with flood-hazard assessment studies and with operational systems, is that rainfall-runoff flooding can be neglected when modeling a storm surge event, since the impact of the cyclone is relatively short in comparison to the time it takes for any rainfall-runoff flooding to reach the coast (Blanton et al., 2018; Orton et al., 2018; Ray et al., 2011; Silva-Araya et al., 2018; Tang et al., 2013; Torres et al., 2015). This assumption has been shown to not always be correct since the time of arrival of both flooding mechanisms (i.e. storm surge and rainfall-runoff) depends on several factors such as watershed properties, antecedent conditions, and storm characteristics (Kumbier et al., 2018b; Orton et al., 2018, 2015; Santiago-Collazo et al., 2017; Silva-Araya et al., 2018).

There is an urgent need to simulate the potential compound effects of rainfall-runoff and storm surge flooding. A direct capability to define flood transition zones (Bilskie and Hagen, 2018) can lead to transdisciplinary research outcomes that will prove beneficial to society. Numerical models provide information about complex physical processes (e.g. compound flooding) and have shown to aid in disaster and evacuation planning, which is a critical tool for decision-makers (Blanton et al., 2018; Chen and Liu, 2014; Georgas et al., 2016; Kew et al., 2013; Olbert et al., 2017; Serafin et al., 2019). One of the flooding mechanisms that is often neglected in coastal inundation modeling (i.e. storm surge modeling) is rainfall-runoff. When it is considered, some physical processes are missing or simplified, such as momentum exchange of fluxes, which is important in delineating the spatial extent of the inundation (Maskell et al., 2014; Orton et al., 2018). Recently, compound inundation models have been focused on quantifying streamflow and storm surge interaction, while neglecting the out-of-bank flow/surface runoff and storm surge interaction. In addition, the direct effect of the precipitation over a study area (i.e. model domain) has also been neglected. The majority of these models have been implemented with loosely-coupled or linked techniques, which simplifies the interaction between both inundation models and may be misrepresenting the actual physical processes. In fact, Bilskie and Hagen (2018) demonstrate how the superposition of runoff with surge can overestimate total water levels. Modeling approaches that integrate multiple flooding mechanisms (e.g. storm surge, surface runoff, and streamflow) and simulate their compound influences would be more effective in supporting a wide range of decision-making (Orton et al., 2018; Saleh et al., 2017).

The current techniques for joining two or more numerical models can be summarized into four classifications: linking technique, loose-coupling, tight-coupling, and full-coupling (Table 1). These classifications vary on the technique employed to transfer or exchange information between each numerical model, which represents the individual physical processes. Flowcharts for each joining technique is shown in Figure 3. A linking technique is defined as a method that transfers the results from one model (i.e. courier model) to be used as an input for a second model (i.e. recipient model) as shown in Figure 3i (Silva-Araya et al., 2018; Sulis et al., 2010). This technique is also known as one-way coupling since the transfer of information only occurs in one direction (Cheng et al., 2010; Hühne et al., 2016). Usually, the courier model is run first and independently from the recipient model. Then, the results are transferred by means of boundary conditions to the recipient model, which is run with all the required input information and boundary conditions. Finally, the results from the recipient model are analyzed and if further changes are necessary to the courier model, the process will repeat again. An example of an application of this technique is the resulting wind field from an atmospheric model that is transferred as an input to an ocean circulation model.

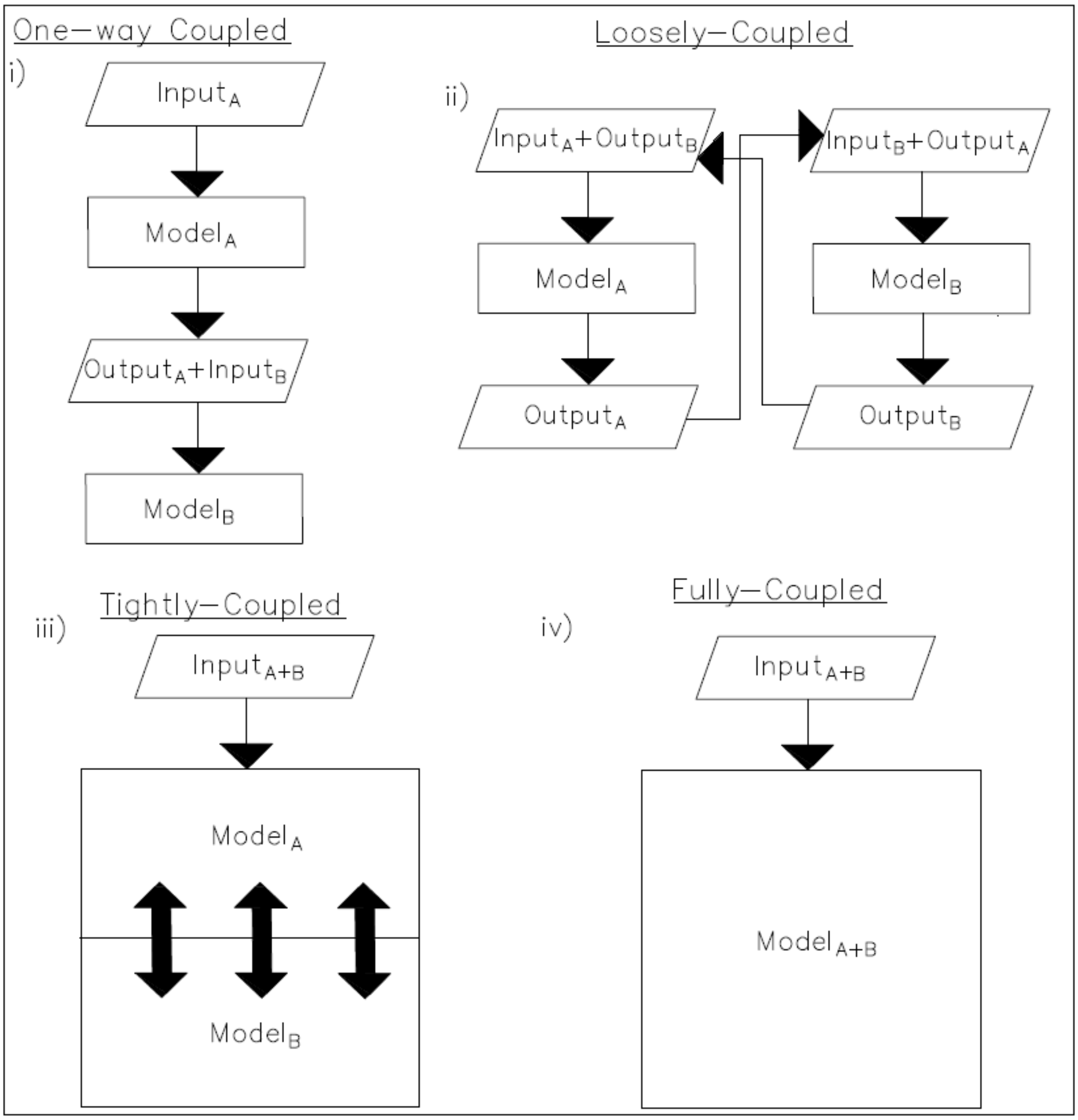

Figure 3. Flowcharts representing the four classifications of the different joining techniques used to combine different numerical models: A) one-way coupled, B) loosely-coupled, C) tightly-coupled, and D) fully-coupled. The parallelograms represent input or output data and the rectangles represent a numerical model. The arrows point towards the direction of the transfer/exchange of data. *[This Figure will be a 1.5-column fitting image]*

Alternatively, a loosely-coupled technique is defined as a method that couples models, which are run separately, using information exchange in an iterative manner (Figure 3ii) (Blanton et al., 2018; Goodall et al., 2011; Hühne et al., 2016; Sulis et al., 2010). This technique is also known as two-way coupling since the transfer of information occurs in two directions (Cheng et al., 2010; Hühne et al., 2016). The process of a loosely-coupled technique between two models (e.g.

model A and model B) can be described by the following: i) the results from model A are transferred to model B via boundary conditions; ii) model B uses this information to compute new results and transfer the new information to model A; iii) model A uses the information received to compute updated new results and transfers it to model B; iv) the process is repeated until it reaches the end of the simulation period.

On the other hand, a tightly-coupled technique is defined as a method that joins the independent models into a single modeling framework by combining their source code as shown in Figure 3iii (Blanton et al., 2018; Goodall et al., 2011). In other words, portions of the source code that describes the physical processes of model A are incorporated into the source code of model B or vice versa. This means that the information exchange between both portions of the code is performed internally within the same source code (i.e. computer memory) and does not involve the exchange of external input and output files. One example of this technique is the SWAN+ ADCIRC (Simulating Waves Nearshore model + ADvanced CIRCulation model) modeling framework. In this example, SWAN transfers wave radiation stresses to ADCIRC and ADCIRC transfers back to SWAN the updated wind velocities, water levels and currents (Dietrich et al., 2012, 2011b).

Lastly, a fully-coupled technique is defined as a technique in which the governing equations of all the physical processes considered (e.g. storm surge and rainfall-runoff) are solved simultaneously within the same modeling framework as shown in Figure 3iv (Hühne et al., 2016; Sulis et al., 2010). For example, WASH123D (WAterSHed Systems of 1-d Stream-River Network, 2-D Overland Regime, and 3-D Subsurface Media) model (Shih et al., 2012; Shih and Yeh, 2011; Yeh et al., 2011, 2005, 1998), in which many physical processes (e.g. streamflow, surface-runoff flow, subsurface flow) are represented using a common set of governing equations, such as the Navier-Stokes equations for describing motion of a viscous fluid. Unfortunately, WASH123D does not model storm surge conditions.

Coupling Technique	Definition
One-way	Computations that are transferred from one model and used as an input in another (i.e. linking technique)
Loosely	Separately-running models are coupled using information exchange in an iterative manner (i.e. two-way coupling)

Tightly	Independent models are integrated into a single modeling framework by combining their source code
Fully	Governing equations of all the physical processes considered are solve simultaneously within the same modeling framework

Table 1. Summary of the definition of the four joining techniques used to combine different numerical models.

The remainder of this paper consists of a review of the widely-used inundation models to simulate rainfall-runoff and storm surge in low-gradient coastal landscapes. Three categories of inundation models are discussed: rainfall-runoff driven, storm surge driven, and compound inundation models. The most recent and relevant studies using these models are described, including their advantages and limitations. Furthermore, the four classifications of compound inundation models, depending on the coupling approach, will be explained in additional detail. Finally, conclusions are drawn and future research is discussed.

2. Inundation Models

In the context of this paper, we focus on inundation models that are typically developed to quantify and delineate the flood zone due to a certain atmospheric event (e.g. tropical cyclone, low-pressure system, prolonged and intense precipitation event). Such models can be categorized by the mechanism that drives the flooding. We do not consider inundation models that account for subsurface flow (i.e. groundwater flow) and/or storm-water drainage systems or flooding from tsunamis. Due to the challenging numerical representation of the physical processes of a compound flood event, both types of models (i.e. rainfall runoff-driven and storm surge-driven) have been developed and used independently. With the advancement of computer technology and numerical modeling, both models have been recently one-way/loosely coupled to produce a better estimate of total water levels. The remainder of the section will discuss the inundation models driven by rainfall-runoff and storm surge, as well as the compound inundation model.

2.1. Rainfall Runoff-driven Inundation Models

A rainfall runoff-driven inundation model, commonly known as a hydrologic model, can be defined as the characterization of real hydrologic features and systems, such as rainfall-runoff, evapotranspiration, interception, infiltration, etc. In general, two types of hydrologic models have been developed and applied in recent years: conceptual-based, lumped-parameter hydrologic models and physically-based, distributed-parameter hydrologic models. These models differ in the mathematical representation of the hydrologic processes, spatial representation of the watershed properties, and data requirements (El Hassan et al., 2013). The conceptual-based, lumped-parameter hydrologic model assumes the watershed properties (e.g. soil type, land use cover, initial soil moisture, surface roughness, etc.) are uniform over the entire domain and may be used to simulate total watershed runoff using basin average input data and empirical parameters (Andréassian et al., 2004; El Hassan et al., 2013; Fatichi et al., 2016; Kalyanapu et al., 2009; Sharif et al., 2013; Torres et al., 2015). Such models produce reasonable estimates of runoff, but due to the distributed nature of hydrological properties, the models cannot accurately represent the spatial variation of the watershed conditions (El Hassan et al., 2013). However, a common workaround is to divide basins into hydrologically similar sub-basins to take advantage of the spatial resolution of rainfall and watershed properties (Sharif et al., 2013).

Alternatively, physically-based, distributed-parameter hydrologic models are capable of having a spatial distribution of precipitation and watershed properties through a computational grid. Thus, hydrologic processes (e.g. conservation of mass, momentum, and energy for overland runoff) are mathematically represented in each grid cell (El Hassan et al., 2013; Torres et al., 2015). Some advantages of these models include the capability to produce simulation data at any point within the model domain, initialization with minimal historical data, and greater flexibility in the calibration process for the watershed properties (Hunter et al., 2003; Sharif et al., 2013, 2010a; Torres et al., 2015). Contrarily, this type of hydrologic model may require more time to develop and greater computer power than the conceptual-based, lumped-parameter hydrologic models.

Usually, all types of hydrologic models are comprised of two primary components: rainfall-runoff estimation and a routing scheme to transport the rainfall-runoff. The routing scheme used in a hydrologic model can be a limitation for flood modeling since the “real” physical characteristics of the rivers are not considered (Nguyen et al., 2016). Therefore, hydraulic models have been used to simulate floods together with hydrologic models, in which the rainfall-runoff estimated from the hydrologic model is used as an input in the hydraulic model. Some of the most popular hydraulic models used are the Hydrologic Engineering Center- River Analysis System (HEC-RAS) model (Brunner, 2001), the MIKE HYDRO River (i.e. MIKE 11) model (Danish Hydraulic Institute, 1997), the LISFLOOD-FP model (Bates and De Roo, 2000), the

FLO-2D model (O'Brien et al., 1993), and the MSN_Flood model (Falconer, 1984). The HEC-RAS model, developed by the U.S. Army Corp of Engineers (USACE), computes the water depth in a river cross-section given a flow rate. This model is widely used due to its freely available software (Anees et al., 2016; Ray et al., 2011). Also, the LISFLOOD-FP model was designed by the University of Bristol to simulate floodplain inundation over complex topography (Bates et al., 2005; Bates and De Roo, 2000; Lewis et al., 2013; Smith et al., 2012). One of the main advantages of hydraulic models is that the modeling is based on the topography of the channel and floodplain, which is in accordance with the continuity and momentum principles and minimal parameters (Nguyen et al., 2016).

The selection of an appropriate hydrologic modeling methodology is a key step of any flood modeling system (Sharif et al., 2010b). This research only focuses on the to-date application of hydrologic models at the coast and are not necessarily including all rainfall runoff-driven inundation model advancements (e.g., Curtu et al., 2014; Demir and Krajewski, 2013; Elsaadani and Krajewski, 2017; Quintero et al., 2016). The USACE has developed two of the most popular conceptual-based, lumped-parameter hydrologic models: Hydrologic Engineering Center-1 (HEC-1) model and the Hydrologic Engineering Center- Hydrologic Modeling System (HEC-HMS) model. The HEC-1 model (Hydrologic Engineering Center, 1998) was developed in the 1990s and was replaced by the HEC-HMS model (Scharffenberg, 2016) in the early 2000s. HEC-HMS was originally designed to simulate the rainfall-runoff processes of drainage basins in a wide range of geographic areas and has been extensively used in the US (El Hassan et al., 2013).

The U.S. Environmental Protection Agency (EPA) has developed a conceptual-based, lumped-parameter hydrologic model named Storm Water Management Model (SWMM). It is used throughout the world for planning, analysis, and design related to storm-water runoff, combined and sanitary sewers, and other drainage systems in urban areas (Rossman, 2015). For long-term modeling, the Agricultural Research Service, from the U.S. Department of Agriculture (USDA), developed the Soil and Water Assessment Tool (SWAT) model to predict the impact of land management practices on water, sediment, and agricultural chemicals in large complex watersheds on a daily basis (Neitsch et al., 2002). In addition, this model has been used for quantifying rainfall-runoff flooding events when linked to other hydraulic models such as HEC-

RAS (Duvvuri and Narasimhan, 2013), international River Interface Cooperative (iRIC) model (Jamrussri and Toda, 2017), and LISFLOOD-FP (Rajib et al., 2016), and also for determining river discharges if used independently (Singh et al., 2005; Wu and Xu, 2006).

Within the category of physically-based, distributed-parameter hydrologic models, two of the most prominent models are the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Downer et al., 2002) and the Vflo hydrologic model (Vieux and Vieux, 2002). GSSHA was developed by the USACE as an enhancement to the hydrologic model CASC2D (Downer et al., 2003). GSSHA has been implemented on a wide variety of watersheds around the US to determine rainfall-runoff inundation for forecasting and evaluating extreme precipitation events (Chintalapudi et al., 2012; El Hassan et al., 2013; Hunter et al., 2003; Sharif et al., 2013, 2010b, 2010a, 2006; Yang et al., 2016). In a similar manner, the Vflo model has been applied under various watershed characteristics and conditions to estimate the real-time urban rainfall-runoff, evaluate flood control systems, and forecast flash floods (Fang et al., 2010; Kim et al., 2008; Looper et al., 2012; Looper and Vieux, 2012; Teague et al., 2013; Vieux et al., 2005). Other models such as the MIKE-SHE (Mike, 2017) and the Hydrology Laboratory-Research Distributed Hydrologic Model (HL-RDHM) (Colorado Basin River Forecast Center, 2008) have been also used for quantifying the rainfall-runoff inundation on different watersheds (Fares et al., 2014; Geoghegan et al., 2018; Kitzmiller et al., 2011; Nguyen et al., 2016; Sahoo et al., 2006; Wang et al., 2012; Xevi et al., 1997; Z. Zhang et al., 2008).

2.2. Storm Surge-driven Inundation Models

Coastal inundation is one of the most hazardous events that can occur on a low-lying coastal watershed and can result from a wide variety of environmental impacts (Bhaskaran et al., 2014). Storm surge is a temporary rise of the total water level at the coast generated by extreme wind and low atmospheric pressure (Krestenitis et al., 2011; Lewis et al., 2013; McInnes et al., 2002). To assess coastal flood hazards, an ocean circulation model is an essential component to predict water levels and inundation extent (Bates et al., 2005; Bhaskaran et al., 2014; Lewis et al., 2013). An ocean circulation model simulates the surges in water level due to wind-driven and pressure-induced events (i.e. storm surge events) and by astronomic tides. In addition, a wave-induced surge can be simulated by including the effects of wind-waves on storm surge by coupling between an ocean circulation model and a wave model. Wave models that have been coupled include the Simulating Waves Nearshore (SWAN) model (Booij et al., 1999), the Steady State Spectral Wave (STWAVE) model (Resio, 1987), and the WAVEWATCH-III (WW3) model (Sheng et al., 2010; Tolman, 2009). Some of the most popular ocean circulation models are Sea, Lake, and Overland Surges from Hurricanes (SLOSH) (Jelesnianski et al., 1992), the ADvanced CIRCulation (ADCIRC) (Luettich et al., 1992), the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), Delft3D (Deltares, 2009), and the Finite Volume Coastal Ocean Model (FVCOM) (Chen et al., 2003).

ADCIRC is a robust model that has been successfully validated with numerous historical hurricanes over varying coastal regions, such as the US Atlantic coast (Bacopoulos et al., 2012; Colle et al., 2008; Garzon and Ferreira, 2016; Hagen et al., 2012; Yin et al., 2016), the North Indian Ocean (Bhaskaran et al., 2014; Gayathri et al., 2016), and the Gulf of Mexico (Bilskie et al., 2016b; Bunya et al., 2010; Dietrich et al., 2011a; Hagen et al., 2012; Hope et al., 2013), with a high accuracy. ADCIRC has been used to produce real-time storm surge and wave forecast for the Northern Gulf of Mexico (Dietrich et al., 2013), the US Atlantic coast (Blanton et al., 2012; Dresback et al., 2013; Garzon et al., 2018), and the North Western Pacific Ocean (Suh et al., 2015). ADCIRC has also been used to simulate numerous synthetic storms, based on historical tracks and storm intensity, to explore the effects of these storms making landfall in another location and/or with greater storm intensity (Kennedy et al., 2012; Rao et al., 2013; Sebastian et al., 2014). Others have implemented ADCIRC for simulating coastal inundation for the past, present, and future conditions of the coastal landscape with or without projected sea level rise (Bilskie et al., 2019, 2016a, 2014; Passeri et al., 2015a; Siverd et al., 2018).

Similar to the ADCIRC model, the FVCOM model has been implemented on the wide variety of hurricane conditions, either in forecast or analysis mode, for several coastlines within the US mainland and the Korea Peninsula (J. Rego and Li, 2009; J. L. Rego and Li, 2009; Rego and Li, 2010; Weisberg and Zheng, 2006, 2008; Yang et al., 2014; Yoon and Shim, 2013, 2016). Similarly, the POM (Peng et al., 2006, 2004; Xia et al., 2008; Xie et al., 2008, 2004), SLOSH (Mercado, 1994; Murdukhayeva et al., 2013; K. Zhang et al., 2008), and Delft3d (Brown et al., 2007; Cranston and Tavendale, 2012) models have been implemented under complex environments for historical hurricanes.

2.3. Compound Inundation Models

Simulation of storm surge propagation in rivers and estuaries, including the backwater effects of river flow, is important for coastal inundation modeling in low-gradient coastal watersheds (Lewis et al., 2013). A compound inundation model consists of one or more numerical models that are combined with the aim of obtaining an accurate total water level. The numerical models that comprise a compound inundation model may be a combination of hydrologic, ocean circulation or hydraulic models. Commonly, these numerical models have been combined with each other using a one-way, loose-, or a tight-coupling approach. The definition of each joining technique has been defined previously in Section 1 and are summarized in Table 1. Implementation of full- and tight-coupling for these types of numerical models (e.g. hydrologic, ocean circulation, and hydraulic model) is more complicated than loose- or one-way coupling . This difficulty is attributed to the complex mathematical representation of their physical processes, the computational power required, and the temporal and spatial resolution (varying time and length scales) of the numerical models. For example, the fully-coupled WASH123D model has been used successfully in idealistic cases but has not been able to simulate real-world scenarios accurately. However, due to the continuous advances in computer technology, tight-coupling these numerical models is more feasible today than in the past.

Several efforts to couple both storm surge and rainfall-runoff have been developed in the last decade. The joining technique used for combining different models depends greatly on the physical processes to be simulated. For example, when coupling an ocean circulation model with a wave model, Funakoshi et al. (2008) found that numerical problems increased when the tight-coupling technique was used and that a loose-coupling technique may be sufficient to capture this interaction. Also, the physical interactions between the flooding mechanisms (e.g. atmospheric, hydrological, and coastal oceanic) are typically handled via loose-coupling (Blanton et al., 2018). Conversely, the tight-coupling technique is necessary to accurately account for watershed-nearshore interactions during storm events (Cheng et al., 2010). From the available literature, only one study used a loosely-coupled technique to produce the compound inundation model, (Cheng et al., 2010), which is described in Section 2.3.4. Also, only one study used a tightly-coupled technique to produce the compound inundation model, (Tang et al., 2013), which is described in Section 2.3.5. The remaining publications found used a linking technique and are summarized in Table 2 through Table 4, which lists the year it was published, the location of the study area, the numerical models used and the joining technique. These linked models are characterized based on the type of base model (i.e. recipient model) used when joining both the hydrologic and ocean circulation model. Therefore, they are categorized as i) linked hydrological model, ii) linked ocean circulation model or iii) linked hydraulic model. Unfortunately, studies that used a fully-coupled technique to produce a compound inundation model were not found in the available literature. The remainder of this section will focus on discussing published studies that employed a one-way, loosely-, and tightly-coupled technique.

2.3.1. Linked Hydrologic Model

Thirteen percent of the publications found used a linked hydrologic model for the compound model (See Table 2). This linking technique is based on independently running the ocean circulation model first, which requires wind speed and atmospheric pressure data as input. The results from the ocean circulation model (e.g. total seawater level) are used as an input for the hydrologic model, in addition to the precipitation data, by means of boundary conditions. The results from the linked hydrologic model can be considered as compound water level inundation. This procedure is summarized in Figure 4. For example, Silva-Araya et al. (2018) first employed an ocean circulation model (i.e. ADCIRC) to produce time series of total seawater level and used it as an input to a hydrologic model (i.e. GSSHA) by means of time-varying boundary condition points at the downstream end of the watershed. The studies within this category applied the models in coastal watersheds in the US mainland and its territories. The vast majority of these studies used the GSSHA hydrologic model, while ADCIRC was the most common ocean circulation model. Also, the majority of these studies used observed data from a tide gauge to force the hydrologic model instead of results from an ocean circulation model. Some studies considered future climate change conditions, including varying sea-level rise (SLR), precipitation, and storm characteristics, while others considered flooding scenarios from different return periods.

In a compound model that uses a linked hydrologic model, information is transferred at the boundary condition points located at the downstream end of the hydrologic model. The location of the boundary points limits the influence of the storm surge, which is typically greater at the river outlet (i.e. bay or estuary margin). These methods neglect any interaction between the rainfall-runoff and the storm surge in the coastal floodplain or in the flood transition zone (Bilskie and Hagen, 2018). For example, the interaction between the surface runoff/storm surge, and the out-of-bank flow/storm surge is not considered (See Figure 1). This can result in underestimating the total water level.

On the other hand, the low computational power needed for this technique makes it suitable for simulating multiple flooding scenarios within a short period. This technique requires less effort since only the hydrologic model has to be developed if observed data for storm surge is used instead of an ocean circulation model. Also, accurate flooding maps can be produced using this technique, since Karamouz et al. (2017b) reproduce the flooding map from Hurricane Sandy (2012) at lower Manhattan (New York City, NY) with a 3% overestimate of the floodplain area. Nevertheless, the conclusion from these studies supports the need for developing a more holistic model that can account for potential interactions between storm surge and rainfall-runoff.

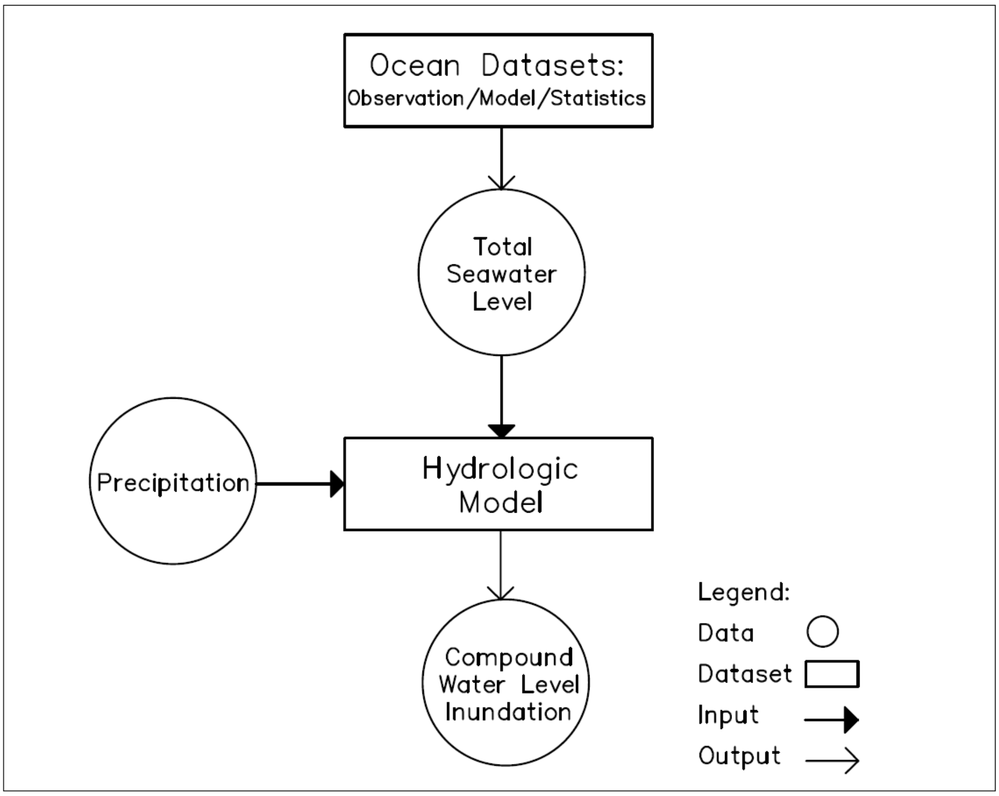

Figure 4. Flowchart that represents a compound inundation model using a linked hydrologic model. The ocean dataset can be obtained through a numerical model, observations or statistically simulated records. A legend

specifies which models and data (used as an input or an output) are used as part of the compound inundation model.

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Reference	Study Location	Modeled Event	Models Used	Linking Method
Karamouz et al., 2014	New York, US	Flooding Scenarios from different return periods considering future climate change	GSSHA*	Time-variant boundary conditions points of WSE
Loftis et al., 2016	Virginia, US	Hurricane Isabel (2003) and Irene (2011); Different Sea Level Rise Scenarios	Sub-grid Hydrological Transport Model*	Time-variant boundary conditions points of WSE
Santiago-Collazo et al., 2017	Puerto Rico, US	Hurricane Georges (1998)	ADCIRC, GSSHA	Time-variant boundary conditions points of WSE
Karamouz et al., 2017b	New York, US	Hurricane Irene (2011) and Sandy (2012); Flooding scenarios from different return periods	GSSHA*	Time-variant boundary conditions points of WSE
Karamouz et al., 2017a	New York, US	Flooding scenarios from different return periods	GSSHA*	Time-variant boundary conditions points of WSE
Silva-Araya et al., 2018	Puerto Rico, US	Hurricane Georges (1998)	ADCIRC, GSSHA	Time-variant boundary conditions points of WSE
Joyce et al., 2018	Florida, US	Varying SLR, storm characteristics, and precipitation for future scenarios at 2030	ADCIRC, SWAN, ICPR	Time-variant boundary conditions points of WSE

*Used observed data to represent the storm surge inundation in the compound inundation model.

Table 2. Summary of all the publications obtained that used a hydrologic model as the base model for a linked compound inundation model to estimate the total inundation due to an extreme atmospheric event. The publications are sorted in chronological order of published date.

2.3.2. Linked Ocean Circulation Model

Forty-five percent of the publications found used a linked ocean circulation model for the compound model (See Table 3). This linking technique is based on independently running the hydrologic model first, which requires precipitation data as input. The freshwater discharge results from the hydrologic model are used as an input for the ocean circulation model, in addition to the wind speed and atmospheric pressure data, by means of boundary conditions. The results from the linked ocean circulation model can be considered as a compound water level inundation. This procedure is summarized in Figure 5. For example, Dresback et al. (2013) first employed a hydrologic model (i.e. HL-RDHM) to produce freshwater discharge hydrographs and used them as input to their ocean circulation model (i.e. ADCIRC) by means of time-varying boundary condition points. The boundary condition points were located at four areas in the watershed, well upstream the coast where any tidal or storm surge effects would be experienced. The studies within this category applied this method to coastal watersheds in the US mainland, Taiwan, Australia, Germany, England, and the Korean Peninsula. The vast majority of these studies used the ADCIRC model, while HL-RDHM was the most used hydrologic model. In addition, the majority used observed streamflow data from a river gauge to force the ocean circulation model instead of using a hydrologic model. Some of these studies linked both numerical models through the use of time-variant boundary conditions of riverine discharge (i.e. freshwater flow), while others used river stage level to set boundary conditions, and some used time-invariant riverine flow-drive radiation boundary conditions. Only one study used rating curves (i.e. discharge versus water level plot).

In a compound model that uses a linked ocean circulation model, the boundary condition that transfers information from the hydrologic model is specified at the upstream end of the ocean circulation model. Usually, the location of these boundary condition points is upstream in the river system, where the influence of the estuary conditions (i.e. storm surge, tide, seawater level) can be neglected. A limitation of this approach is that the out-of-bank flow, which exits from the stream to the floodplain (See Figure 1 and Figure 2), is not considered in the total compound inundation model. Since when the freshwater discharge is transferred to the ocean circulation model as a boundary condition point, it only transfers data from a single point and the recorded or simulated discharge data may not include the out-of-bank flow. Chen and Liu (2014 and 2016) reported a mean absolute error ten times higher and a Root-Mean-Square (RMS) error nine times higher in the river than on the coast. This can be attributed to the lack of the out-of-bank flow processes within the linked model. Also, the precipitation that falls directly into the ocean circulation model domain is neglected. These precipitation amounts may be negligible, but it can be significant for slow-moving storms that dump an excessive amount of precipitation over a long period of time, such as Hurricane Harvey (2017) and Hurricane Florence (2018). Therefore, the surface runoff produced by this precipitation (i.e. rainfall-runoff) and the direct volume contribution over the seawater domain is not accounted for the total compound inundation. Despite these limitations, most studies demonstrated the importance of including the hydrology component in numerical simulation of compound inundation in low-lying coastal watershed during extreme atmospheric events (Bacopoulos et al., 2017; Bilskie and Hagen, 2018; Chen and

Liu, 2016, 2014; Herdman et al., 2018; Kumbier et al., 2018b; Maskell et al., 2014; Orton et al., 2012, 2018, 2015).

Similar to the linked hydrologic model, the low computational power needed for this technique makes it suitable for simulating multiple flooding scenarios within a short period of time. This can be useful as a first approximation of the flood levels when forecasting the impact of a tropical cyclone to a low-gradient coastal watershed. Some researchers had simulated water levels with RMS errors within 10.5cm to 34cm using this technique, which may be considered accurate when modeling surge events on the order of tens of meters (Bacopoulos et al., 2017; Georgas et al., 2016; Kumbier et al., 2018a; Orton et al., 2018). Also, this technique requires less effort since only the ocean circulation model has to be developed if observed data for riverine flow is used instead of a hydrologic model.

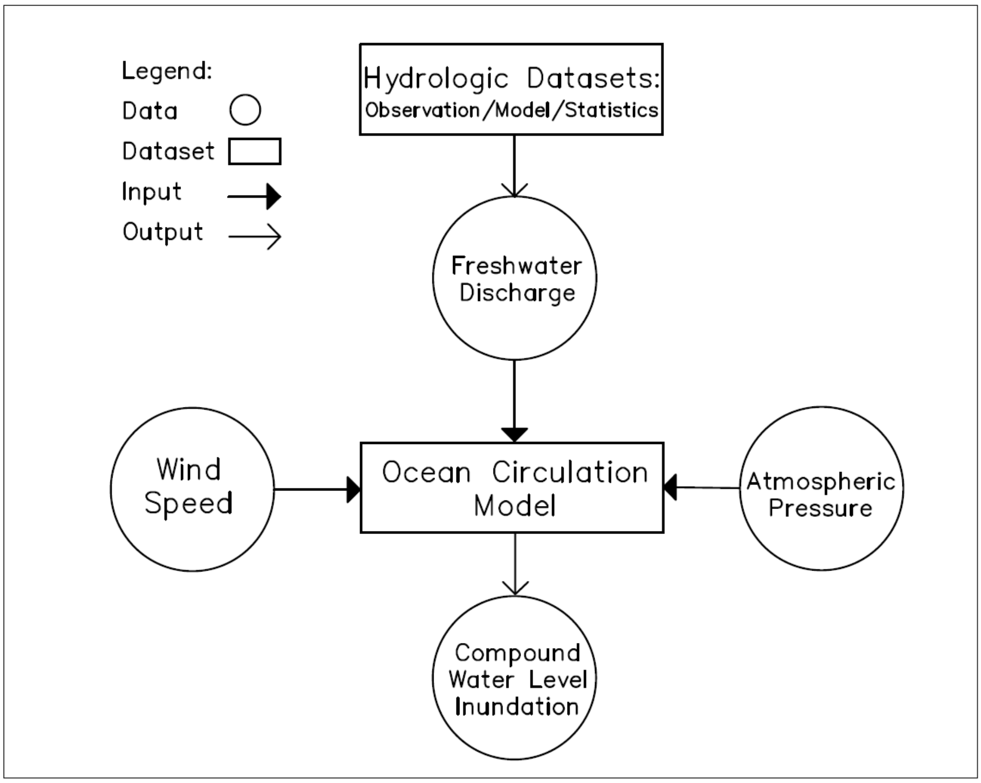

Figure 5. Flowchart that represents a compound inundation model using a linked ocean circulation model. The hydrologic dataset can be obtained through a numerical model, observations or statistically simulated records. A legend specifies which models and data (used as an input or an output) are used as part of the compound inundation model. *[This Figure will be a single column fitting image]*

Reference	Study Location	Modeled Event	Models Used	Linking Method
McInnes et al., 2002	Gold Coast, Australia	2 Tropical Cyclones (April 1989 and January 1974)	RAM, GCOM2D$^+$	Time-variant boundary conditions points of flow hydrographs
Stamey et al., 2007	Virginia & Maryland, US	Hurricane Isabel (2003), Tropical Storm Ernesto (2006), and November 2006 Northeastern storm	ELCIRC, ROMS, WRF, RAMS, AHPS	Time-variant boundary conditions points of flow hydrographs
Tromble et al., 2010	North Carolina, US	Tropical Storm Alberto (2006)	ADCIRC, HL-RDHM, Vflo	Rating curve boundary condition
Park et al., 2011	Korean Peninsula	Typhoon Meami (2003)	Holland model, MATLAB$^+$	Time-variant boundary conditions points of WSE
Tromble et al., 2011	North Carolina, US	Hurricane Floyd (1999)	ADCIRC, HL-RDHM	Time-variant riverine flow-drive boundary condition
Van Cooten et al., 2011	North Carolina, US	Hurricane Earl (2010) and Irene (2011); Tropical Storm Nicole (2011)	HL-RDHM, ADCIRC	Time-variant riverine flow-drive boundary condition
Orton et al., 2012	New York, US	Hurricane Irene (2011) and a March 2010 Northeaster storm	sECOM, WRF$^+$	Time-variant volume flux boundary condition
Blanton et al., 2012	North Carolina, US	Hurricane Irene (2011)	HL-RDHM, ADCIRC	Time-variant riverine flow-drive boundary condition
Martyr et al., 2013	Louisiana, US	Hurricane Gustave (2008)	ADCIRC$^+$	Time-variant riverine flow-drive radiation boundary condition
Dresback et al., 2013	North Carolina, US	Hurricane Irene (2011)	HL-RDHM, ADCIRC	Time-variant riverine flow-drive boundary condition
Kerr et al., 2013	Louisiana, US	Hurricane Betsy (1965), Camille (1969), Andrew (1992), Katrina (2005), Rita (2005), Gustav (2008), Ike (2008) and 15 hypothetical storms	ADCIRC$^+$	Time-invariant riverine flow-drive radiation boundary condition
Beardsley et al., 2013	Massachusetts, US	December 2010 Northeaster storm	FVCOM$^+$	Time-variant boundary conditions points of flow hydrographs
Chen and Liu, 2014	Tainan City, Taiwan	Typhoon Krosa (2007), Kalmegei (2008), Morakot (2009), and Haiyan (2013) (modified track)	SELFE$^+$	Time-variant boundary conditions points of flow hydrographs
Maskell et al., 2014	England, UK	Idealized sinusoidal hydrographs with M2 tides simulation	FVCOM, LISFLOOD-FP$^+$	Time-variant boundary conditions points of flow hydrographs and WSE

Ge et al., 2014	Hamburg, Germany	Winter Storm Anatol (1999) and Kyrill (2007); flooding from Anatol plus different SLR scenarios	FVCOM[+]	Time-variant boundary conditions points of flow hydrographs
Thompson and Frazier, 2014	Florida, US	Different Storm Intensities, SLR scenarios, and 24-hr rainfall depths	SLOSH, ICPR	Overlay analysis of 3 inundation hazard extent outputs
Orton et al., 2015	New York, US	533 Synthetic Tropical Cyclones	sECOM, Statistical Bayesian approach	Time-varying volume flux boundary condition
Chen and Liu, 2016	Kaohsiung City, Taiwan	Typhoon Kalmegei (2008), Morakot (2009), Fanapi (2010), Nanmadol (2011), and Talim (2012)	SELFE[+]	Time-variant boundary conditions points of flow hydrographs
Georgas et al., 2016	New York & New Jersey, US	Winter Storm Jonas (2016)	sECOM-NYHOPS, sECOM-SNAP, HMS-HYDRO	Time-variant boundary conditions points of flow hydrographs and WSE
Bacopoulos et al., 2017	Florida, US	Tropical Storm Fay (2008)	SWAT, ADCIRC	Time-variant riverine flow-drive boundary condition
Bilskie and Hagen, 2018	Louisiana, US	Historic Flood August (2016) and Hurricane Gustav (2008)	ADCIRC[+]	Time-variant riverine flow-drive boundary condition
Blanton et al., 2018	North Carolina, US	Hurricane Isabel (2003)	WRF, CREST, ADCIRC	Time-variant riverine flow-drive boundary condition
Orton et al., 2018	New York, US	76 historical storms (1900-2010)	sECOM, Statistical Bayesian approach	Time-variant volume flux boundary condition
Erikson et al. (2018)	San Francisco, US	Flooding scenarios from different return periods considering future climate change	CoSMoS[+]	Time-variant boundary conditions points of flow hydrographs
Herdman et al. (2018)	San Francisco, US	Flooding scenarios from different forcing combinations	Delft3D-Flow[+]	Time-invariant boundary conditions points of river discharge
Lee et al. (2019)	Korean Peninsula	Typhoon Maemi (2008)	Delft3D-Flow, HEC-HMS	Time-variant boundary conditions points of flow hydrographs

[+] Used observed data to represent the rainfall-runoff inundation in the compound inundation model.

Table 3. Summary of all the publications obtained that used an ocean circulation model as the base model for a linked compound inundation model to estimate the total inundation due to an extreme atmospheric event. The publications are sorted in chronological order of published date.

2.3.3. Linked Hydraulic Model

Thirty-eight percent of the publications found used a linked hydraulic model for the compound model (See Table 4). This linking technique is based on independently running the hydrologic model and the ocean circulation model first with their required data inputs (e.g. precipitation, wind speed, and atmospheric pressure). The results from the hydrologic model (e.g. freshwater discharge) and the ocean circulation model (e.g. total seawater level) are both used as inputs for the hydraulic model by means of boundary conditions. The results from the linked hydraulic model can be considered as compound water level inundation. This procedure is summarized in Figure 6. For example, Torres et al. (2015) first employed a hydrologic model (i.e. Vflo) and ocean circulation model (i.e. ADCIRC) to produce freshwater discharge hydrographs and total seawater levels to be used as inputs to a hydraulic model (i.e. HEC-RAS) by means of time-variant boundary condition points at upstream and downstream portions of the watershed, respectively. The studies within this category applied this method to coastal watersheds in the US mainland, China, United Kingdom, Ireland, Bangladesh, and Taiwan. The vast majority used the HEC-RAS hydraulic model. In addition, the majority of these studies used, in a combination or separately, observed data from a river gauge and/or a tide gauge to force the hydraulic model instead of using a hydrologic model or an ocean circulation model, respectively. All of these studies employed a linking technique with the use of time-variant boundary conditions points of freshwater discharge, time-variant boundary conditions points of seawater level elevation, or a combination of both.

In a compound model that uses a linked hydraulic model, the boundary condition that transfers information from each model (e.g. hydrologic and ocean circulation model) are specified at two different locations within the hydraulic model. The hydrologic model passes information at the upstream end of the hydraulic model, while the ocean circulation model passes information at the downstream end of the hydraulic model. One of the limitations of this approach is the additional effort of developing a third model (i.e. hydraulic model) to estimate the compound inundation. The development of a model may require the collection and processing of data, as well as the calibration and validation of the model. Also, most of the ocean circulation models (e.g. FVCOM, ADCIRC) have the capability of computing the flow hydrodynamics as the hydraulic model, and therefore, at some instance, it may substitute the hydraulic model from their compound model configuration. Similar to the approach of using an ocean circulation model to link both models, the direct effects of the precipitation over the model domain is neglected. Since the hydraulic model does not have the capacity to transform rainfall into surface runoff, the total compound inundation may be underestimated. However, for most of these studies, the implementation of a hydraulic model (i.e. 1D models) with boundary conditions derived from hydrologic and ocean circulation models (i.e. 2D/3D models) can be a viable approach to reduce numerical modeling gaps that exist for coastal rivers (Christian et al., 2015; Ikeuchi et al., 2017; Mashriqui et al., 2010, 2014; Ray et al., 2011; Skinner et al., 2015; Torres et al., 2015).

This technique requires less effort since only the hydraulic model has to be developed if observed data for storm surge and riverine flow are used instead of an ocean circulation model and a hydrologic model, respectively. Also, this technique may be useful to estimate the flood levels in the transition zone (Bilskie and Hagen, 2018) since this technique extends well enough upstream to isolate the effects of the storm surge in the riverine flow at the upstream boundary and extends well enough downstream to isolate the effects of the riverine flow in the storm surge. This linking technique can estimate accurate water levels since some researchers had simulated water levels with RMS errors within 15cm to 27cm (Comer et al., 2017; Feng and Brubaker, 2016; Mashriqui et al., 2014; Olbert et al., 2017; Wang et al., 2014).

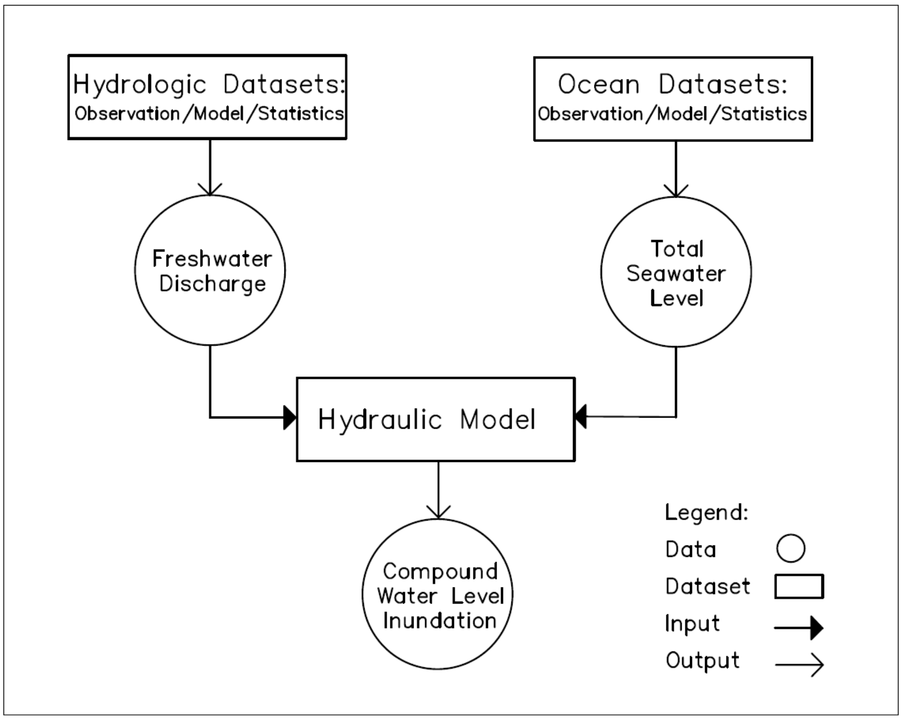

Figure 6. Flowchart that represents a compound inundation model using a linked hydraulic model. The ocean and hydrologic dataset can be obtained through a numerical model, observations or statistically simulated records. A legend specifies which models and data (used as an input or an output) are used as part of the compound inundation model. *[This Figure will be a single column fitting image]*

Reference	Study Location	Modeled Event	Models Used	Linking Method
Mashriqui et al., 2010	Washington D.C., US	Hurricane Isabel (2003) and 1996 Historical Flood	HEC-RAS [*, +]	Time-variant boundary conditions points of flow hydrographs and WSE
Ray et al., 2011	Texas, US	Hurricane Ike (2008)	HEC-RAS, HEC-HMS*	Time-variant boundary conditions points of flow hydrographs
Lian et al., 2013	Fuzhou City, China	Typhoon Longwang (2005) and flooding scenarios from different return periods.	HEC-RAS[*, +]	Time-variant boundary conditions points of flow hydrographs
Chen et al., 2013	Tainan City, Taiwan	Typhoon Haitang (2005) and Kalmaegi (2008); flooding scenarios from different return periods.	SELFE, ArcGIS[+]	Time-variant boundary conditions points of flow hydrographs and WSE
Mashriqui et al., 2014	Washington DC, US	Hurricane Isabel (2003)	HEC-RAS[*, +]	Time-variant boundary conditions points of flow hydrographs and WSE
Wang et al., 2014	New York, US	Hurricane Sandy (2012)	SELFE, UnTRIM^{2} [+]	Time-variant boundary conditions points of flow hydrographs

Loftis et al., 2014	New York/New Jersey, US	Hurricane Sandy (2012)	Sub-grid Inundation Model$^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE
Torres et al., 2015	Texas, US	Hurricane Katrina (2005), Ike (2008), and Isaac (2012)	HEC-RAS, Vflo, ADCIRC+SWAN	Time-variant boundary conditions points of flow hydrographs
Christian et al., 2015	Texas, US	Hurricane Ike (2008)	ADCIRC, Vflo, HEC-RAS	Time-variant boundary conditions points of flow hydrographs
Karamouz et al., 2015	New York, US	Flooding scenarios from different return periods considering future climate change	HEC-RAS, SWMM, MLP	Time-variant boundary conditions points of flow hydrographs and WSE
Skinner et al., 2015	Humber Estuary, UK	December 5, 2013 Storm	CESAR-Lisflood$^{*,+}$	Time-variant boundary conditions points of WSE
Wang et al., 2015	Washington DC, US	Hurricane Isabel (2003)	UnTRIM^{2} $^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE
Feng and Brubaker, 2016	Washington DC, US	Future flood scenarios due to climate change	HEC-RAS$^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE
Olbert et al., 2017	Cork City, Ireland	November 2009 Extreme Flood	POM, MSN_Flood^{+}	Time-variant boundary conditions points of flow hydrographs and WSE
Comer et al., 2017	Cork City, Ireland	November 2009 Extreme Flood	POM, MSN_Flood^{+}	Time-variant boundary conditions points of flow hydrographs and WSE
Saleh et al., 2017	New York/New Jersey, US	Hurricane Irene (2011) and Sandy (2012)	HEC-RAS 2D, HEC-HMS, sECOM-NYHOPS, sECOM-SNAP	Time-variant boundary conditions points of flow hydrographs and WSE
Ikeuchi et al., 2017	Bangladesh	Cyclone Sidr (2007)	CaMa-Flood, GTSR, MATSIRO-GW	Time-variant boundary conditions points of WSE
Sopelana et al., 2018	Betanzos, Spain	40 characteristic cases from a 500-yr long time series	Iber$^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE
Kumbier et al. (2018b)	New South Wales, Australia	Low-Pressure Cyclone (June 2016)	Delft3D-Flow$^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE
Kumbier et al. (2018a)	New South Wales, Australia	Low-Pressure Cyclone (June 2016) plus different SLR scenarios	Delft3D-Flow$^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE
Serafin et al. (2019)	Washington, US	Joint water surface level and discharge events from probabilistic simulations	HEC-RAS$^{*,+}$	Time-variant boundary conditions points of flow hydrographs and WSE

*Used observed data to represent the storm surge inundation in the compound inundation model; $^+$Used observed data to represent the rainfall-runoff inundation in the compound inundation model.

Table 4. Summary of all the publications obtained that used a hydraulic model as the base model for a linked compound inundation model to estimate the total inundation due to an extreme atmospheric event. The publications are sorted in chronological order of published date.

2.3.4. Loosely-Coupled Models

As mentioned before, only one publication that used a loosely-coupled technique for developing a compound model was found (Cheng et al., 2010). When both numerical models are loosely-coupled, the zone where both flooding mechanisms (i.e. storm surge and rainfall-runoff) interact must be specified using boundary condition points. This technique will require transferring the results from one model to another at a certain time interval specified by the user. A third party software typically carries out the exchange of information. This tight-coupling technique is based on running the hydrologic model and the ocean circulation model with their required data inputs (e.g. precipitation, wind speed, and atmospheric pressure) simultaneously. The results from each model (e.g. freshwater discharge and total seawater levels) are used as inputs to the other model (e.g. freshwater discharge used as an input to the ocean circulation model) by means of boundary conditions and the models are run again with their new inputs. The results from the loosely-coupled hydrologic/ocean circulation model can be considered as compound water level inundation. This procedure is summarized in Figure 7.

For example, Cheng et al. (2010) loosely-coupled an ocean circulation model (i.e. ADCIRC) with a hydrologic model (i.e. pWASH123D) using this boundary condition points. They simulated Hurricane Katrina (2005) impact over the Mississippi (US) coast using synthetic rainfall instead of the actual hurricane rainfall. A limitation of this approach is that the interaction between the two models occurs at the coastline only, where it could naturally occur upstream in the river outlet or in the coastal floodplain. Nonetheless, this technique is capable of improving the interaction between both flooding mechanisms (i.e. rainfall-runoff and storm surge) since their results supported the use of a loose-coupling technique over the linking technique for watershed-nearshore interaction. For example, the comparison of results between different coupling techniques (e.g. one-way vs two-way) shows a difference in river stage and in overland water depth of 60cm and 1.0m during the storm peak, respectively. Therefore, the linking technique may be insufficient for intense storms since the greatest watershed-nearshore interaction is during the storm peak.

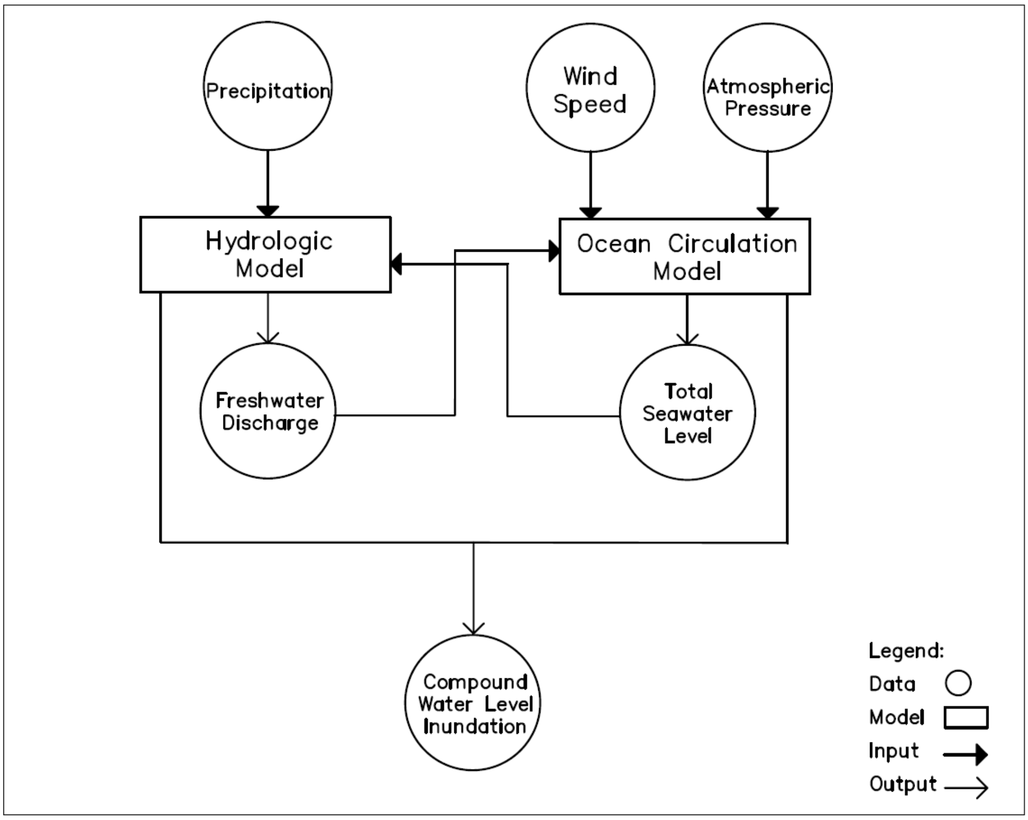

Figure 7. Flowchart representing the loosely-coupling between an ocean circulation model and a hydrologic model for the compound inundation model. A legend specifies which models and data (used as an input or an output) are used as part of the compound inundation model. *[This Figure will be a single column fitting image]*

2.3.5. Tightly-Coupled Models

Only one publication that used a tightly-coupled technique for developing a compound model was found (Tang et al., 2013). Tight-coupling two numerical models at code level require that the mathematical representation of one of the physical processes (e.g. storm surge or rainfall-runoff) be included in the numerical code of the other model. This approach is more complicated than the boundary condition method since it involves programming and modifying the numerical model algorithm. Tang et al. (2013) used this approach to couple a hydrologic model (i.e. Flood Potential Model) to an existing loosely-coupled hydraulic/ocean circulation model (i.e. FVCOM and Shallow Water Model). They simulated varying storm conditions with different sea-level rise scenarios over the New Jersey (US) coastline. A limitation of their study is that the hydrologic model used does not consider any infiltration, precipitation losses, surface routing scheme or runoff volume computations. Some physical processes, such as infiltration, are often neglected for a simplified case but in some cases contributes to improving the results. For example, when Loftis et al. (2016) considered infiltration their mean difference between modeled and observed water levels reduced from 10% to 2-5%. Also, the equations that represent their hydrologic model are implemented within the other model on a per-pixel basis, which may not capture the full-physics behind each physical process. On the other hand, this technique requires less effort since only one numerical model has to be developed. Also, this technique requires the running of only one numerical model, which might be computationally more expensive, and may require less user interaction versus when multiple numerical models need to be run sequentially or simultaneously.

3. Conclusion and Future Research

Extreme weather events may bring intense rainfall and high storm surges along their trajectory. Surface runoff is produced when an excess of water cannot infiltrate to the soil and this excess is transported across the landscape by means of the gravity force until it reaches a channel or a river. Storm surge is produced by a combination of strong winds blowing towards the shore and the uplift of the water surface due to a decrease in barometric pressure. These two flooding mechanisms can affect low-gradient coastal watersheds and their frequency is increasing due to effects of climate change (Chen et al., 2013; Feng and Brubaker, 2016; Karamouz et al., 2017a; Passeri et al., 2015b). Also, these flooding mechanisms can occur simultaneously or in close succession (i.e. compound flooding), which can exacerbate flooding for coastal communities. Some recent examples are Hurricane Florence (2018) that brought record-breaking rainfall (912-mm) to North Carolina, while a 3.0-m maximum storm surge was recorded at the Neuse-Pamlico estuary (Erdman, 2018; The Weather Channel, 2018). Also, Hurricane Harvey (2017) was the most significant tropical cyclone rainfall event in US history producing a storm total rainfall of 1539-mm and a 3.2-m maximum storm surge within the Texas region (Blake and Zelinsky, 2018). Therefore, there is an urgent need to develop new technologies that are capable to comprehensively study and simulate compound flood events.

Many numerical models or algorithms have been developed to determine the flooding caused by rainfall-runoff in the past few decades. Similarly, numerical models for computing coastal inundation caused by tropical cyclones have been developed. Researchers have coupled both numerical models (i.e. hydrologic and ocean circulation model) successfully using various approaches (e.g. one-way, loosely-, tightly-coupled technique) to quantify compound inundation brought by a cyclonic event. The linking technique may be useful as a first attempt to quantify the compound inundation since it requires less effort and computational resources than loosely- or tightly-coupling techniques. However, it neglects many of the natural interactions between both flooding mechanisms, such as storm surge/surface runoff, storm surge/out-of-bank flow, and storm surge/streamflow interactions. Also, the direct effects of the precipitation over the model domain are neglected, while the additional effort of developing a third model (e.g. hydraulic model) may be time-consuming. However, despite the use of the coupling technique (e.g. loosely or tightly), some limitations are still encountered, such as limiting the exchange of information to a single boundary (e.g. coastline only) and not including essential components of the hydrologic model (e.g. infiltration, precipitation losses, surface routing scheme or runoff volume computations). To address the current limitations for compound inundation estimates, future research should focus on the following:

i. Assessments of compound flood events in low-gradient coastal regions must move beyond the current one-way and loosely-coupled techniques to tightly- and fully-coupled approaches. Fortunately, computational resources can now favor tight-coupling techniques
ii. The direct effect of the precipitation falling over the entire model domain must be assessed. This domain includes the ocean circulation model domain, the hydrologic model domain, and the transition zone (Bilskie and Hagen, 2018) between both flooding mechanisms. The contribution can be included by means of an increase in the volume of water at the ocean domain and as a surface rainfall-runoff computation at the land surface where both flooding mechanisms interact. Also, these contributions can be included by using a tightly-coupled technique to introduce the corresponding equations within the hydrodynamic model.

iii. The complete interaction between storm surge and rainfall-runoff at the coastal floodplain must be quantified. These interactions include storm surge/surface runoff, storm surge/out-of-bank flow, and storm surge/streamflow. They may be accounted for by means of tight-coupling techniques.

To the authors' knowledge, no numerical model that considers all possible interactions (e.g. storm surge/surface runoff, storm surge/out-of-bank flow, and storm surge/streamflow) between both storm surge and rainfall-runoff in a single framework has been developed, published, or employed in practice. Despite that many researchers have stated that there is an urgent need for such a modeling framework (Cheng et al., 2010; Herdman et al., 2018; Mashriqui et al., 2010, 2014; Orton et al., 2012; Serafin et al., 2019; Skinner et al., 2015; Thompson and Frazier, 2014; Wang et al., 2015). A comprehensive compound inundation model that considers all physical processes can describe a more complete interaction between the flooding mechanisms that commonly occur during an extreme event (e.g. hurricanes or typhoons). The improvement in describing this interaction can translate into a more realistic simulated total flood hazards in coastal watersheds, which affects millions of people around the world. This comprehensive compound inundation model can serve as a more accurate complete flood forecast tool that can help decision-makers and authorities create better coastal resiliency measurements (e.g. delineation of no-build zones and flood insurance map) and emergency plans (e.g. identifying evacuation routes for communities and issuing early warning advisories) that can save lives and reduce damages to property.

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