MODELING FLOOD INUNDATION & HYDROLOGICAL CONNECTIVITY ACROSS THE CONGAREE RIVER FLOODPLAIN, CONGAREE NATIONAL PARK

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ABSTRACT. An understanding of the factors controlling the permanent and episodic links between the main stem of a river and the various waterbodies lying in its alluvial floodplain is critical for evaluating the influence of modern river processes on floodplain ecology and habitat diversity, and for the successful implementation of flow regimes that meet human needs for water in a manner that sustains the ecological integrity of affected systems. In this study, we examined relationships between river hydrology and lateral hydrological connectivity, which is crucial to directing fluxes of water, material, and organisms into and across a floodplain. We did so by translating measures of river discharge for the Congaree and Wateree Rivers into high resolution maps of flood conditions for the floodplain at Congaree National Park using a 2-D flood inundation model. Observed flood depths for a specific event in levee breaches, the primary point where flood waters initially enter the floodplain prior to bankfull discharge, were generally predicted with an accuracy of ca. 15-20 cm. Utilizing a graph network approach, we then analyzed the connectivity of floodplain waterbodies to the mainstem river and to other floodplain waterbodies under different flows. Our methods demonstrate the sensitive and non-linear response of floodplain connectivity to river flows and provide useful information to facilitate the management of flood processes in the Congaree River watershed.

INTRODUCTION

The structure, composition and function of southern floodplain ecosystems are shaped by complex interactions among hydrology, geomorphology and ecology (Sharitz and Mitsch 1993). These interactions are especially evident in places where actively migrating alluvial rivers create cutoffs of meander bends that persist as ox bow lakes and other abandoned channel waterbodies. Such features are the sources of numerous ecosystem services and benefits, including flood water storage and flood wave attenuation, habitat provision for aquatic and wetland species, non-point source pollution mitigation, and recreation (Kellison and Young 1997).

The ecological integrity and values of abandoned channel waterbodies are directly influenced by their hydrological connectivity with active channel mainstem rivers (Poff et al. 1997; Hudson et al. 2012). Unfortunately, floodplain systems have suffered from extensive fragmentation and deterioration due to flow alterations, urbanization, commercial harvesting, and clearing for agriculture, both globally (Opperman et al. 2010) and in the Southeast (McWilliams and Rosson 1990). The creation of levees, which disconnect floodplains from mainstem channels, has further impaired the health and integrity of remaining systems and complicated efforts to manage and restore degraded areas (Franklin et al. 2009). Collectively, these human impacts have made the maintenance of hydrological connectivity of critical interest to scientists and wetland resource managers (Brinson et al. 1995; Phillips 2011).

While hydrological connectivity operates on four distinct dimensions of fluvial hydrosystems, we focused on *lateral connectivity*, “the permanent and episodic links between the main course of a river and the various waterbodies lying in the alluvial floodplain” (Amoros and Bornette, 2002: 761). Specifically, we documented changes in floodplain connectivity related to hydrological regime as expressed by changing surface connections, which are crucial to directing fluxes of water, material, and organisms into and across a floodplain. We did so by creating high resolution maps of flood conditions for the floodplain at Congaree National Park using a LiDAR-derived digital terrain model and 2-D flood inundation modeling. We then utilized a graph network approach to quantify the connectivity of 22 floodplain waterbodies to the mainstem river and each other under varying flows.

METHODS

The study site was the floodplain at Congaree National Park (NP), which is located downstream of Columbia, SC. Originally set aside as a national monument in 1976 and re-designated as a national park in 2003, Congaree NP protects the largest intact expanse of old-growth bottomland hardwood floodplain forest in the southeastern U.S. It has been named a Ramsar Wetland of International Importance and an International Biosphere Reserve, and as such, one of its central functions is to serve as an environmental baseline for research and resource monitoring. The floodplain contains numerous abandoned channel waterbodies that differ in their time since formation, ranging from dozens to thousands of years, and stages of development. We selected 22 perennially flooded features that varied in their location on the floodplain and expected hydrological connectivity.

Flows of the Congaree River for the 1940-2010 period of record varied considerably, with daily mean discharge averaging 180 m^3s^{-1}, lowest flows measuring less than 30 m^3s^{-1}, and highest flows exceeding 4,248 m^3s^{-1} (USGS 02169500). To translate discharge data into floodplain inundation maps, we used a spatially-distributed, 2-D unsteady flow hydrodynamic model developed to simulate flow patterns in coastal waterways, estuaries, and river floodplain environments (Syme 1991). Previous applications of floodplain inundation modeling at Congaree NP by Meitzen (2009) and Kupfer et al. (2010) used the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis Systems (HEC RAS) model, which produces static 1-D maps of water surface elevations by coupling a digital elevation model and peak stream flow information. In both studies, the static 1-D model provided valuable information for analyzing large-magnitude floods that inundate the entire floodplain, (i.e. 100-year floods). However, the 1-D scheme lacks the functionality for modeling the complex, dynamic overland flow processes that are central in driving floodplain connectivity during lower discharge flows (e.g., 1-5 year recurrence floods). In bottomland ecosystems, these frequent seasonal floods drive the process-pattern controls linked to the flood dynamics which maintain specific ecosystem functions.

We therefore used a 2-D model, TUFLOW. 2-D models offer many advantages over 1-D models, including their ability to model flow accumulation and movement through multiple, intricately-connected overland flow pathways (Horritt and Bates 2002). This advantage is particularly important for modeling distributary and backwater flood pulses that occur with greater frequency, as is the case at Congaree NP. TUFLOW thus provides a more useful platform for examining pulse flows that control the frequency and duration of inundation and shape the lateral dispersal of sediment, seeds, nutrients, and organisms from the mainstem river to the floodplain and its waterbodies.

TUFLOW required four primary inputs: (1) a high-resolution topographic data set with terrain elevations for the river channel and floodplain surface, which we developed using LiDAR-derived bare-earth elevation points of the floodplain and a hydrographic sonar survey of the river channel bed profile, (2) stream discharge and accompanying water-surface elevations, based on USGS gage data, (3) flow resistance “roughness” parameters, which were estimated using a combination of data layers including floodplain hydrography, our digital terrain model, aerial photography, and forest community surveys, and (4) model boundary conditions that relate the terrain and flow data. Simulated flood depths were validated using surface water elevations from a stage gage on Cedar Creek, and twelve additional depth measurements collected during the peak of a 1-year recurrence flow event. Flood depth measurements were collected from floodplain channels that breach the natural levee complex and hydraulically connect the main stem river to the floodplain interior. Modeled flood depths were generally within 15-20 cm of field observed depths.

To examine the relationship between hydrological responses and floodplain inundation and connectivity, we selected a range of discharge levels on the basis of an annual flood frequency analysis, which calculates the probability that a given flood event will occur in any single year based on the historic annual peak flow record. Conrads et al. (2008) calculated duration hydrographs for the Congaree River and recognized the “normal” range of flows to occur between the 25-75th percentile range which included flows between 115-700 m^3s^{-1}. Our additional analyses allowed us to select ten flows, ranging from lower discharge events that occur multiple times per year but only inundate portions of the floodplain, to less common higher discharge events that inundate most or all of the floodplain.

Surface hydrological connectivity was determined by mapping all areas inundated during a given discharge event. To account for potential inaccuracy in the source data and insure that surface connectivity better related to functional connectivity, we only counted pixels with flood depths exceeding 30 cm as ‘flooded’. We then calculated least cost distances (Adriaensen et al. 2003) between each pair of waterbodies and the mainstem river. Finally, to quantify the degree of hydrological connectivity associated with each waterbody and with the overall network of waterbodies, we calculated: (1) the number of abandoned channel waterbodies connected to the Congaree River, (2) the average minimum connection distance to the mainstem river for all connected waterbodies, and (3) the mean number of connections to other waterbodies within 10 km.

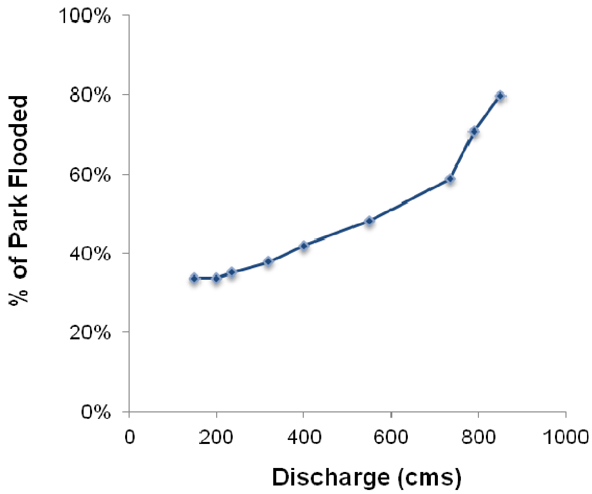

Figure 1. Percentage of the area within Congaree NP flooded as a function of Congaree River discharge.

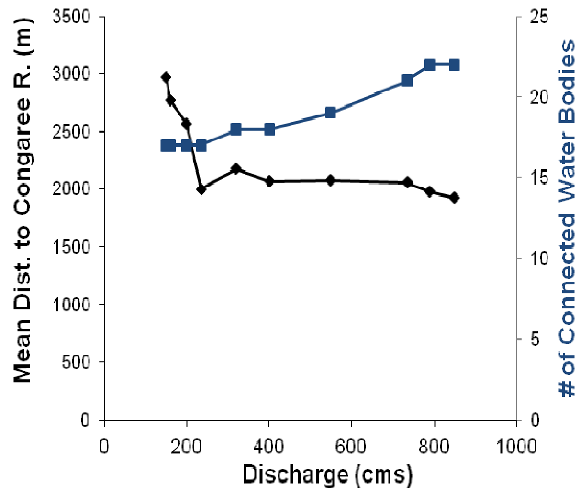

Figure 2. Number of abandoned channel waterbodies connected to the mainstem Congaree River, and the average minimum connection distance.

RESULTS

Hydrological connectivity between the river and floodplain was noted by Conrads et al. (2008) and Doyle (2009) to begin at an elevation of 30 m on the Congaree River, which corresponds to a flow discharge of 225 m^3s^{-1}. Results of our simulations support this general finding but provide a much richer and spatially-detailed picture of flood processes and hydrologic regimes at the park.

At the lowest flows examined (150-235 m^3s^{-1}), roughly 35% of the park was flooded (Fig. 1). Inundation was initiated through back-flooding of Cedar Creek, Old Dead River (an abandoned meander connected to the river), and several breaches in the channel banks. Flood waters were then distributed away from the river to the floodplain interior through a dense network on internal flow pathways. The greatest flood depths were in abandoned meander features, floodplain channel networks, and low-lying backswamp areas. At these stages, 17 of the 22 abandoned channel waterbodies were connected to the mainstem river, with a mean distance of more than 2.5 km (Fig. 2). Waterbody connectivity was greatest in the low-lying Bates Fork and Riverstone areas of the eastern portion of the park, and promoted *via* backflooding of Cedar Creek in the central part of the park (Fig. 3a).

Flood extent increased steadily for discharges between 320-735 m^3s^{-1} (Fig. 1), with inundation still driven by backflooding, the activation of levee breaches, and flood transport through the network of floodplain channels. Additional waterbodies that were not connected to the Congaree River by surface flows at lower discharges become connected, and the mean distance of connected waterbodies to the mainstem river decreased, eventually

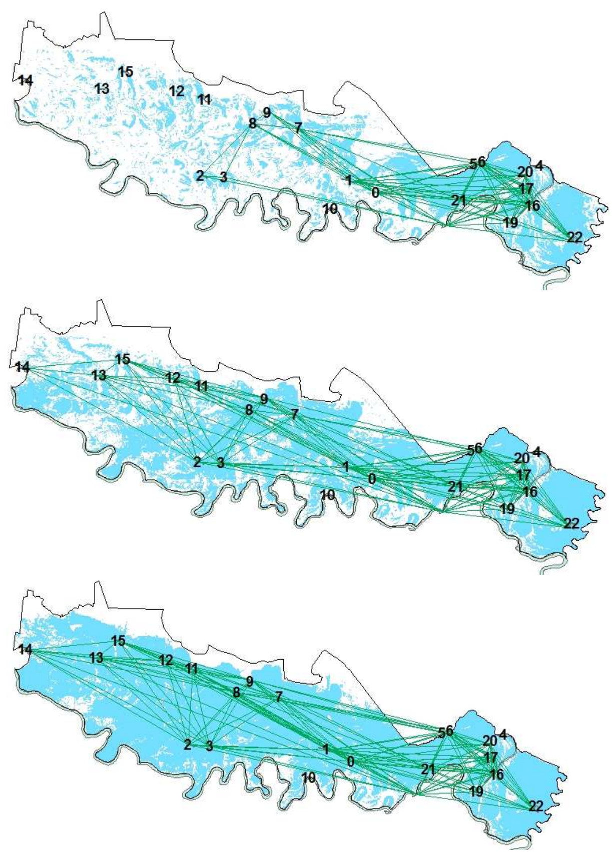

Figure 3. Maps showing all waterbodies linked within a distance of 10 km for three discharge values: 160 m^3s^{-1} (top), 735 m^3s^{-1} (middle) and 850 m^3s^{-1} (bottom). Flooded areas are shown in blue.

leveling off at 2 km (Fig. 2). Connectivity continued to increase in the central and western portions of the park (Fig. 3b), but many natural levee sites remained dry during the peak of these low discharge events.

At discharges > 735 m^3s^{-1}, flood extent increased rapidly as nearly the entire floodplain was inundated due to the widespread initiation of overbank flooding (Figs. 1 and 3). All of the waterbodies were connected to the mainstem river (Fig. 2), although the nature of the connections differed from that during lower discharge events, as many waterbodies were connected directly by cross-floodplain flows rather than backflooding up larger channels or movements through distributary channel networks. The mean distance of waterbodies to the mainstem river decreased slightly.

CONCLUSIONS

Understanding the nature of linkages among rivers and their floodplains is vital for a range of reasons. Such connections channel the movements of water, sediment and nutrients that are crucial for maintaining ecosystem processes. The length, timing and nature of connections are also central to maintaining biotic and genetic diversity, for example, in providing habitat access for floodplain spawning fish species or promoting exchanges of genetic material among aquatic species in abandoned channel waterbodies. In the long term, results from these efforts can facilitate water management strategies that help to promote resource stewardship while protecting floodplain resources.

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