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Characteristics and causal factors of hysteresis in the hydrodynamics of a large floodplain system: Poyang Lake (China)

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ABSTRACT

A previous modeling study of the lake-floodplain system of Poyang Lake (China) revealed complex hysteretic relationships between stage, storage volume and surface area. However, only hypothetical causal factors were presented, and the reasons for the occurrence of both clockwise and counterclockwise hysteretic functions were unclear. The current study aims to address this by exploring further Poyang Lake's hysteretic behavior, including consideration of stage-flow relationships. Remotely sensed imagery is used to validate the water surface areas produced by hydrodynamic modeling. Stage-area relationships obtained using the two methods are in strong agreement. The new results reveal a three-phase hydrological regime in stage-flow relationships, which assists in developing improved physical interpretation of hysteretic stage-area relationships for the lake-floodplain system. For stage-area relationships, clockwise hysteresis is the result of classic floodplain hysteretic processes (e.g., restricted drainage of the floodplain during recession), whereas counterclockwise hysteresis derives from the river hysteresis effect (i.e., caused by backwater effects). The river hysteresis effect is enhanced by the time lag between the peaks of catchment inflow and Yangtze discharge (i.e., the so-called Yangtze River blocking effect). The time lag also leads to clockwise hysteresis in the relationship between Yangtze River discharge and lake stage. Thus, factors leading to hysteresis in other rivers, lakes and floodplains act in combination within Poyang Lake to create spatial variability in hydrological hysteresis. These effects dominate at different times, in different parts of the lake, and during different phases of the lake's water level fluctuations, creating the unique hysteretic hydrological behavior of Poyang Lake.

1. Introduction

Interactions between floodplains, rivers and/or lakes create significant exchanges of water, sediments, nutrients and organic matter, providing fundamental structure and function for wetland plants and aquatic animals (Maltby and Ormerod, 2011; Zedler and Kercher, 2005). In addition to providing unique habitats, particularly for migratory species, floodplains also play an essential role in attenuating flood peaks through the temporary storage of floodwater (Bullock and Acreman, 2003; Hung et al., 2012). The hydrology of floodplains is a function of complex interdependencies between floodplains and adjoining rivers or lakes, involving both surface and subsurface flow pathways (Bates et al., 2000). In some cases, the relationships between different factors pertaining to floodplain hydrological processes have spatial and temporal variations that exhibit some degree of hysteresis (Bates et al., 2000; Hung et al., 2014).

Hysteresis refers to the non-uniqueness of relationships between two variables that arises under cyclic variations (such as seasonal wetting and drying in the case of floodplains), leading to a lag in parameter values depending on the direction of fluctuation (Ewing, 1885). Hysteretic functions have been encountered within a wide range of hydrological processes. These include the moisture retention functions of soils during cyclic wetting and drying (Werner and Lockington, 2006; Zhang et al., 2009), relationships between saturated soil water content and subsurface flow during hillslope runoff events (Norbiato and Borga, 2008), and the stage-discharge rating curves of rivers (Ajmera and Goyal, 2012; Fread, 2007).

Hysteresis in the hydrological relationships that describe water movement and storage within floodplains arises in a number of forms. For example, Rudorff et al. (2014) found hysteresis in the relationship between flooded area and water level in the large

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Curuai floodplain, located in the lower reach of the Amazon River. This was attributed to bathymetric features of the Curuai floodplain that direct flood waters to different regions of the floodplain, depending on whether the water level is rising or falling (Rudorff et al., 2014). Hughes (1980) observed hysteresis in the relationship between floodplain inundation volume and the discharge within the neighboring Teifi River (Wales). During recession periods, ponded water remained within the floodplain due to restrictions to drainage, such as slow flows through ebb channels and subsurface pathways. This led to larger inundation volumes during recession relative to periods of flow accession, for a given channel discharge (Hughes, 1980).

Recently, Zhang and Werner (2015) observed hysteretic functions in area-volume-stage relationships for the lake-floodplain system of Poyang Lake (China) based on hydrodynamic modeling. They observed for the first time both clockwise and counterclockwise hysteretic relationships in a single setting. Various modeling scenarios were created to examine the influence of the upstream (i.e., catchment inflows) and downstream (i.e., Yangtze River) boundary conditions, and the role of surface roughness. They concluded that the upstream condition has more influence on the development and magnitude of hysteresis than the downstream condition. In addition, the degree of hysteresis increased for higher values of surface roughness, particularly in relation to the surface roughness of floodplains rather than regions of permanent inundation. Zhang and Werner's (2015) analysis of hysteresis was based on model simulations (MIKE 21) and has not been substantiated by direct field measurements. What's more, the conditions leading to clockwise and counterclockwise hysteretic relationships have not been established.

This paper aims to extend the knowledge of Poyang Lake hysteretic relationships provided by Zhang and Werner (2015) through the application of remotely sensed imagery and measured data, and by adding catchment inflows and Yangtze River discharge to the list of hydrological parameters that are considered in terms of their hysteretic behavior. It is anticipated that the results of the current study will provide insights into hysteretic processes occurring within other large lake-floodplain settings, such as Lake Tinco (Venezuela; Hamilton and Lewis, 1987), Lake Calado (central Amazon in Brazil; Lesack and Melack, 1995), Lake Tonle Sap (Vietnam; Kummu et al., 2014), and Dongting Lake (China; Chang et al., 2010), where the degree of hysteresis in hydrological relationships has not be determined. The purposes of this research are to: (1) validate Poyang Lake's hysteretic stage-area relationships using remotely sensed imagery; (2) investigate relationships between the flow patterns of the Yangtze River and the Poyang Lake catchment, and lake stage; (3) evaluate the clockwise and counterclockwise hysteresis encountered by Zhang and Werner (2015). The results of this study are expected to provide a more comprehensive understanding of hysteretic behavior within similar systems comprising extensive floodplains and considerable seasonality in water levels.

2. Description of study area

Poyang Lake is located in the middle reach of the Yangtze River (China), within the range 28 °24′–29 °46′N and 115 °49′–116 °46′E (Fig. 1). The catchment topography varies from mountainous (with maximum elevation of about 2200 m above sea level) to floodplain regions (around 30 m above sea level), covering an area of some 1.62×10^5 km^2 (Zhang et al., 2014). The catchment area of the river gauging stations shown in Fig. 1 is 1.37×10^5 km^2, leaving an ungauged area of 0.25×10^5 km^2, which includes the lake surface (Zhang et al., 2014). Land use data from 2005, interpreted from remotely sensed imagery, were categorized into forest (57%), farmland (29%), water bodies (6%), urbanization (6%), pasture (1%) and bare land (1%), with minor changes since 2000 (Li et al., 2014). The catchment has a subtropical wet climate. The mean annual precipitation during 2001–2010 was 1620 mm, calculated from 14 national meteorological stations (Fig. 1), with 53% falling between March and June (Fig. 2). The mean annual evapotranspiration from the catchment was 780 mm during the period 2001–2010, based on the remote sensing investigation by Wu et al. (2013). The mean annual temperature during the same period was 18.1 °C, with summer average (June–August) 27.5 °C and winter average (December–February) 7.7 °C.

Poyang Lake has the most expansive floodplains in China. The extent of flooding varies seasonally under the combined effects of catchment inflow and interactions with the Yangtze River. The lake area varied between 714 and 3163 km^2 during 2001–2010 (Feng et al., 2012). Hydrodynamic models and remote sensing have been applied to study the hydrology of Poyang Lake, and in particular to investigate the seasonal variation in water surface area (Feng et al., 2012; Wu and Liu, 2015a). Previous studies have shown that Poyang Lake has experienced modified conditions in terms of water level and surface area behavior in recent years (e.g., Wu and Liu, 2015a). This has been at least partly attributed to modified interactions between the Yangtze River and Poyang Lake, resulting from the construction and operation of the Three Gorges Dam (Lai et al., 2014; Liu et al., 2016; Zhang et al., 2012).

Poyang Lake receives inflows from five major rivers: the Ganjiang, Xinjiang, Fuhe, Xiushui and Raohe Rivers, for which gauging data are available from national hydrological stations near their downstream limits (Fig. 1). The Lake is connected to the Yangtze River through a relatively narrow channel at its northern extremity. Flows between Poyang Lake and the Yangtze River are monitored at Hukou Station (Fig. 1).

Previous attempts to quantify the water balance of Poyang Lake have been made by Zhang et al. (2014). They attributed the outflow at Hukou Station to the summation of gauged runoff, ungauged runoff, groundwater net inflow to the lake and the change in lake volume. In their study, long-term (1953–2010) average outflow at Hukou was 1490×10^8 m^3/y. The average gauged inflow was 1230×10^8 m^3/y. The groundwater inflow was just 1.3% of the water balance and the unknown water balance component, including ungauged runoff and lake volumetric change, was 21% of the inflow. During 2001–2010, the respective proportions of gauged runoff from the Ganjiang, Xinjiang, Fuhe, Xiushui and Raohe Rivers were 57.6%, 14.8%, 9.7%, 9.3% and 8.6%. The average gauged catchment inflow (2001–2010) to Poyang Lake was 1150×10^8 m^3/y. The average inflow from the ungauged catchment area was determined through simple linear extrapolation of the gauged runoff, and equal to 180×10^8 m^3/y. The mean annual precipitation of the lake was about 1650 mm and the potential evaporation was about 1000 mm estimated using the data of nearby meteorological stations (i.e., the Boyang, Lushan and Nanchang Stations; Fig. 1) and Penman-Monteith equation (Allen et al., 1998), leading to average net inflow (rainfall minus evaporation) to the lake surface is relatively small (approximately 13×10^8 m^3/y) based on a mean lake surface area of about 1900 km^2. The average net outflow to the Yangtze River, obtained from gauged records (2001–2010) at Hukou Station, was 1430×10^8 m^3/y. This value accounts for occasional inflows from the Yangtze River (i.e., "backflow"; Li et al., 2017). The difference between average inflows and outflows to Poyang Lake during 2001–2010 is about 270×10^8 m^3/y, or 23% of the total inflow, including groundwater flux into the lake. The above-mentioned estimates of lake water balance components neglect changes in lake storage, because a 10-year average was used and the change in lake storage between the start and end dates was relatively small.