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Research papers

Spatial-temporal changes in the longitudinal functional connectivity of river systems in the Taihu Plain, China

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ABSTRACT

The longitudinal functional connectivity of river systems refers to the process-based connections between upstream and downstream areas and is fundamental to understanding the dynamic and nonlinear hydrological behaviour of river basins. However, the quantification of such connectivity remains a challenge due to the absence of a consensus on the appropriate data and methods, especially in delta plains. In this study, based on the difference between water level fluctuations at adjacent stations, a new and quantitative longitudinal functional connectivity index (LFCI) was developed for delta plains. Focusing on the Taihu Plain, we then analysed the spatial-temporal changes in the LFCI during 1960–2012 and investigated the correlations between the LFCI and climate change and human activities. We found that the decadal, annual and seasonal changes in the average LFCI all presented slightly increasing trends in the recent 50 period, but the annual average LFCI increased significantly after 1978; the average LFCIs in June, July, and August of the flood season were less than those in other months in the Taihu Plain. We also found that the spatial-temporal changes in the average LFCI exhibited larger differences at the subregional and station scales; those in the Wu-Cheng-Xi-Yu subregion were least, and the average LFCIs at stations near the borders of adjacent subregions were less than those at other stations. Moreover, we found that the average LFCI had significant correlations with precipitation, river density and water surface ratio. Our results were consistent with common sense facts, which demonstrated that the indicator developed in this study can quite effectively quantify the longitudinal functional connectivity of river systems in delta plains.

1. Introduction

Connectivity as a key term in hydrology, geomorphology and ecology, generally refers to the connections between different parts of a catchment, and their influences on water and sediment transfers and biological processes (Michaelides and Chappell, 2009). Although connectivity is regarded as an essential factor for ensuring species persistence, ecosystem integrity, and human well-being (Jaeger et al., 2014), it had not been introduced and studied as a broad and specific scientific question until the late 20th century (Bracken et al., 2013; Good et al., 2015).

Connectivity has also been broadly classified as hydrological connectivity, ecological connectivity, and geomorphological connectivity (Okin et al., 2015; Wohl et al., 2017; Lu et al., 2018). Of these types, hydrological connectivity is closely related to the transfer of matter, energy and organisms and to the physical, chemical and biological processes of river systems; the anthropogenic reduction in this property may result in major negative environmental effects (Pringle, 2003). Therefore, hydrological connectivity transcending different disciplines has received increasing interest, and how to quantify hydrological connectivity has become a research focus in the past decades (Michaelides and Chappell, 2009; Rinderer et al., 2018).

Hydrological connectivity is commonly grouped into two categories: (1) structural (or static) connectivity, which refers to spatial patterns of river systems and the extent of physical connections between rivers and lakes (Smith et al., 2010); and (2) functional (dynamic) connectivity, which refers to the interconnection of different areas in the same catchment by a process (Turnbull et al., 2008). The interaction of structural and functional connectivity is conducive to determining the dynamic and nonlinear hydrological behaviour (Michaelides and

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Chappell, 2009). Although there are successful measures to quantify structural connectivity (e.g., topographic indices), standardized quantitative methods for functional connectivity are more rare due to the absence of a consensus on the appropriate data and methods (Bracken et al., 2013; Okin et al., 2015; Rinderer et al., 2018).

Meanwhile, hydrological connectivity can also be developed along the longitudinal dimension (e.g., from upstream to downstream areas), lateral dimension (e.g., from riparian/flood zones to river channel), and vertical dimension (e.g., from surface to subsurface) in addition to the temporal dimension (Amoros and Bornette, 2010; Covino, 2017). Among these dimensions, the longitudinal connectivity of river systems is extensively altered by anthropogenic impoundments and diversions throughout the world (Nilsson et al., 2005). However, the natural transfers of water and sediments and the regular migration of organisms are prevented by these transverse obstacles, resulting in important ecological consequences due to variations in the hydromorphological and biological conditions of the ecosystem (Solà et al., 2011). For the aforementioned reasons, longitudinal functional connectivity is more difficult to quantify than longitudinal structural connectivity (Chi et al., 2018; Ramulifho et al., 2018).

Unlike mountainous areas in sparsely populated upper basins (Caruso, 2015), delta plains are generally located in populous downstream zones. River systems in these regions are more vulnerable to interference by various human activities, and longitudinal functional connectivity is also easily altered by urbanization (Wohl et al., 2017). Even so, simulating longitudinal functional connectivity in these regions is still difficult because of the absence of sufficient data. Furthermore, research concerning a quantitative indicator of longitudinal functional connectivity in these regions is extremely rare. Therefore, developing a new indicator with currently available data is imperative to quantify longitudinal functional connectivity in delta plains.

The Taihu Plain is one of the most famous and rapidly urbanizing delta plain in China. However, a multitude of tributaries have been buried or diverted through pipes to increase the amount of land available for urbanization (Deng et al., 2015b). Meanwhile, innumerable floodgates have been constructed to protect against flooding, and the longitudinal functional connectivity of river systems has thus been partly weakened and even cut off by these human activities (Deng et al., 2018). The decrease in longitudinal functional connectivity of river systems along with the increase of extreme rainfall (Han et al., 2015) and pollutant discharge (Stone, 2011) complicates the hydrological cycle and nutrient exchange processes, finally resulting in more frequent flood disasters and serious water environmental pollution in the Taihu Plain (Duan et al., 2009; Wang et al., 2011). In recent years, these issues have gained increasing attention from the central and local governments. A growing number of water conservancy projects, including river channel dredging and returning farmland to lakes, have been executed to ease these crises. These protective projects not only partly restored the original connections between rivers and lakes but also established new links between originally unconnected rivers and lakes, eventually improving longitudinal functional connectivity. Therefore, investigating the spatial-temporal changes in longitudinal functional connectivity will assist in developing a further understanding of the correlations between hydrological connectivity and flood disasters and water pollution. Such investigations will provide support for making policies regarding flood disaster mitigation and water environmental protection in the Taihu Plain.

The goal of this study is to develop a new and quantitative indicator of longitudinal functional connectivity in delta plains and to analyse its spatial-temporal changes in the Taihu Plain. We first developed a longitudinal functional connectivity index (LFCI) based on major hydromorphological characteristics of delta plains and then employed several time series analysis methods including the moving average, linear trend, Mann-Kendall test (M-K), moving t-test (MTT), and Yamamoto method to analyse the spatial-temporal changes in the LFCI. Finally, we also investigated the correlations between the LFCI, climate change and human activities. The conclusions can improve the understanding of longitudinal functional connectivity in delta plains.

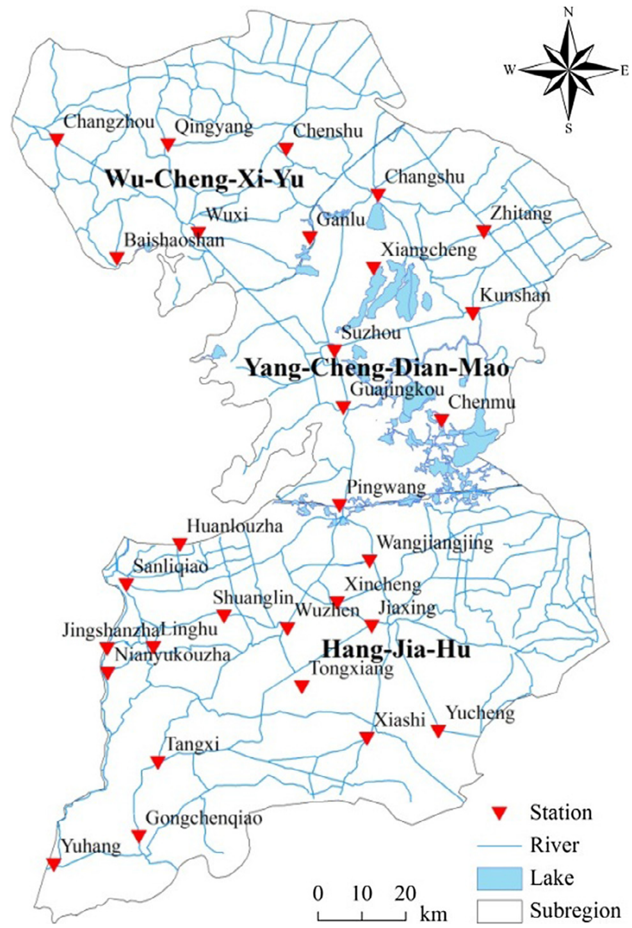

Fig. 1. Sketch map of the Taihu Plain.

2. Data and methods

2.1. Study area

The Taihu Plain is located in the centre of the Yangtze River delta in eastern China, covers an area of 15,757 km^2 and is 2–4 m above sea level. This region is known as Jiangnan Water Country due to the crisscrossing rivers and numerous lakes. The water surface area of 1590 km^2 occupies 9.72% of the total area, the total river length is 50,245 km, and the river density is 3.07 km/km^2 (Deng et al., 2015b). According to the landform conditions and river system distribution, this region can be divided into three subregions (Fig. 1): Wu-Cheng-Xi-Yu (WCXY), Yang-Cheng-Dian-Mao (YCDM), and Hang-Jia-Hu (HJH). Meanwhile, the Taihu Plain has always been a region with one of the most advanced economies and densest populations in China. Currently, the urbanization rate (the urban population as a percentage of the total population) has exceeded 50%, and the percentage of non-agricultural GDP is close to 100% in this region. However, rapid urbanization has given rise to serious pollution and flood disasters, and flood disaster mitigation tracking and water environmental protection have then become the key challenges for the future of the Taihu Plain (Liu et al., 2013).

2.2. Data sources

To analyse the changes in longitudinal functional connectivity through space and time, we collected the daily mean water level data at