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The Impacts of Hydrology and Climate on Hydrological Connectivity in a Complex River–Lake Floodplain System Based on High Spatiotemporal Resolution Images

Suhang Yang [1,2], Jie Liang [1,2,*], Xiaodong Li [1,2,*], Yuru Yi [1,2], Ziqian Zhu [1,2], Xin Li [1,2], Xuwu Chen [1,2], Shuai Li [1,2], Yeqing Zhai [1,2] and Ziming Pei [1,2]

1 College of Environmental Science and Engineering, Hunan University, Changsha 410082, China; 19yangsuhang@hnu.edu.cn (S.Y.); ruy@hnu.edu.cn (Y.Y.); b200300190@hnu.edu.cn (Z.Z.); dklixin@hnu.edu.cn (X.L.); xuwuchen@hnu.edu.cn (X.C.); prime2k@hnu.edu.cn (S.L.); zhaiyq@hnu.edu.cn (Y.Z.); peiziming@hnu.edu.cn (Z.P.)
2 Key Laboratory of Environmental Biology and Pollution Control, Hunan University, Ministry of Education, Changsha 410082, China
* Correspondence: liangjie@hnu.edu.cn (J.L.); lxdfox@hnu.edu.cn (X.L.)

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Abstract: The drivers that determine the hydrological connectivity (HC) are complex and interrelated, and disentangling this complexity will improve the administration of the river–lake interconnection system. Dongting Lake, as a typical river–lake interconnected system, is freely connected with the Yangtze River and their HC plays a major role in keeping the system healthy. Climate, hydrology, and anthropogenic activities are associated with the HC. In this study, hydrological drivers were divided into the total flow of three inlets (T-flow) and the total flow of four tributaries (F-flow). To elucidate the HC of the Dongting Lake, HC was calculated by geostatistical methods in association with Sentinel-2 remote sensing images. Then, the structural equation model (SEM) was used to quantify the impacts of hydrology (F-flow, and T-flow) and meteorology (precipitation, evaporation, and temperature) on HC. The geostatistical analysis results demonstrated that the HC showed apparent seasonal change. For East and West Dongting Lake, the dominant element was north–south hydrological connectivity (N–S HC), and the restricted was west–east hydrological connectivity (W-E HC), but the dominant element was E–W HC and the restricted was N–S HC in South Dongting Lake. The results of SEM showed that N–S HC was mainly explained by T-flow ($r = 0.49$, $p < 0.001$) and F-flow ($r = 0.28$, $p < 0.05$). T-flow, temperature ($r = 0.33$, $p < 0.05$), and F-flow explained E–W HC. The finding of this work supports the management of both the Dongting Lake floodplain and other similar river–lake floodplain systems.

Keywords: floodplain wetland; hydrological connectivity; Dongting Lake; SEM; Sentinel-2

1. Introduction

Floodplain wetlands are crucial ecosystems that not only regulate flooding and provide water and food but also support habitats for animals [1]. The floodplain wetlands system is characterized by complicated topography which includes the seasonal lake, main lake, floodplain, and channel. Hydrological connectivity (HC) can affect flood inundation, nutrient transport, the evaporation process, and biodiversity protection [2–6]. HC, which plays an important role in transferring matter and energy, is usually regarded as a vital driving force of aquatic ecosystem structure and function [7,8]. The health of HC in freshwater ecosystems has far-reaching impacts on ecosystem integrity, species persistence, and human well-being [9]. The condition of HC is tightly related to the biodiversity health of fish and waterbirds in floodplain wetlands. However, due to the complex topography and vast area of floodplains, HC study becomes a challenging task. Consequently, it is worth deeply investigating the relationship between HC and floodplain wetlands.

At present, HC within floodplains can be evaluated by the hydrodynamic model based on the result of a hydrological model and the geostatistical method based on the remote sensing image [2,10]. The results of the hydrological model (MIKE 21 HD model) were utilized to map the inundation and calculate the connectivity duration in northern Australia (Flinders and Gilbert River catchments) and HC in Poyang Lake [11,12]. The results of the MIKE 21 HD model can support long-term continuous floodplain inundation information. Unfortunately, as for complex topography and large area drainages, the resolution of the HD model ranging from 70 m to 1500 m cannot be precisely delicate in the inundation map. More importantly, the precise bathymetry data, (i.e., 10 m or 20 m) and large extended floodplains increase the difficulty of study. Previous works have selected the remote sensing data and geostatistical connectivity methods to calculate the HC in Poyang Lake in China and the Chao Phraya River catchment in Thailand [2,13]. The remote sensing images include the MODIS images, the Earth Observing-1images, and the Landsat images, and the resolutions are 250 m (16 d), 30 m (200 d), and 30 m (16 d), respectively. Nevertheless, the specific spatiotemporal resolutions and clouds covering water inundation limited the use of these images. The inaccurate inundation map will lead to the inaccurate HC. With the rapid development of remote sensing, Sentinel-2 with a spatial resolution of 10 m and temporal resolution of 5 days provides an opportunity to accurately describe fine-scaled water inundation and calculate the accurate HC. Furthermore, Connectivity Assessment Tool 1.0 (CAST 1.0) based on hydrodynamic parameters (water depth, water temperature, and water flow rate) was used to evaluate the HC of Poyang Lake [12]. Consequently, CAST 1.0 based on Sentinel-2 images supplies a productive method to analyze HC.

Owing to global climate change and human activity, the floodplain lakes have suffered considerable challenges [14–17]. Increases in near-surface temperature have responsibility for the more frequent and severe droughts [18,19]. However, rainfall could be an important influence on connectivity and frequency of inundation in northern Australia [11]. Meanwhile, dam construction, land reconstruction, and other human activities are strongly affecting hydrological cycling [20–22]. Recent studies also demonstrated that inlet flows from the surface and ground affected the water level or HC in interconnection river–lake floodplain systems [23,24]. Hence, the health of the floodplain wetland ecosystem and water recycling are closely related to hydrology, climate, and human activity.

Past studies demonstrated that climate, hydrology, and human activity were tightly associated with the HC [11,25]. In the Poyang Lake floodplain wetland, the larger catchment inflow leads to higher HC [26]. Rainfall changes may have large impacts on the duration of the connectivity and the frequency of inundation in the floodplain wetlands of northern Australia [11]. Unfortunately, under the combined influence of hydrology drivers and meteorology drivers, the impacts of the two kinds of drivers on HC are still indistinct [11,26]. Here, we identified the crucial drivers of the HC in the complex river–lake floodplain system and determined how these drivers affected HC both directly and indirectly. Attribution analysis methods are selected to explicate the direct or indirect impact of drivers on HC. For example, the S-HYPE model, probability distribution model, and other attribution analysis methods can analyze the relationship between measured data and potential variables. Unfortunately, these methods fail to identify the direct or indirect impact of drivers [27]. The structural equation model (SEM) can represent the direct and indirect relationship among variables and quantify the relative importance of various driving factors [28,29]. Zhang et al. (2020) studied the direct and indirect influence of hydrological drivers and water properties on Ba-IBI by using SEM. SEM results showed that hydrology and climate affected the food availability of wintering waterbirds in the Dongting Lake wetland [30]. Hence, SEM was selected to explore the indirect and direct influences of meteorological and hydrological variables on HC.

HC was recognized as a crucial factor to protect water safety and ecosystem sustainability. Here, we pay attention to exploring the relationship between surface HC and surface flows (ignoring the influence of turbulence and groundwater). However, the pattern of how climate, hydrology, and human activity affect HC is still unclear. The current research, which combined geostatistical analysis and SEM methods to explore the relative importance of hydrology and climate on HC can fill the knowledge gap. Hence, this research is necessary as it provides useful knowledge that will help to manage and protect floodplain wetland systems. Therefore, the objects of this paper are to (1) analyze the HC characteristics of the whole and three sub-lakes of the Dongting Lake, and (2) investigate the effects of hydrology and meteorology drivers for HC. This work will contribute to a better understanding of the complex river–lake interconnected systems, including the influence of hydrological and meteorological factors on HC.

2. Materials and Methods

2.1. Study Region

Dongting Lake (28°44′–29°35′ N; 111°53′–113°05′ E), the second-largest fresh-water lake in China, is situated on the south bank of the middle Yangtze River (Figure 1). It covers an area of 2625 km^2 and has a volume of 1.67×10^{10} m^3 which is comprised of East Dongting Lake, South Dongting Lake, and West Dongting Lake [23]. As a complicated river–lake interconnected system that receives Yangtze River inflows from three inlets, (i.e., Songzi River, Taiping River, and Ouchi River), four tributaries, (i.e., Xiangjiang River, Zishui River, Yuanjiang River, and Lishui River), and discharges to the Yangtze River through the northern outlet of the lake via Chenglingji [31]. The lakebed terrain is high in the west but low in the east, leading to about 5 m deviations in the water level between West Dongting Lake and East Dongting Lake. The elevations of western Dongting Lake are more than 40 m, while the eastern's are less than 25 m [32]. After the impound of the Three Gorges Dam (TGD), the water level of Dongting lake decreases, and the zero-flow duration of three inlets slightly increases [33].

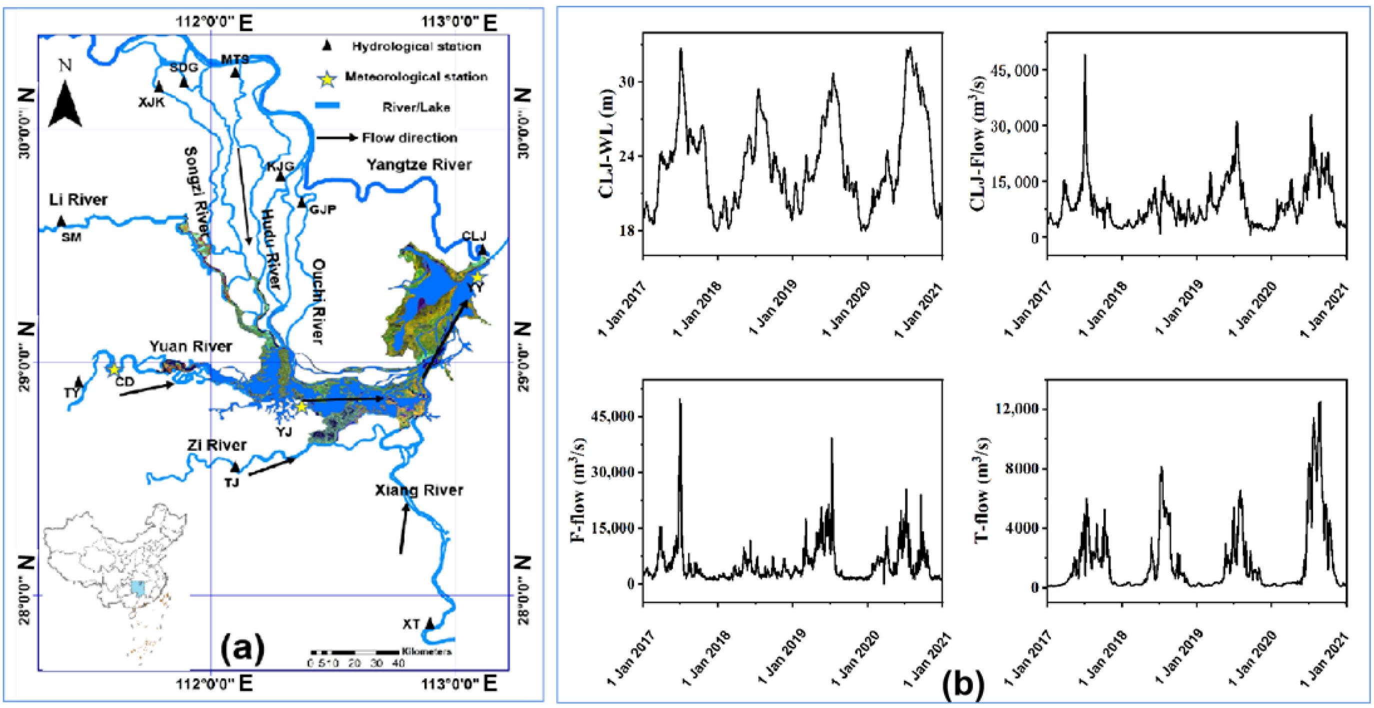

Figure 1. (**a**) Map of Dongting Lake, including three inlets, (i.e., Songzi River, Taiping River, and Ouchi River), four tributaries (i.e., Xiangjiang River, Zishui River, Yuanjiang River, and Lishui River), Yangtze River, hydrometeorological stations ((Xiangtan (XT), Taojiang (TJ), Yuanjiang (YJ), Changde (CD), Taoyuan (TY), Shimen (SM), Xinjiangkou (XJK), Shadaoguan (SDG), Mituosi (MTS), Kangjiagang (KJG), Guanjiapu (GJP), Yueyang (YY)) and flow directions. (**b**) Observations of flow and water level from 2017 to 2021: water level of Chenglingji (CLJ-WL), flow of Chenglingji Station (CLJ-flow), total flow of four tributaries (F-flow), and total flow of three inlets (T-flow).

The Dongting Lake has an East Asian monsoon climate, with a mean annual temperature of 16.5–17.2 °C and annual precipitation of 1289.8–1556.2 mm. As an important seasonal floodplain lake, it suffers from a severe turn in which the area changes from 500 km^2 to 2520 km^2, and water levels fluctuate by as much as 12–14 m [34]. In normal years, the water level increases in early March and reaches the highest water level in July. The lake supplies water for crop irrigation, production, and residential life. As a Ramsar site located in the wintering habitats and migration routes for the migratory birds of East Asia–Australia, it plays a crucial role in protecting wintering waterfowls and other animals [32]. There are more than 1428 plant species, 217 bird species, and 114 fish species in Dongting Lake National Preserve [34].

2.2. Data Sources

Remote sensing data were downloaded from Copernicus Open Access Hub (https://scihub.copernicus.eu/, accessed on 5 March 2021) [35]. The Sentinel-2 Multispectral Instrument (MSI) holds 13 spectral bands which include the visible, red-edge, near-infrared (NIR), and short-wave infrared (SWIR) wavelengths. The two satellite sensors were launched in June 2015 (Sentinel-2A) and March 2017 (Sentinel-2B) which have higher temporal frequency (up to 5 days) and much finer spatial resolution (10 m–20 m) [36]. Sentinel-2 data were broadly used in the fields of agricultural monitoring, landcover classification, and disaster management [37,38]. The missed data were replaced by these images which have the same water level or phenological period in the previous or next year [39]. Finally, 86 Sentinel-2 remoting sensing images during 2017–2020 were obtained. SNAP 8.0 (The sentinel Application platform) and Sen2Cor (Sentinel 2 Atmospheric Correction) were taken to pre-process the Sentinel-2 images. SNAP is used for the Sentinel product process and Sen2Cor is used as a Sentinel-2 Level2A processor which processes Sentinel-2 Level-1C (L1C) top-of-atmosphere (TOA) image to Level-2A (L2A) bottom-of-atmosphere (BOA) by pre-processing tasks [40]. In the process, all Level-1C images were processed to Level-2A by Sen2Cor algorithm firstly, then all image bands were resampled to 10 m by S2 Resampling processor of SNAP and modified normalized difference water index (MNDWI) water index was calculated in ENVI 5.3.

The hydrological data (2017–2020) of the water level and discharge were collected from the Hunan Hydrology and Water Resources Survey Center (https://www.hnsw.com.cn, accessed on 8 March 2021) [24]. We selected the flow (at 8:00 AM) as the inlet hydrological data and the water level (at 8:00 AM) of the Chenglingji (CLJ) station as the level of the whole lake. To keep the same geomatics system with the elevation data of the basin, the water level at Chenglingji Gauge Station is converted from the Wusong Datum (WSD) to the 1985 National Elevation Datum (NED) by subtracting 1.94 m [41]. To comprehensively consider the effect of three inlets and four tributaries on HC, the total flow of three inlets (T-flow) and the total flow of four tributaries (F-flow) were used to explore their relationship with HC.

Compared with different evaporation estimation methods, actual evaporation of the ground station was selected to present the lake evaporation condition [42]. Meteorological data were collected by ground stations in Dongting Lake basin. The daily climate data (2017–2020), which consists of precipitation, evaporation, and temperature, were obtained from China Meteorological Data Center (http://data.cma.cn, accessed on 5 March 2021) [30]. The average climate in Yueyang, Changde, and Yuanjiang Weather stations represented the climate of the whole lake.

2.3. Data Pre-Processing

The MNDWI water index and Otsu's histogram shape-based method was selected to extract surface water from Sentinel-2 data [2,43]. The accuracy and kappa efficiency ranged from 82–96% and 0.80–0.98, respectively.

In this work, the connectivity function was selected to quantify the HC. For any distance, the connectivity function (CF) uses binary data to estimate the probability of any two points that are connected [44]. Trigg et al. (2013) use the CF method to evaluate the HC for a severe flood disaster that took place in 2011 in Bangkok of Thailand [2]. This analysis is effective for using wet–dry binary data, (e.g., 0 or 1) to quantify the connectivity. These binary data are generally derived from the water inundation of remote sensing or outputs of the hydrodynamic model. This method selects 8-way connectivity, which permits cells to connect by corner vertex or edge.

$$CF(n; Z_c) = Pr\left\{\prod_{j=1}^{n} I(U_j; Z_c) = 1\right\} \tag{1}$$

$$\text{If } Z\,(U_j) > Z_c,\ I\,(U_j;\,Z_c) = 1. \tag{2}$$

$$\text{If } Z\,(U_j) \le Z_c,\ I\,(U_j;\,Z_c) = 0. \tag{3}$$

where n is the total number of points; Π represents the product operator; Z_c represents the threshold value; $I\,(U_j;\,Z_c)$ is a connectivity indicator; Pr is the calculated probability. The connectivity function (CF) statistic shows a probability distance function for Dongting Lake (Figure 2). The individual wet cell is always connected to itself, and the wet cells are the connection of wet cells when wet cells are connected by edge and corner vertex. The value of the CF at any given distance is the fraction of wet cell pairs at that distance that are connected (Figure 2b). After processing the dry–wet binary raster data of each month, a connectivity function graph can be obtained (Figure 3b). The average of CF values presents the HC. Due to the specific bathymetry, river network distribution, and polder distribution, the flow directions were dominated by the west to east in South Dongting Lake and south to north in East Dongting Lake [34]. Therefore, the wet–dry binary raster derived from Sentinel-2 images was chosen to calculate the north–south and west–east probability distance function by CAST 1.0 [12]. HC was calculated from the probability distance function by MATLAB (Figure 3).

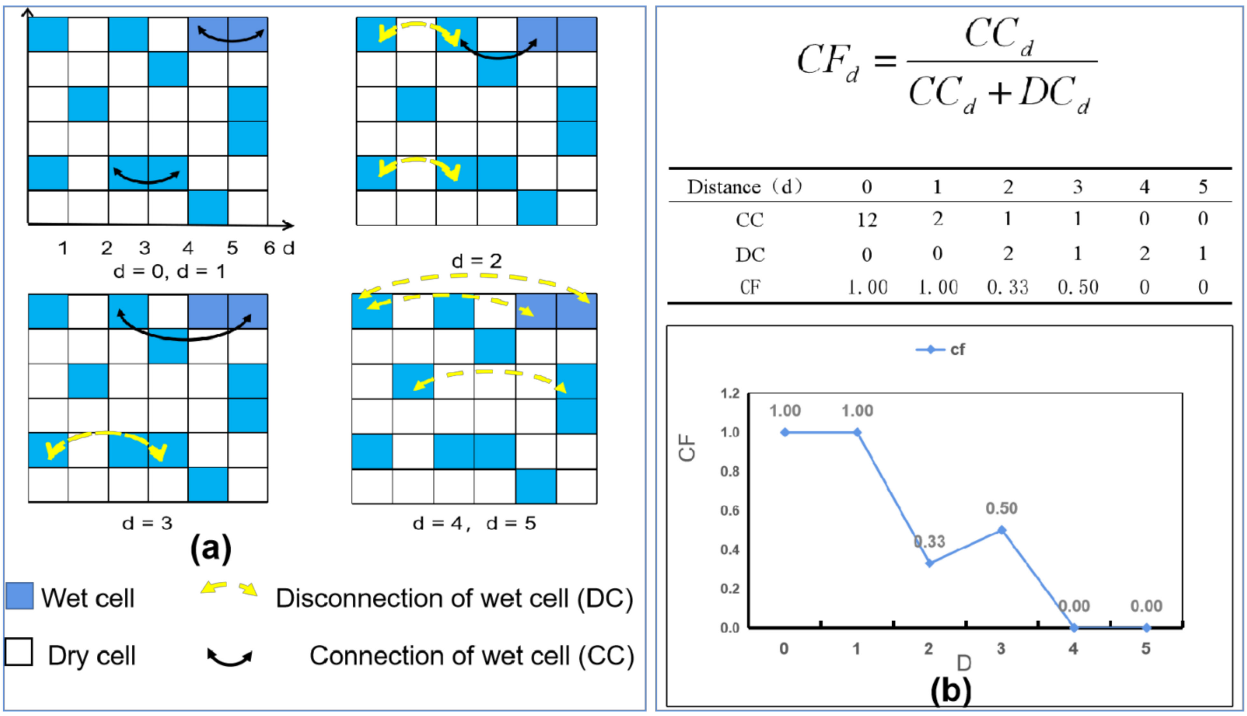

Figure 2. Illustration of the connectivity function (CF) in the west–east direction. (**a**) The connection of wet cell (CC) and disconnection of wet cell (DC). (**b**) The statistics and analyses of probability-distance function (CF).

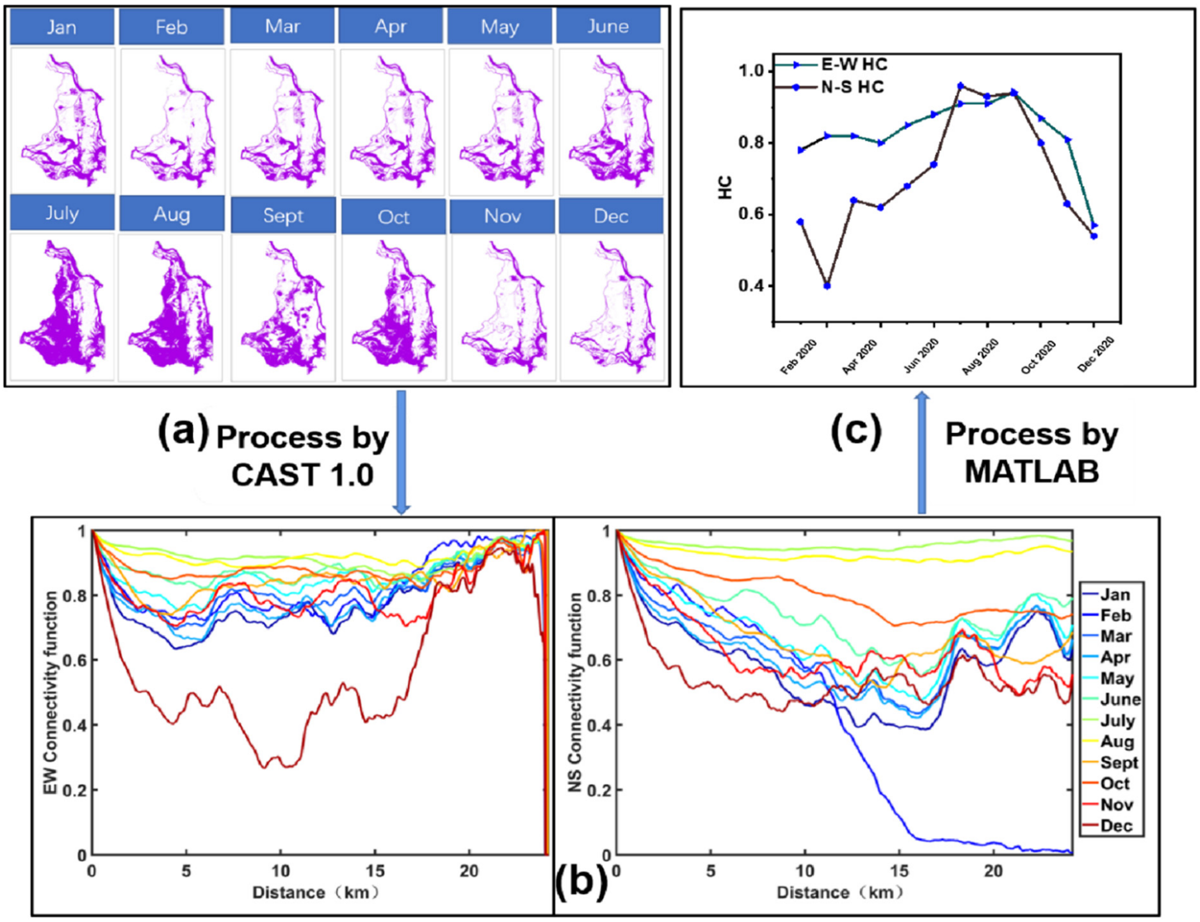

Figure 3. Schematic path of the methodology for the hydrological connectivity (HC) (the example is selected from the West Dongting Lake in 2020). (**a**) Monthly variation of western Dongting Lake georeferenced images in 2020. (**b**) East–west (E–W) and north–south (N–S) probability distance function in 2020. (**c**) Monthly variation of HC in 2020.

2.4. Statistical Analysis

The Pearson correlation coefficient which was processed by the Origin 2021b was used to detect the significant correlation between the hydrological drivers and the meteorological drivers on HC. Ordinary least squares (OLS) regressions were used to evaluate the significant linear relationships between hydrological variables, meteorological variables, and HC. Two hydrological factors (T-flow (m^3/s) and F-flow (m^3/s)) and three climate factors (temperature (°C), precipitation (mm), and evaporation (mm)) were recognized as the explanatory factors of HC. Structural equation models (SEM) were constructed to infer the relative importance of hydrology (T-flow and F-flow) and climate (temperature, precipitation, and evaporation) on HC. SEMs are statistical programs used to verify measurement, function, prediction, and causal hypotheses [29]. The construction of SEM includes the selection of the variables and the construction of path analysis. SEMs are composed of measured data and potential variables, which are real but unknown averages of the underlying data [45]. Combined with the existing studies, the potential correlation equations of these observations and latent factors were constructed with the "piecewiseSEM" R package (https://github.com/jslefche/piecewiseSEM, accessed on 12 January 2021) [46]. Standard path coefficient (r-value) was used to describe the potential effects of measured data on latent variables. The *p*-value represents the level of significant impact.

3. Results

3.1. HC and Temporal and Spatial Inundation Characteristics

It is clear from Figure 1b that there is an apparent seasonal pattern for the flow and water level. HC (Figure 4b) was calculated by the wet–dry binary data which was transferred by the water inundation map. Water inundation was tightly correlated with the Chenglingji water level (CLJ-WL) (Figure 4a) and hydrological regime (Figure 1b). As predicted, the water area was characterized by a significant seasonal change. The water area ranged from 573 km^2 to 2364 km^2 and the corresponding water level ranged from 20.1 m to 34.4 m (Figure 4a).

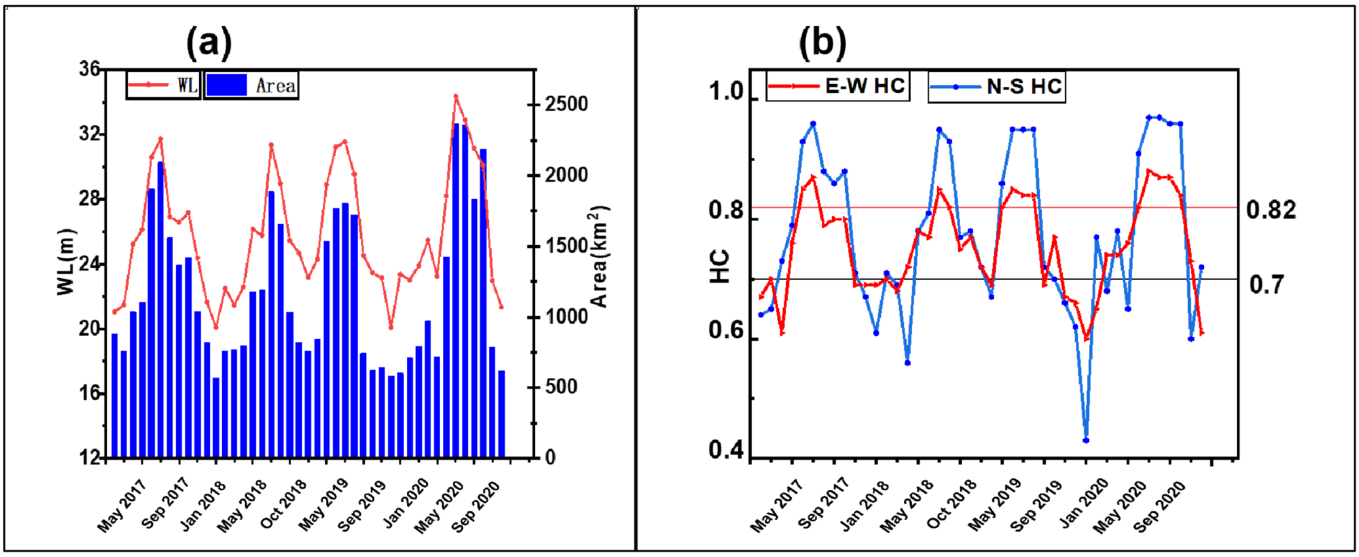

Figure 4. (**a**) Water level and water inundation area during 2017–2020. (**b**) East–west (E–W) and north–south (N–S) HC during 2017–2020 and the threshold value of high and low HC.

Parallel (E–W) and perpendicular (N–S) HC of four consecutive years are shown in Figure 4b. The HC also showed an obvious seasonal change in the inundation area, which varied between 0.43 and 0.97. The increases in HC were corresponding with the increased water level and inundation area in spring and early summer, with the highest HC usually occurring in middle or later July. After the peak of the water level, the HC declined from late August to December. Therefore, a small inundation area was accompanied by a low water level, leading to a low HC. According to the water level, inundation, and HC plots, low HC, (i.e., HC < 0.7) occurred during low water levels, and high HC, (i.e., HC > 0.82) usually occurred in the high-water level and area periods, while medium HC, (i.e., 0.7 < HC < 0.82) arose in other water levels (Figure 4b). The threshold of HC was corresponding to the specific inundated area and water level. The N–S HC was larger than W–E HC in the wet season, and N–S HC also showed a broader range than W-E HC. This result indicated that the HC of Dongting Lake was dominated by the N–S HC in wet seasons and restricted in dry seasons.

Figure 5 shows the seasonal trend of the HC in the three sub-lakes in 2017–2020. The seasonal changes of HC impacted the three sub-lakes, including the whole of Dongting Lake. However, the three sub-lakes presented specific characteristics, which were distinct from the whole lake. The average N–S HC was larger than E–W HC in East Dongting Lake (Figure 5a). However, other sub-lakes showed the opposite situation, in that the E–W HC was higher than N–S HC, especially for South Dongting Lake (Figure 5b,c). As for East Dongting Lake, the HC was dominated by the N–S HC, and W-E HC was the restricted element. On the contrary, for South Dongting Lake and West Dongting Lake, HC was restricted by the N–S HC and W–E HC was the dominant element. In South Dongting Lake, it was worth mentioning that in the two directions HC showed a larger discrepancy, the average discrepancy of E–W HC and N–S HC was greater than approximately 0.3, and the discrepancy was about 0.1 when the HC reached the maximum in the summer. Accordingly, the HC of the three sub-lakes was different from the whole lake.

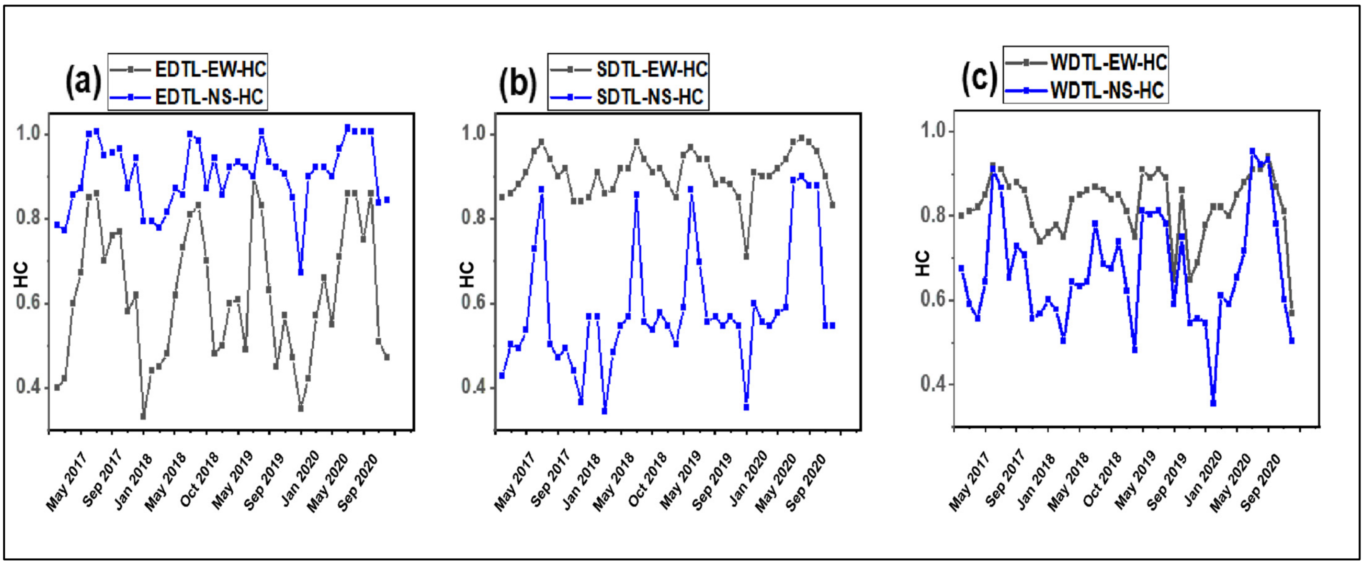

Figure 5. HC (E–W HC and N–S HC) of three sub-lakes of the Dongting Lake in 2017–2020. (**a**) HC of East Dongting Lake. (**b**) HC of South Dongting Lake. (**c**) HC of West Dongting Lake (EDTL represents east Dongting Lake, SDTL represents south Dongting Lake, WDTL represents west Dongting Lake).

During this study period (2017–2020), the highest HC was 0.97, when the water level was 34.36 m and the water area was 2364 km^2 accounting for 87% of the study area except for the high lake stage zone (Figure 6a); the lowest HC was 0.43 when the water level was 20.08 m (water shrunk for the main stream and main lake) and the water area was 584 km^2 accounting for 21.5% of the study area (Figure 6d); on the high HC threshold (HC = 0.82), the water level was 28.9 m and the water area was 1534 km^2 accounting for 56.7% of the study area (Figure 6b); on the low HC threshold (HC = 0.70), the water level was 24.29 m and the water area was 842 km^2 accounting for 31% of the study area (Figure 6c). With the decrease in HC, the water inundation map gradually transferred from the broad area zone to the slimline when the seasonal lakes nearly disappeared.

3.2. Direct and Indirect Effects of the Hydrological and Meteorological Factors on HC

Correlation analysis (Figure 7) showed that HC (E–W HC and N–S HC) were positively correlated with T-flow (r = 0.77, $p < 0.05$) and F-flow (r = 0.57, $p < 0.05$). Temperature was positively correlated with E–W HC (r = 0.78, $p < 0.05$) and N–S HC (r = 0.74, $p < 0.05$). Meanwhile, temperature was positively correlated with F-flow (r = 0.48, $p < 0.05$) and T-flow (r = 0.69, $p < 0.05$). Ordinary least squares (OLS) regressions (Figure 8) were conducted to examine whether there was a significant linear relationship between hydrological and meteorological variables on HC. As predicted, T-flow and F-flow were positively linear correlated with E–W HC and N–S HC, but climate effect varied among components: the temperature was positively related with E–W HC and N–S HC, while precipitation and evaporation were not related to E–W HC and N–S HC.

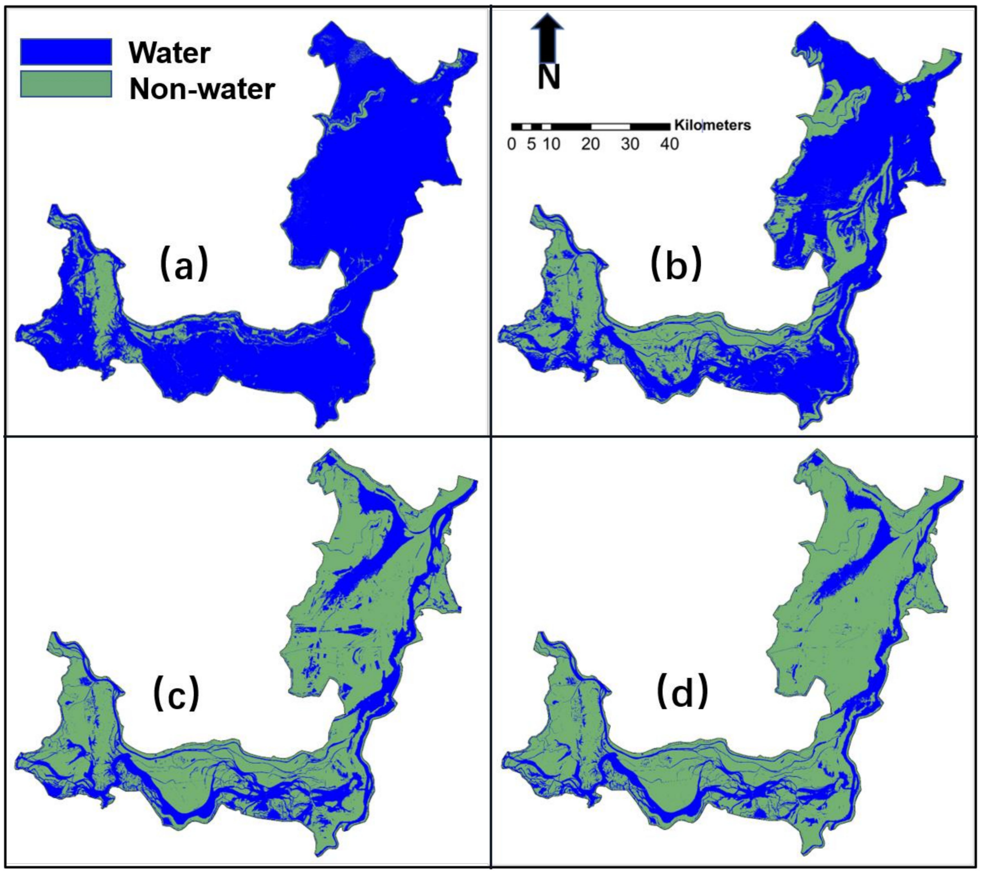

Figure 6. Water inundation: (**a**) in the highest water level, (**b**) in the threshold of high HC, (**c**) in the threshold of low HC, (**d**) in the lowest water level.

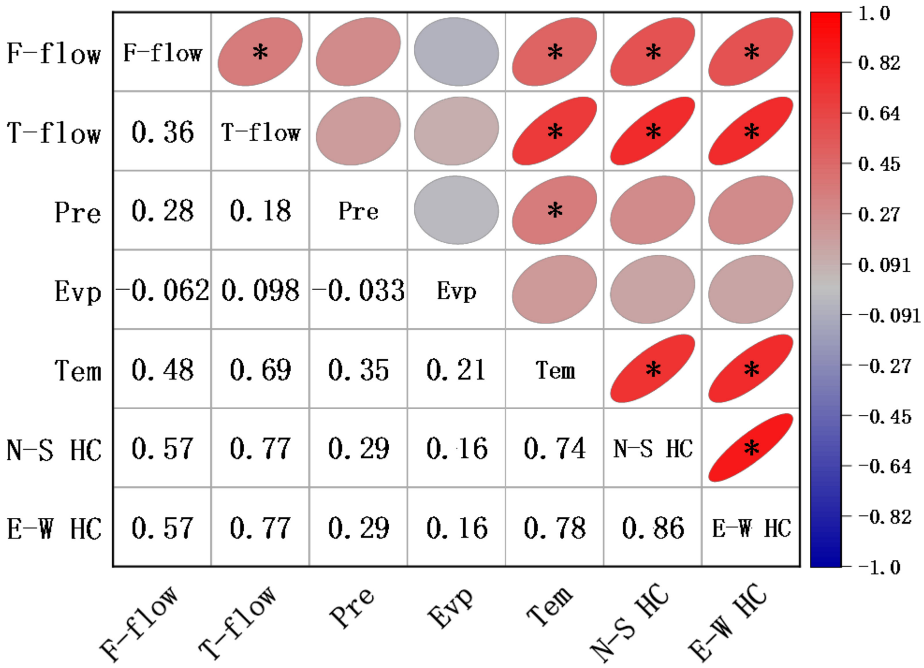

Figure 7. Pearson's correlation coefficient between the environmental factors and HC. The number in each square represents the correlation coefficient between the two corresponding variables. "*" represents $p < 0.05$ (Pre represents precipitation, Evp represents evaporation, and Tem represents temperature).

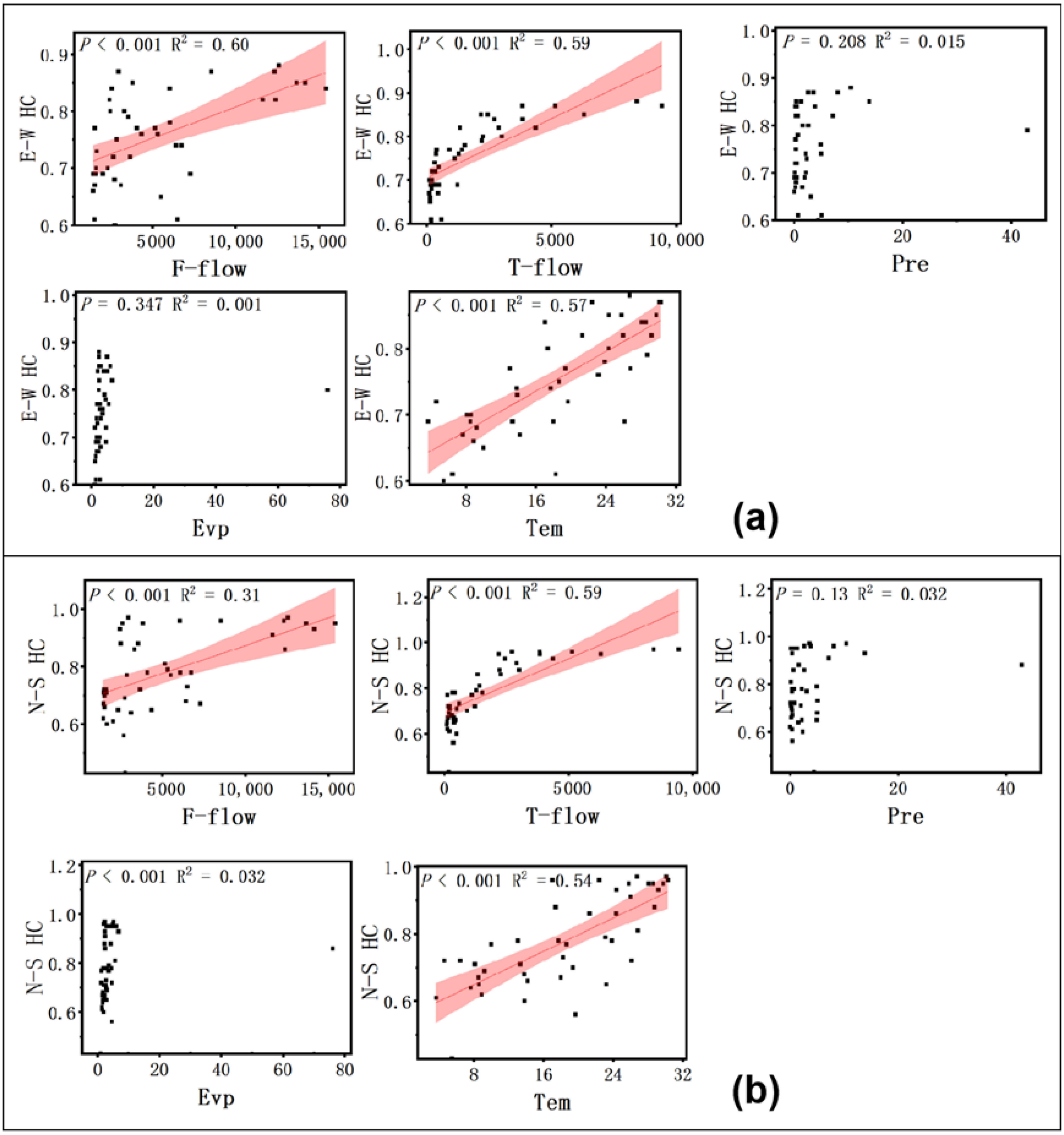

Figure 8. Ordinary least squares (OLS) regression between various environmental factors and hydrological connectivity. (**a**) Relationships between F-flow, T-flow, Pre, Evp, Tem, and E–W HC. (**b**) Relationships between F-flow, T-flow, Pre, Evp, Tem, and N–S HC. There were no significant linear relationships between HC and Pre or Evp. The red fitted lines are from OLS regression. Only significant fitted lines are displayed on the graphs. Shaded areas show a 95% confidence interval of the fit.

According to the SEM analysis results (Figure 9), T-flow and F-flow were the more crucial factors than precipitation and evaporation variables for HC (temperature also played a direct positive impact on E–W HC), and T-flow was the dominant element. The SEM results revealed the pathways that the climate and hydrological variables impacted HC in Dongting Lake (Figure 9). T-flow had a positively direct impact (r = 0.49, $p < 0.001$) on the N–S HC, and F-flow also had a direct impact (r = 0.28, $p < 0.05$) on the N–S HC. On the contrary, the evaporation, precipitation, and temperature have shown a positive indirect effect on N–S HC, and the standard path coefficients were 0.04, 0.07, and 0.24, respectively. For E–W HC, T-flow and F-flow also had a significant positive direct influence, and the standard path coefficients were 0.44 ($p < 0.001$) and 0.25 ($p < 0.05$), respectively. Compared with the results of N–S HC, the temperature played a significant positive direct effect on E–W HC (r = 0.33, $p < 0.05$), while precipitation and evaporation showed a positive indirect effect on E–W HC.

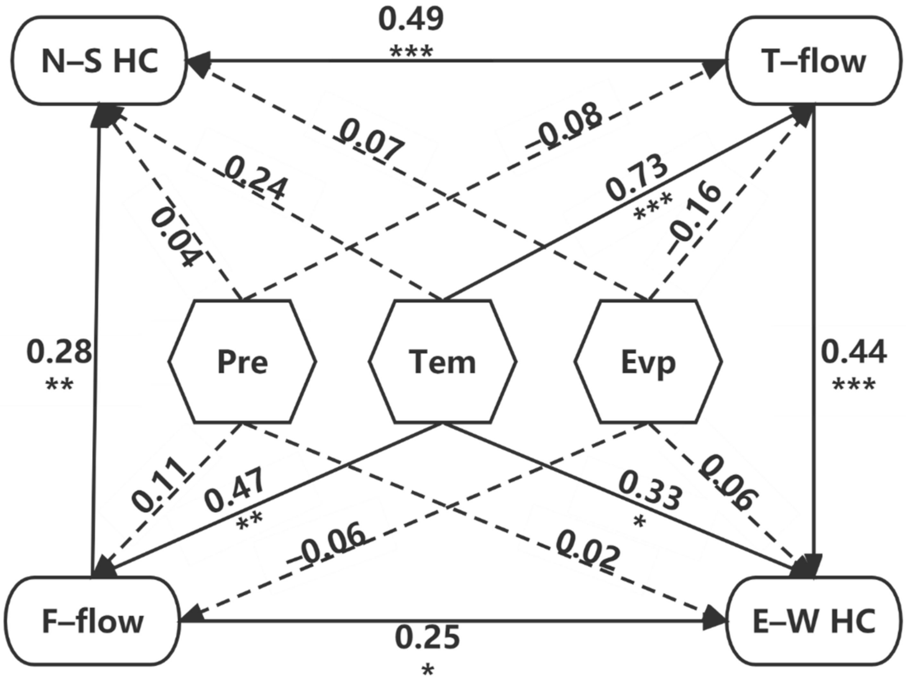

Figure 9. Direct and indirect impacts of hydrological drivers and meteorological drivers on hydrological connectivity based on structural equation models. "*" represents $p < 0.05$, "**" represents $p < 0.01$, "***" represents $p < 0.001$.

4. Discussion

4.1. Relative Importance of Hydrological and Meteorological Factors on HC

Inflow fluctuations directly modify the hydrological regime and HC. In Poyang Lake, catchment inflow influenced the HC, where higher flows led to larger HC [23]. The results showed that the inflow represented a more important influence on the HC during Phase I than in Phase II and Phase III. In this study, T-flow exerted a more significant positive impact on Dongting Lake HC than F-flow. Due to upland tributaries and rainfall inputs filling the main lake before the whole lake flooded, the water level at the floodplain gradually increased [47]. Seasonal sub-lakes were easily affected by streamflow under a changeable climate. The previous study also demonstrated that the three inlet flows played a key role in changing the water level in Dongting Lake from the 1990s to the 2010s [24]. Additionally, the change of three inlet flows reduced water levels by about 0.5 m and 0.67 m during June–August and September–November.

Rainfall, temperature, and human activity are important parameters that affect hydrological cycling. Particularly, temperature or rainfall controls the HC of the floodplain system during the dry season when flow decrease. In addition, climate variability was responsible for the streamflow alteration from 1981 to 2002 in Dongting lake [16]. In this study, temperature plays a direct impact on HC, but evaporation and precipitation do not show a direct impact on HC. The relationship between HC and temperature is linear. The linear correlation cannot identify actual causal links from dependencies resulting from confounding factors [48]. Indeed, dependencies between two variables could result from a third confounding cause influencing both. Hence, the dependencies of climate factors may lead to the discrepancy in driving factors analysis. Compared with the temperature in Dongting Lake, the average evaporation and precipitation (Yueyang, Changde, and Yuanjiang Weather stations) condition can not represent the whole lake, which may lead to the discrepancy in driving factor analysis. During the dry year and wet year of the Poyang Lake, the high HC (HC values approach to 1) occurs during the high-temperature seasons (June-August), while low connectivity (CF approach to 0) occurs during low-temperature months (December–January), whereas intermediate connectivity arises during other months of the year [13,49]. The climate affects the hydrological regimes and HC via rainfall and temperature. Temperature and precipitation influence the water yield, surface runoff, and groundwater [15,50]. In particular, the decrease in rainfall and the increase in temperature exert a more prominent influence on hydrological regimes in dry seasons. In addition, the temperature warming, which leads to severer drought, breaks the continuity and connectivity rule of streams and endangers the endangered fishes [9]. Rainfall exerts a more important influence on HC than potential dams in the Flinders and Gilbert River catchments [11]. However, the more dams built on main tributaries, the more connectivity of the river network decline in the Pearl River basin [51]. Dam construction leads to an increase in river network fragmentation and worse stream continuity. In conclusion, hydrological variables, meteorological variables, and human activities jointly affect the HC of floodplain wetlands.

4.2. The Threshold of HC and Management Implications

According to this study, low HC, (i.e., HC < 0.7) occurred in winter, and high connectivity, (i.e., HC > 0.82) occurred in summer, while intermediate connectivity, (i.e., 0.7 < HC < 0.82) occurred in other seasons (Figure 4b) which was corresponding with the result of Li et al. (2019). Compared with the complicated HC of the whole lake, the three sub-lake HCs demonstrated a noteworthy difference, especially for South Dongting Lake. The leading HC was N–S HC and the limiting HC was E–W HC in East Dongting Lake (Figure 5a). On the contrary, as for South and West Dongting Lake (Figure 5b,c), the dominated HC was E–W HC and the limited HC was N–S HC, respectively. The differences between the three sub-lake HCs may account for the complicated HC regime in the entire lake.

Seasonal floodplain lakes are characterized by recurrent inundation changes. The water inundation showed an apparent difference in different HC and water levels (Figure 6). Due to the relationship between HC and water level, the main lake connected the floodplain and rivers via the channelized and overbank flow paths when HC increases in the floodplain of PLNNR [39]. Meanwhile, the threshold of HC changed with different lakes and hydrological years. HC affected the water storage of the main lake and floodplain. In addition, the floodplains showed a higher variability inundation and shorter connectivity duration, and the main lake showed a stable inundation area and longer connectivity duration [10]. HC increased with the channelized flow through the network in floodplains until the water level reaches the largest height. In addition, channelized flows, overbank flows, and other connectivity processes showed different roles in floodplain hydrogeomorphology [52]. In Baiyangdian wetland, because of permanent and temporary barriers, HC became worse [53]. Consequently, the floodplain is a complicated HC system influenced by the hydrological regime, climate, and lake stage. Surrounding land use and surface HC also played crucial roles in controlling water quality change [54]. A recent study also found that improved HC may contribute to improving water quality in seasonal floodplain wetlands [55]. The HC plays an important role in mass and energy transport in floodplain lakes. The dominant HC can also enhance the continuity time and the connectivity distance of the main lake with the season lakes in floodplain wetland. The long continuity time and connectivity distance can influence the frequency of water exchange, which in turn improves the water quality between the main lake and seasonal lakes.

Scientists not only care about the value of HC on hydrology but also pay more attention to the values of HC on ecology and the environment [26,54,56–58]. Dongting lake supports a crucial habitat for wintering waterbirds migration [32,59]. A previous study demonstrated that climate changes and worse food availability resulted in waterbirds' diversity reduction [30]. The results showed that the abnormal water levels could influence the diversity and quantity of Anatidae, especially for the lesser white-fronted goose. More natural connectivity sub-lakes attracted much higher diversity and populations of waterbirds which include tuber eaters, sedge foragers, and invertebrate feeders than isolated lakes [4]. Because of delayed water recession, low EVI value led to poor habitat quality for wintering geese [60]. HC also impacted fish in the floodplain. Floodplain connectivity, seasonality, and habitat characteristics triggered remarkable structural changes for fish [56,61]. The results showed that HC played a decisive role in the fish structure. The removal of the road improved the degree of HC, the complexity of the habitat, and improved the diversity of fish in the Las Cabras floodplain. For Dongting Lake, the river–lake system, the dominant HC keeps the river–lake connection ecosystem in healthy hydrological connectivity status which is crucial for fish to breed and find suitable habitat [3]. The river–lake connection is essential for the river–lake migratory fishes. The dominant HC facilitates the lateral migration of fishes, keeping the ecosystem in hydrological connective status and maintaining a high concentration of aquatic biodiversity. River floodplain lateral HC directly influenced the community characteristics of aquatic invertebrates, and it played profound indirect effects by changing local habitat features [62].

4.3. Data Limitations and Future Research

Sentinel-2 images are suitable to quantity the HC of Dongting Lake based on the geostatistical method. However, owing to long-time cloud disturbance, only 43 months of high spatiotemporal resolution images in four years were suitable to extract water inundation, which limited the connectivity analysis. Here, this study only paid attention to the relationship between hydrological factors, meteorological factors, and surface HC. However, the remote sensing data without water depth and complex lakebed terrain lead to uncertainties in HC analysis. Additionally, the groundwater and aquifers also play an important role in affecting floodplain wetland recharge and discharge process; thereby it is crucial to evaluate the influence of the surface–groundwater recycling on HC and ecological processes in future research. The water area and water level play crucial roles in protecting biosystem health [63]. Waterbirds preferred to choose small inundation depth areas as habitats and fish choose the large inundation area as habitats [12]. Due to the temporal and spatial distribution differences of rainfall and evaporation and abnormal weather conditions, the average precipitation and evaporation at the ground station (Yueyang, Changde, and Yuanjiang) may not represent the real precipitation and evaporation of the whole lake in the short study period (2017–2020). The discrepancy between the average value and the real value may lead to the impact of precipitation and evaporation on HC being weakened. In addition, the analysis was conducted on a monthly scale. In addition, the hydrology and climate data are the averages of the station data. However, the HC obtained from the remote sensing image cannot represent the average of the month. Therefore, the different study time steps (HC and hydrology, and climate drivers) may lead to the uncertainty of the SEM results [64]. Therefore, it is important to elucidate how HC affects biodiversity and the environment via long-time climate observation, water level, and water area in future work. The hydraulic project constructed in the lake outlet improved the water level during the dry period, but it changed the ecological landscape and even deteriorated the water quality [65]. Hydraulic project construction not only changes downstream hydrological characters but also fragments the water habitats of freshwater organisms [31,50,57]. To improve the water shortage, some studies proposed to structure inner dikes with sluice gates or structure dams in Chenglingji to increase water levels in the dry season [23]. In addition, optimizing the dispatching of the Three Gorges and increasing the inflow of water from the three inlets may improve the connectivity of Dongting Lake during the low-water period [31]. Furthermore, the increase in inlet inflow will enhance the habitat quality of fish and the food availability of birds. Hence, it is a challenge to improve the HC during a low water level period for the ecosystem process in the future.

5. Conclusions

The floodplain wetlands system is characterized by an important ecosystem that not only regulates flooding, and provides food and water but also supports habitat for animals. HC has been a hotspot for hydrologists, ecologists, and environmental scientists. This paper selected high temporal and spatial resolution Sentinel-2 remote sensing images, which enhanced the precision of the inundation map to calculate HC. Meanwhile, this paper extended the previous study by comprehensively considering the influence of hydrology variables (T-flow and F-flow) and meteorology variables (precipitation, temperature, and evaporation) on HC. According to the SEM, hydrological variables played a predominant role in determining the HC than meteorology variables. T-flow (r = 0.49, $p < 0.001$; r = 0.44, $p < 0.001$) had more significant positive direct effect than F-flow (r = 0.28, $p < 0.01$; r = 0.25, $p < 0.05$) on N–S and E–W HC. Temperature played a significant positive direct effect on E–W HC (r = 0.33, $p < 0.05$). Therefore, regulating the flow of three inlets and four tributaries may enhance the HC and habitat quality of fish and birds in the dry period. In the winter, increasing the water supply from the TGD to Dongting Lake via the three inlets can control the water level and keep the vegetation in a suitable exploitation condition for waterbirds during the low water period. The suitable HC can also play an important role in water purification, navigability, and fish lateral migration. Detailed HC analysis of floodplain wetland is applicable for flood impact assessment, navigability analyses, and wetland ecology estimation. This study is helpful to deepen the understanding of HC in the complicated river–lake interconnected system, and elucidate the relationship between hydrology and meteorology on HC. Hence, the presented methodology can be applied to the neighboring Poyang Lake and support strategies for floodplain wetland management.

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