Using InSAR to identify hydrological connectivity and barriers in a highly fragmented wetland

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Abstract
Hydrological connectivity is a critical determinant of wetland functions and health, especially in wetlands that have been heavily fragmented and regulated by human activities. However, investigating hydrological connectivity in these wetlands is challenging due to the costs of high-resolution and large-scale monitoring required in order to identify hydrological barriers within the wetlands. To overcome this challenge, we here propose an interferometric synthetic aperture radar (InSAR)-based methodology to map hydrologic connectivity and identify hydrological barriers in fragmented wetlands. This methodology was applied along 70 transects across the Baiyangdian, the largest freshwater wetland in northern China, using Sentinel 1A and 1B data, covering the period 2016–2019. We generated 58 interferograms providing information on relative water level changes across the transects that showed the high coherence needed for the assessment of hydrological connectivity. We mapped the permanent and conditional (temporary) barriers affecting connectivity. In total, 11% of all transects are permanently disconnected by hydrological barriers across all interferograms and 58% of the transects are conditionally disconnected. Areas covered by reed grasslands show the most undisturbed hydrological connectivity while some of these barriers are the result of ditches and channels within the wetland and low water levels during different periods of the year. This study highlights the potential of the application of Wetland InSAR to determine hydrological connectivity and location of hydrological barriers in highly fragmented wetlands, and facilitates the study of hydrological processes from large spatial scales and long-time scales using remote sensing technique.

KEYWORDS
coherence, fragmented wetland, fringes, hydrological barriers, hydrological connectivity, InSAR
1 INTRODUCTION

Wetlands are important natural systems that provide important ecosystem services such as habitat provision, pollutant removal, freshwater storage and microclimate regulation (McLaughlin & Cohen, 2013; Singh & Sinha, 2019). Hydrological connectivity is the transfer of matter, energy or organisms within or between hydrologic elements and it is a critical determinant of wetland functions (Foti, Del Jesus, Rinaldo, & Rodríguez-Iturbe, 2012; Jaramillo et al., 2018a). Hydrological connectivity in wetlands may be altered by climatic drivers such as droughts or floods or man-made perturbations such as hydraulic structures, roads and urban developments, changing hydrological processes that can potentially lead to the degradation of these ecosystems (Saco et al., 2020). Thus, hydrological connectivity has gradually become an important proxy of wetland health and degradation (Galat et al., 1998; Pringle, 2001, 2003; Freeman, Pringle, & Jackson, 2007; Liu et al., 2019; Saco et al., 2020). The status of hydrological connectivity is also relevant for the sustainable management and restoration of wetlands (Clark et al., 2015; Liu et al., 2020; Saco et al., 2020), the delivery of ecosystem services (Quin, Jaramillo, & Destouni, 2015; Thorslund et al., 2017) and to reach recent sustainable development goals in many regions and wetlands across the world (Jaramillo et al., 2019).

Several methods have been developed recently to investigate the hydrological connectivity in wetlands, with differences depending on the research aim, scale and location. These methods can be categorized into two main groups: index-based and process-based approaches. Index-based approaches study implicit evidence of connection or disconnection within the wetland system, focusing on the identification of critical thresholds in variables such as soil moisture and water level/depth that once transgressed provides evidence of hydrological connectivity (e.g., Ali & Roy, 2010; McLaughlin & Cohen, 2013; Nanda, Sen, & McNamara, 2019). For example, Karim, Kinsey-Henderson, Wallace, Arthington, and Pearson (2012) identified a threshold of hydrologic connectivity during overbank flooding in north Queensland when water depth surpassed 30 cm. Process-based approaches, on the other hand, capture the evolutionary dynamics of water flow, providing explicit evidence of connection or disconnection. Using this approach, Karim et al. (2015) and Ameli and Creed (2017) used hydrodynamic modelling to track water movement and to determine if water flow generated in one wetland water body reached the other water bodies by hydrologic connectivity. In situ tracers such as chemical compounds or isotopes used to track flow paths are also process-based approaches useful for assessing hydrological connectivity across various scales (Ala-aho et al., 2018; Golden et al., 2017; Mcdonnell & Beven, 2014). Despite these former calls to the importance of hydrological connectivity for the assessment of wetland functions (Ponette-González et al., 2014; Pringle, 2001; Hiatt & Passalaquca, 2015; Thorslund et al., 2017), it is still challenging to study hydrological connectivity due to the lack of event data of high temporal and spatial resolution required for such assessment (Jaramillo et al., 2018a; Kang & Guo, 2011; Wdowinski & Eriksson, 2009).

A remote sensing technique termed Wetland interferometric synthetic aperture radar (Wetland InSAR; Wdowinski, Amelung, Miralles-Wilhelm, Dixon, & Carande, 2004) is a complementary radar-based tool of high spatial resolution used to monitor surface hydrological processes in wetlands. Water level changes, sheet flow and water flow have been studied in different regions of the world with this methodology (Chen et al., 2020; Hong, Wdowinski, & Kim, 2010; Kim et al., 2014; Lee, Yuan, Jung, & Beighley, 2015; Palomino-Ángel, Anaya-Acevedo, Simard, Liao, & Jaramillo, 2019; Xie, Shao, Xu, Wan, & Fang, 2013; Zhou, Bin, & Li, 2009). Wetland InSAR generates maps representing changes in the water surface, over time, from differences in the phase-path length of two satellite acquisitions, taken from the same orbital position, at the same resolution and over the same region.

As shown by recent studies, Wetland InSAR can be successfully used to study hydrological connectivity in poorly ungauged wetlands ranging from coastal marshes to mangroves floodplains (e.g., Jaramillo et al., 2018a, 2018b; Oliver-Cabrera & Wdowinski, 2016; Palomino-Ángel et al., 2019; Xie et al., 2013). All of these studies have given general guidelines on the state of hydrologic connectivity in wetland resources; however, focus on the barriers to hydrologic connectivity and their characteristics, and actual inventories of these barriers are lacking. This knowledge gap is understandable as barrier identification is costly and logistically complex, considering the complexity of wetland systems. Nevertheless, addressing this knowledge gap is of utmost importance since hydrological barriers continue to degrade wetlands worldwide by limiting water and nutrient movement, and in some cases subjecting the wetlands to unsustainable conditions that lead to the collapse of their aquatic and terrestrial ecosystems. Such is the case of the Ciénega Grande de Santa Marta wetland complex in Colombia, being one of the most tragic and known cases, where hydrological barriers have hyper salinized the wetland and led to the collapse of mangrove populations and fisheries (Jaramillo et al., 2018a, 2018b; Röderstein, Perdomo, Villamil, Hauffe, & Schnetter, 2014; Vilardy, González, Martín-López, & Montes, 2011; Zipper et al., 2020).

We here use Wetland InSAR to identify and inventory hydrological barriers impeding connectivity in wetland systems. As the Ciénega Grande de Santa Marta, the Baiyangdian wetland in the Northern China has experienced deteriorating hydrological conditions mainly driven by decreasing water inflow, increasing surface evaporation and decreasing water level (Cao, Yi, Liu, & Yang, 2020; Yang, Yin, Chen, & Yang, 2014). Furthermore, its complex wetland ecosystems, composed of freshwater lakes, herbaceous marshes and terrestrial lands, currently present a large degree of fragmentation due to drainage, channelization, agricultural, urban expansion and road construction (Cao et al., 2020; Liu et al., 2019). The resulting impact is the disappearance of the wetland system, and large impacts on both of its terrestrial and aquatic ecosystems. The Baiyangdian wetland comprises 140 small lakes of different sizes, 39 villages, over 3,700 ditches and 80 km² of reeds. With such a fragmented landscape, it is difficult to determine the current level of hydrologic connectivity of the wetland and the locations of the barriers responsible for such decrease in connectivity.
Previous hydrological studies of the wetland have focused mainly on the understanding of water level fluctuations, water flows and corresponding eco-environmental responses (Wang, Wang, Zhao, & Yang, 2012; Wang & Yang, 2010; Yan et al., 2017; Yang et al., 2014; Yang & Yang, 2014). An assessment of hydrological connectivity and the identification of hydrological barriers are yet to be conducted. We here propose an InSAR-based methodology based on synthetic aperture radar observations to identify hydrologic connectivity or barriers based on Sentinel 1A and 1B data covering the period 2016–2019.

2 | METHODS

2.1 | Study area

The Baiyangdian wetland is located in northern China, in the heart of the Beijing-Tianjin-Hebei (Jing-Jin-Ji) region and Xiong’an new area, a newly developed centre for government functions and employees relocated from Beijing (see Figure 1a). The wetland receives water from nine upstream rivers, serving important ecological services and functions such as water supply, flood storage, climate regulation and habitat to local communities and both aquatic and terrestrial ecosystems (Cao et al., 2020; Yan et al., 2017). This is the reason why this wetland is also referred to as “the kidney of North China.” Contrasting with its importance, the Baiyangdian wetland has suffered a serious ecological degradation due to the heavy pollution loads related to agriculture development and urbanization and the repeated and strong droughts occurring since the 1960s. As a response to such degradation, the government of China has attempted to limit the degradation of the wetland by limiting pollutant loads and restricting projects that withdraw water from the feeding rivers and the wetland itself. Although significant improvements have been achieved, it is still far from becoming a healthy sustainable ecosystem (Kumar, Mishra, & Sharma, 2015; Xu, Yang, Chen, & Zhao, 2012). The Baiyangdian wetland covers an area of 366 km² and has a water storage of $1.32 \times 10^9$ km³, with average water depth in the range of 2–4 m. Since the 14th century, water resource allocation, land reclamation, urbanization and construction of villages, fish ponds and lotus ponds have modified its original hydrologic, ecologic and social characteristics. Such modifications have resulted in a mosaic of urban, cultivated lands, reed grasslands and open water bodies (including deep and shallow water zones with slight sporadic emergent aquatic vegetation; Figure 1b; Yan et al. (2017)).

2.2 | Wetland InSAR and hydrological connectivity

Interferometric synthetic aperture radar (InSAR) is a reliable technique for monitoring centimetre-level displacements of the earth-surface (Wdowinski & Hong, 2015). It compares pixel-by-pixel SAR phase (i.e., phase shift between transmission and reception of the radar signal) observations acquired from the same orbital position, at different times and over the same region, to generate high-spatial-resolution map of vertical ground displacement, termed interferograms (Jaramillo et al., 2018a, 2018b; Wdowinski & Hong, 2015). The interferograms are maps of phase change in both time and space, visualized as repeating fringes similar to contour lines with a full colour scale. For the particular case of InSAR studies focusing on surface water connectivity, the interferograms are studied in the wrapped phase of the radar signal (i.e., $0$ to $2\pi$ or $-\pi$ to $\pi$).

Wetland InSAR is the use of the InSAR technology to detect changes in elevation of aquatic surfaces. This technique works where vegetation emerges above the water surface due to the double bounce effect in which radar pulse is backscattered twice from the water surface and vegetation (Chen et al., 2020; Richards, Woodward, & Skidmore, 1987). Since interferogram observations are not absolute but relative in value, absolute changes of water level in wetlands can only be computed when combined with stage monitoring or altimeter observations (Hong & Wdowinski, 2014; Kim et al., 2009). For the case of the Baiyangdian wetland, we limit ourselves to the calculation of relative changes in water level, as obtained directly from InSAR, as actual observations of water level are scarce and/or not available. More specifically, the data in Baiyangdian wetland are not accessible to the general public due to the establishment of the Xiong’an new area and to issues of national security according to local officials. However, Wetland InSAR can also be used to determine

![FIGURE 1](image-url)
hydrological connectivity by studying the characteristics of the fringes generated in the interferograms to derived relative water level changes.

We now explain how Wetland InSAR can be used to detect barriers that obstruct hydrological connectivity by studying water level (h) in the wetland and its change (Δh) (Figure 2). Consider water level in two adjacent water bodies (or pixels), A and B, that are separated by a hydrological barrier (hA and hB, respectively). Their changes between two different radar acquisition dates in time (ΔhA and ΔhB, respectively) should be different and independent, visualized in the interferogram as a discontinuous fringe (Wdowinski & Hong, 2015). Under almost the same incidence angle (ii), the values of ΔhA and ΔhB are obtained from a corresponding phase change representing the difference in the line of sight of the radar (ΔΦA and ΔΦB) as the path length changes from the first to the second acquisition. The unwrapped phase changes (ΦA and ΦB) of δA, δB are measured in radians, are related to ΔhA and ΔhB by the characteristics of the radar such as θ and the wave length (λ), and can be used to calculate the difference in water level in each pixel, relative to that of neighbouring pixels in the interferogram as follows:

\[ Δh = \frac{d}{\cosθ} = \frac{iΔΦ}{4π\cosθ} \]

(1)

If Δh is markedly different between two adjacent pixels, with the difference being much greater than that expected by sheet flow or waves, a hydrological barrier can be identified. We define a spatial rate of change in the water level change (ξ) along the transect to identify hydrological barriers along transects of varied lengths, as follows:

\[ ξ = \frac{(Δh_B - Δh_A)}{D} \]

(2)

where D is the horizontal distance between the pair of adjacent pixels evaluated. In this study, we assume that a hydrological barrier occurs when > 200% * ξ, where ξ is the mean value for the entire transect.

2.3 Data and processing

As Sentinel-1 images, covering Baiyangdian wetland on the Alaska Satellite Facility website (where we retrieved images from), are available only since 2016, we downloaded 77 Sentinel-1A or Sentinel-1B C-band Single Look Complex (SLC) images with VV-polarization between January 2016 and December 2019. Interferometric coherence, referring to the spatial consistency of the SAR phase is a measure of quality of the signal in an interferogram; in this study, we assumed that good coherence is larger than 0.4 (Sato & Suzuki, 2017). Interferometric coherence depends on the type of surface vegetation, the temporal baseline and the separation between the radar locations of the two satellite acquisitions. As the distance between satellite positions for the wetland location varies between 5 and 150 m, we used pairs of SAR images with temporal baselines of less than 70 days (Wdowinski & Hong, 2015). According to Wdowinski and Hong (2015), herbaceous vegetation like saw grass and cattail, as found in the Baiyangdian wetland, has lower coherence than woody wetlands. Since the Baiyangdian wetland is mainly covered by reeds and lotus, we use interferometric pairs with temporal baselines shorter than 12 days to obtain a good coherence for the existing herbaceous vegetation.

The Sentinel 1A and 1B SLC data were processed using ENVI SARscape, which is a modular set of ENVI software. For each interferometric pair, the earlier acquisition is referred to as the master image, and the latter as the slave image. Following co-registration of the two images with the 30 m digital elevation model (DEM), the interferograms were generated by multiplying the master image by (the complex conjugate of) the slave. The 30 m-DEM of SRTMGL1 was also used to simulate the topography-induced phase shifts, which were removed in order to obtain the flattened interferogram. To reduce phase noise related to temporal and geometric effects, we applied a Goldstein 5 × 5 phase filter to the flattened interferogram (Goldstein & Werner, 1998).

We generated in total 58 interferograms of the wetland area, of which 15 marked with the red line in Figure 3, and characteristics described in Table 1) during the period 2017–2019 showed the highest coherence, the largest amount of and the clearest fringes of phase change. We focused the analysis in these 15 interferograms in their wrapped phase, ranging in a 2π-cycle, and extracted coherence and phase change data over 70 transects. We calculated the mean coherence (i.e., 0 for no coherence and 1 for perfect coherence) over each transect and focused only on transects with mean coherences larger than 0.4. We extracted phase changes every 10 m along the transects and in order to calculate the real magnitude of changes in water level with Equation (1), we unwrapped the phase changes with minimum cost flow algorithm (Jiang, 2011) assuming a water level change of zero at the last pixel of the transect. Evident outliers of

FIGURE 2 Schematic diagram of hydrological barriers along a transect. Water level changes (ΔhA and ΔhB) between two images (R1, R2) taken at different times (t1, t2) in the two water bodies, A and B, are related to the corresponding phase changes (ΦA and ΦB) proportional to path changes (δA and δB) along the line of the satellite when the water level changes from WL1 to WL2.
phase change across the transects that point to noise rather than changes in the water surface were removed from the unwrapped phase profiles. We identified the presence of hydrological barriers by Equation (2) in each combination of interferogram (15 in total) and transect (70 in total) and summarized for each transect (1–70) the number of interferograms showing poor coherence (Table 2). For the transects, 20, 39, 47 and 65, hydrological connectivity could not be analysed due to their poor coherence across all interferograms. We analysed the status of hydrological connectivity of the remaining 66 transects and recognized corresponding barriers and their locations.

Finally, if a hydrological barrier was identified along the transect throughout all the analysed interferograms, we categorized the barrier as "permanent," otherwise as a "conditional" barrier. We categorized all transects as either "connected" or "disconnected," depending on the presence of hydrological barriers. Whereas a connected transect has no barriers, a disconnected transect can be "permanently disconnected" or "conditionally disconnected" depending on the recurrence of the presence of hydrological barriers across the interferograms (i.e., existence of at least one hydrological barrier along the transect under all analysed interferograms and under only a number of interferograms, respectively).

**TABLE 1** The 15 interferograms with the highest coherence and their main characteristics

| No | Interferogram                      | Season | Sensor   | Inc. angle (°) | Direction | Baseline (m) | Mean coherence |
|----|-----------------------------------|--------|----------|----------------|-----------|--------------|----------------|
| In1| February 1, 2017–February 13, 2017 Winter Sentinel-1A 39.1 Ascending 113.46 0.42 |
| In2| February 25, 2017–March 9, 2017   Spring Sentinel-1A 39.1 Ascending 25.06 0.44 |
| In3| April 2, 2017–April 14, 2017     Spring Sentinel-1A 39.1 Ascending 77.57 0.41 |
| In4| November 28, 2017–December 10, 2017 Winter Sentinel-1A 39.1 Ascending 111.33 0.49 |
| In5| December 10, 2017–December 12, 2017 Winter Sentinel-1A 39.1 Ascending 55.64 0.49 |
| In6| December 22, 2017–January 3, 2018 Winter Sentinel-1A 39.1 Ascending 71.66 0.50 |
| In7| January 27, 2018–February 8, 2018 Winter Sentinel-1A 39.1 Ascending 59.51 0.42 |
| In8| February 8, 2018–February 20, 2018 Winter Sentinel-1A 39.1 Ascending 70.30 0.49 |
| In9| November 11, 2018–November 23, 2018 Autumn Sentinel-1A 39.1 Ascending 72.06 0.45 |
| In10| November 23, 2018–December 5, 2018 Winter Sentinel-1A 39.1 Ascending 112.13 0.47 |
| In11| January 10, 2019–January 22, 2019 Winter Sentinel-1A 39.1 Ascending 15.12 0.47 |
| In12| March 11, 2019–March 23, 2019 Spring Sentinel-1A 39.1 Ascending 13.96 0.44 |
| In13| March 23, 2019–April 4, 2019 Spring Sentinel-1A 39.1 Ascending 14.72 0.43 |
| In14| April 4, 2019–April 16, 2019 Spring Sentinel-1A 39.1 Ascending 38.32 0.43 |
| In15| December 12, 2019–December 24, 2019 Winter Sentinel-1A 39.1 Ascending 62.49 0.50 |

**FIGURE 3** Interferograms (lines) between pairs of SAR observations (dots). The horizontal axis refers to each acquisition date and the vertical axis to the distance between the satellites in the two acquisitions. Interferograms with high mean coherence, exceeding 0.4, are shown in red.
3 | RESULTS

3.1 | Variability of interferometric coherence and wrapped phase

We first studied the characteristics of interferometric coherence and wrapped phase over each of the mentioned land-cover classifications found within the wetland. We find that the order of mean coherence per land cover type is consistent across all interferograms, with decreasing coherence from urban, cultivated land and reed grassland to open water (Figure 4). This result is expected as urban areas present higher coherence due to the stability of their structures and vegetation. Furthermore, we find that the distributions of wrapped phase-change values for urban areas and cultivated land occur within a limited range of values, in comparison to reed grasslands and water surfaces in which the distribution has a wider range due to the low coherence of the radar signal (Figures S1-S2). Unfortunately, this hinders the application of InSAR to study hydrological connectivity in these two low-coherence land covers.

3.2 | Identifying hydrological connectivity and barriers

The interferogram generated with the pair of images on December 10, 2017, and December 22, 2017 (In5) has a high coherence and the largest number of fringes of the group of generated interferograms (Figure 5a). High interferometric coherence is shown by consistent fringe patterns (Figure 5b), whereas low coherence occurs as a fuzzy phase pattern (Figure 5c). In order to explain how hydrologic connectivity can be inferred along a transect, we use the case of the 1.2-km transect Nr. 3, located in the southwest of the wetland (black rectangles [iii] in Figure 5a) and covered mostly by reed grasslands. Three interferograms, In5, January 27, 2018—February 8, 2018 (In7) and November 28, 2017—December 10, 2017 (In4), have good coherence and clear fringe patterns despite the known low coherence for such land cover (Figure 6a). The phase change and water level changes extracted and calculated for transect Nr. 3 are shown in Figure 7 for the three interferograms. The continuous phase-change patterns of the wrapped and unwrapped phases of interferograms, In5 and In7,
indicate a continuous change in water level between the two dates, consistent with the flow movement and sheet flow in open water bodies. Since no abrupt changes in water level can be seen across the transect, we here assume full hydrological connectivity between these dates.

The maximum water level changes along the transect in interferograms In5 and In7 are, respectively, 1.1 and 1.5 cm at 520 and 40 m from the start of the transect. These profiles of water level changes are explained by either wetland sheet flow, local rain events or surface waves occurring in one of the two dates, or in both dates. For the case
of interferogram ln4, although the wrapped and unwrapped phase of the transect show a large variability of phase change along the first 150 m, we here assume hydrological connectivity after this spatial interval. As such, hydrological connectivity occurs throughout the three interferograms and there is no evident barrier to water flow.

Conversely, we take the example of the 2.4-km transect Nr. 13 (Figure 6b), located in the east of the wetland (black rectangles [iv] in Figure 5a and which is mostly covered by reeds and open water), to illustrate how the pattern of phase change can infer the presence of a hydrological barrier (Figure 8). We take again the two interferograms yielding the highest coherence, ln5 and ln4, but replace ln7 with December 12, 2019–December 24, 2019 (ln15) due to the poor coherence for the former along this transect. The unwrapped phase change in interferogram ln5 evidences a discontinuity in the middle of the transect (i.e., around 1.2 km from the starting location) with water level changing abruptly at a rate of 372 mm/km between the two images. The change is 78.5% the mean phase change along the transect (47 mm/km). For the case of the other two interferograms, there is a pronounced change in the phase at the same midway location, although the change is not as abrupt as in ln15, 69 mm/km (23.7%) and ln4, 80 mm/km (28.8%), respectively.

In any case, this analysis suggests the presence of a hydrological barrier 1.2 km from the beginning of the transect, corresponding to a ditch stretching across two reed grasslands, which developed after dredging practices (Figure 6b).

We visualize all identified hydrological barriers in Figure 9. According to our initial transect selection, 74% of all transects are disconnected, indicating a general poor hydrological connectivity within the Baiyangdian wetland. We find that 40% of the permanent barriers and 33% of the conditional barriers are located in ditches beside reed grasslands such as the case of transect Nr. 13. Conditional barriers account for 88% of all barriers, highlighting the fact that most hydrological barriers are temporary and may depend on water level in the lake and water input to the lake. We expect that the lower the water level in the wetland, the lower the hydrological connectivity and more the occurrence of hydrological barriers.

The transects cover different land covers: 19% are located on reeds, 7% on open water, 43% on a combination of reeds and open water and 19% of urban areas, reed and open water (inner pie chart in Figure 10), with the remaining percentage covered by other combinations. To explore the causes behind the existence of hydrologic barriers, we summarize transects and categories of hydrological connectivity and barriers per land cover (outer pie chart in Figure 10). In total, 11% of all transects are permanently disconnected as they present barriers across all interferograms and 58% of the transects are conditionally disconnected, probably due to high-elevation reed...
grasslands near water or sediment deposits beside ditches after dredging activities (as found by Jaramillo et al., 2018a, 2018b). For reeds specifically, 50% of all transects are disconnected, showing a relatively good hydrological connectivity in comparison to urban areas or mosaics of urban areas and other land covers where there is a high presence of hydrological barriers. Regarding cultivated lands, the existence of active irrigation ditches may be responsible for the low hydrologic connectivity, although ground truthing is needed to confirm this. That is to say, urban areas, high-elevation reed grasslands and some cultivated areas present hydrological barriers affecting hydrological connectivity within the Baiyangdian wetland.

4 | DISCUSSION

Hydrological connectivity within wetlands is highly temporal and spatially dynamic, depending on the landscape heterogeneity, the volume of water in the wetland and the water inflows and outflows (Bracken & Croke, 2010; Epting et al., 2018). Heretofore, hydrological monitoring of wetlands is mostly conducted by stage (i.e., water level) measurements in gauging stations that provide good temporal resolution. However, gauging renders expensive and logistics-demanding when attempting to map hydrological connectivity with high spatial resolution (Wdowinski & Hong, 2015). It is because of this that hydrological connectivity is in most cases studied as sporadic “snapshots” of hydrological characteristics in time and space. Although this InSAR methodology is also based on temporal and spatial “snapshots,” it enables a detailed analysis of hydrologic connectivity and identification of specific barriers over wide areas ($100–400$ km) and with high-spatial-observations ($1–100$-m pixel resolution) (Wdowinski & Hong, 2015). Particularly, the Sentinel-1 satellite, launched in 2014, can provide cost-free SAR datasets with a short repeat cycle of 6–12 days, allowing a consistent long-term observation of hydrological connectivity in wetlands. The easily accessible data contribute to the great potential use of Wetland InSAR for investigating hydrological connectivity. Nevertheless, due to observations dependent on the revisiting time of the satellites (radars), the InSAR-based method can only assess hydrological changes between dates with radar acquisitions, and more specifically, between the two instantaneous moments when the acquisitions take place. Thus, the InSAR method is subject to the environmental conditions that apply in the two times of acquisition. Furthermore, water level changes can only be assessed from the moment that the satellite holding the radar is in orbit. Depending on the radar used, the InSAR analysis can only be used within the following time periods corresponding to each satellite: ERS1/2 (1995–2000), Envisat (2003–2010), Alos PALSAR (2007–2011) and S1 (2014–2019).
InSAR observations can be complemented with water level in situ observations to validate measurements and even improve the understanding of hydrological processes, as it has been done in similar studies (e.g., Hong et al., 2010). Nevertheless, in the case of ungauged wetlands or wetlands with limited availability of water level data, such as the case of this study, InSAR observations are currently the only way to understand hydrological processes in wetlands that are ungauged. InSAR has been used in a similar way in other data-limited regions to understand wetland and floodplain hydrological connectivity where no data exist (e.g., Jaramillo et al., 2018a, 2018b). However, previous studies have identified hydrological connectivity only by large-scale interferograms and specific transect cases, in comparison to the high-resolution study on hydrological connectivity performed here.

The main challenge of utilizing Wetland InSAR is finding the good coherence in the interferograms necessary to obtain reliable phase-change information related to water level changes. In this study, we used C-band Sentinel-1A and Sentinel-1B data to generate interferograms, with all high-coherence interferograms occurring in spring or winter and low-coherence interferograms occurring during summer and autumn (see Table 1). The seasonal dependency is caused by high vegetation densities in summer and autumn, when the C-band radar signal cannot penetrate the vegetation or because of the instability in time of the vegetation. Previous Wetland InSAR analysis of L-band ALOS data acquired in summer indicated a good interferometric coherence over the reed grassland vegetation in the Yellow River.
of guaranteeing freshwater inputs into the wetland and/or regulating and can vary depending on the wetland and the environmental pres-

improving or decreasing hydrological connectivity is then case-specific can be constructed to prevent the mixing or inflow of these pollut-

allows to identify areas of hydrological connectivity where barriers can be isolated from specific wetland ecosystems. In this case, InSAR also render convenient when heavily polluted or anoxic waters want to be isolated from specific wetland ecosystems. When sufficient transects are used to assess hydrological connectivity and barriers, the spatial and temporal variations of water level can be assessed at a high spatial resolution. For instance, the results of Figure 9 can be used to infer locally the type of vegetation expected and the conditions of water quality. Areas with low hydrological connectivity as shown by the presence of hydrological barriers may be subject to conditions of low water quality, such as high salinity, nutrients or pollutants due to the lack of sufficient water pulses, sheet flow and flushing and consequent long water residence times (Zhang et al., 2020; Zhao, Xia, Yang, & Wang, 2012). As such, by locating the hydrological barriers in the wet-

land, removing or modifying the barriers can be targeted in these specific locations to improve hydrological connectivity. For the specific case of this study, we have found that the ditch in the middle of transect 13 obstructs the flow of water along the transect (Figure 6). Its existence could not have otherwise been confirmed from optimal imagery or fieldwork. The management measures required to improve water circulation and connectivity vary depending on the wetland and the specific environmental problems generated by the undesired level of hydrological connectivity (See as examples Adeli et al., 2020; Feagin, Johns, Huff, Abdullah, & Fritz-Grammond, 2020; Lee, Yuan, & Jung, 2020; Siles, Trudel, Peters, & Leconte, 2020; Wemiple et al., 2017). Dredging can be used to remove sediments or installing culvert pipes across the ditch may help to improve the connectivity of this area. For the specific case of mangrove areas in tropical regions, InSAR observations may be used to suggest regions where channeling improves the access of freshwater to areas subject to hypersaline conditions. Interestingly, although ditches are used to connect and transport water to needed locations, we here find that ditches in wet-

lands, such as the one in transect 13, can become hydrological barriers between water bodies on both sides of the ditch. This effect has been found in wetlands in other latitudes (e.g., Jaramillo et al., 2018a, 2018b; Kim et al., 2014). On the contrary, obstructing water flow may also render convenient when heavily polluted or anoxic waters want to be isolated from specific wetland ecosystems. In this case, InSAR allows to identify areas of hydrological connectivity where barriers can be constructed to prevent the mixing or inflow of these pollutants, maintaining the target ecosystem healthy. The convenience of improving or decreasing hydrological connectivity is then case-specific and can vary depending on the wetland and the environmental pressures to which the ecosystem is subject to.

For the particular case of the Baiyangdian wetland, our finding of a high number of transects with conditional barriers pinpoints the need of guaranteeing freshwater inputs into the wetland and/or regulating outflows to maintain or allow the high water levels that guarantee hydrological connectivity and wetland sheet flow. Particularly, in areas where conditional barriers are widely distributed (see yellow circle in Figure 9), increasing water levels may be more convenient, in ecological and monetary terms, than modifying barriers to improve connectivity. Unfortunately, water level information is not available for this wetland during the period of analysis, as happens so often in many other wet-

lands worldwide. Complementing InSAR-based results, such as the ones obtained in this study, with water level gauging information would strengthen the assessments of hydrological connectivity and water management. Studies such as this one can be then used as preliminary assessment before designing and constructing engineering solutions, saving costs, shortening time of wetland recovery and increasing efficiency of measures dealing with hydrological connectivity.

5 | CONCLUSION

We introduce a Wetland InSAR-based method to map hydrological connectivity in fragmented wetlands and identify locate permanent and conditional hydrological barriers. With this method, we develop a map of hydrological connectivity for the Baiyangdian wetland, finding a general condition of poor hydrological connectivity. The poor connectivity is caused by hydrological barriers mostly found in urban areas and reed grasslands, and in some cases generated by the construction of ditches within the wetland. We hypothesize that following the procedures executed in other wetlands with problems of hydrological connectivity, hydrological barriers should be removed or modified. We find that a large number of the identified barriers are conditional barriers, that is, occurring only in specific time periods and dependent on the amount of water in the wetland. We emphasize the necessity of maintaining sufficiently high water levels in the wetland, as several hydrological barriers should disappear once the volume of water increases in the wetland is restored. These results can help to develop guidelines for future water management and restoration of wetland ecosystems.

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DATA AVAILABILITY STATEMENT

All Sentinel-1A or Sentinel-1B C-band Single Look Complex (SLC) images are available from the Alaska Satellite Facility website. The land cover data are available from Yan et al. (2017).
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**SUPPORTING INFORMATION**

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