Quantifying intra- and inter-annual dynamics of river-floodplain connectivity and wetland inundation with remote sensing and wavelet analysis

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**Abstract**

We used imagery from remote sensing (FORCE Time Series Analysis submodule (combining Landsat and Sentinel-2 imagery) to derive spatially distributed times series (8 years) of NDWI data to infer patterns of floodplain inundation and river-floodplain connectivity in two contrasting polders in the Lower Oder Valley National Park. The upstream Polder A (14.4 km\(^2\)) was extensively flooded for prolonged periods most winters. Wavelet analysis showed that this strong seasonality was primarily driven by winter water levels in the river Oder that could enter and leave the polder through two opened floodgates. Subsequent drainage was slow and aided by a pumping station. Inundation of the downstream Polder 10 (17.7 km\(^2\)) was lower and had less marked seasonality. This reflected the impact of flood attenuation by storage in Polder A upstream, but also the greater connectivity (via 10 floodgates) to the Oder and a functional network of channels, which facilitated rapid drainage after flood peaks. In Polder A, secondary periods of transient inundation could also occur in response to local intense summer rainfall. Wavelet analysis also showed that groundwater recharge in and around Polder A is primarily induced by floodwater, whilst Polder 10 also reflects the influence of local rainfall-driven recharge. The flood regimes of the two polders showed marked inter-annual variation, largely dependent on flows from the upper Oder catchment. Understanding these patterns and processes of inundation is important for both managing flows and sustaining valuable wetland habitats within the National Park. Given projected climate change in eastern Europe and possible management alterations to the flow regime of the Oder, the potential implications for these habitats needs urgent attention.

**Keywords**

floodplain, Oder river, remote sensing, river-floodplain connectivity, wavelet analysis, wetlands
1 | INTRODUCTION

Large floodplains and associated wetlands are important landscape features forming rich, contrasting habitats that sustain high levels of both plant and animal biodiversity (Holgerson et al., 2019). They are inundated when river flows exceed channel capacity, connecting the floodplain to both the river and upstream catchment (Globevnik et al., 2020). A variety of ecosystem services are provided by hydrological processes on floodplains (Funk et al., 2021), such as flood alleviation, improved water quality, deposition of nutrients and carbon sequestration and so forth. (Felipe-Lucia et al., 2014; Posthumus et al., 2010). These services are influenced by the marked spatial gradients and temporal variations in wetness in floodplains, which in turn are primarily sustained by the dynamics of river-floodplain connectivity processes, which may also involve complex river-aquifer interactions (Czuba et al., 2019). Generally, a lower frequency and longevity of connectivity will occur under a drier climate (Karim et al., 2016) and both climate and land use change affect a floodplain’s capacity for delivering multiple ecosystem services (Gaglio et al., 2019).

In this context, the dynamics of river-floodplain connectivity have been extensively studied and the important role of hydrological processes in floodplains on the delivery of sediments and nutrients, vegetation cover and river flow regimes have been demonstrated (Wohl, 2021). Previously, to quantify carbon balances as well as sediment and nutrient exchange, water storage within floodplains and the associated inundation area have been analysed by remote sensing and GIS techniques (Alsdorf et al., 2010; Townsend & Walsh, 1998). Different hydrological connectivity indices have been used to describe exchanges and connections between rivers and floodplains (Liu et al., 2020b). Furthermore, the dynamics in river-floodplain systems under different wetness scenarios have been analysed via hydrological models or coupled hydrological/hydraulic models (e.g., Czuba et al., 2019; Tull et al., 2022). The relationships between the degree of alteration of hydrological behaviour of floodplains and climatic and anthropogenic controls have been revealed accordingly (Gaglio et al., 2019; Goswami et al., 2021; Mohanty & Simonovic, 2021).

Many large floodplains have been heavily modified by human activities with drainage and flood protection works common to allow exploitation of fertile floodplain soils for agriculture or building on large areas of flat land for urban and industrial development (Nakamura et al., 2006; Tockner et al., 2010). The European Topic Centre on Inland, Coastal and Marine waters (ETC/ICM)’s technical report assessing floodplain conditions in Europe reported that only 10%–30% of the floodplains remain in natural conditions, and most of them are experiencing extensive reduction, structure degradation and process alteration. Thus, conservation of remaining floodplains is urgent and in many areas restoration of river-floodplain connectivity is an important management goal to re-instate natural flood storage functions as part of Nature-Based Solutions (NBS) for downstream flood alleviation (Jakubinsky et al., 2021). Concerns over potential climate change impacts on river flows and the need for building resilience in floodplain management provide another urgent impetus for an improved process understanding. However, better characterization of the dynamics of river-floodplain interactions remains challenging as large floodplains covering extensive areas make adequate spatially-distributed hydrological monitoring difficult (Tan et al., 2019). Further, marked inter- and intra-annual variations in hydroclimate and river flow regimes mean that long-term assessments of inundation patterns and floodplain storage are needed to inform management (Gaglio et al., 2019) but are often unavailable.

Increasingly, remote sensing (RS) products provide larger scale insights into floodplain dynamics (Schultz & Engman, 2012), which are difficult to monitor on the ground. Technological advancements mean that lengthy time series are now available for many RS products that can be ground-truthed against real data (e.g., river levels, groundwater levels, etc.) (Huang et al., 2018). Previously, RS has been employed to estimate the inundation area and storage in floodplains, to classify landscape features or to detect changes in floodplains (Sajjad et al., 2020; Schumann et al., 2019). Similarly, improved methods for analysing concurrent hydrological time series allow potential process-linkages to be identified (Cui et al., 2019). In this regard, wavelet analysis has proved useful in exploring short- and long-term variations in hydrological data and to assess coherence and process coupling (Labat, 2005). However, few studies have used wavelet analysis to investigate connections in river-floodplain systems and utilize their potential. Exceptions include (Regier et al., 2021) who identified short-term connectivity in a tidal creek-floodplain system using wavelet coherence analysis. Likewise, the temporal variations of river-floodplain connections and the driving factors have been analysed through observations or simulations (Karim et al., 2016; Liu et al., 2020b), but few analyses have been conducted to understand, at which frequency scales these variations occur or the driving factors are strongest.

To address this research gap, in this study, we focus on the Lower Oder Valley National Park (LOVNP) on the German-Polish border. This comprises a large river-floodplain system, spanning 50 km along an international boundary, which experiences controlled flooding and is managed by a series of polders with floodgates. The area has been subject to extensive historic management to drain the floodplain for agriculture and to improve navigation for shipping in the river Oder. However, the area is now a National Park and focused on conservation, sustainable land management and the promotion of ecotourism. This has involved maintaining a diversity of wetland habitats in the face of increased impacts of climate change and potential river management changes upstream (Ministerium für Landwirtschaft, 2023). By integrating remote sensing with local hydrometric data over an 8-year period, our overarching aim was to quantitatively assess the patterns river-floodplain connectivity, inundation area and flood storage in two polders with contrasting characteristics and management regimes. Considering different landscape structures and human interventions in the two polders, we hypothesized differences in hydrological function and river-floodplain connectivity.

Using RS products, empirical data and wavelet analysis, the specific research questions were:
1. What are the spatial patterns of flooding in the two polders in terms of inundation area and flood storage?
2. What are inter- and intra-annual variations in the patterns and timing of inundation and storage?
3. What is the relative importance of the Oder River, local groundwater dynamics and/or climatic factors in governing the polders’ flood regimes?

2 | STUDY SITE

The Oder originates in the Czech Republic and flows as the sixth largest river entering the Baltic Sea. The length of 854-km makes the Oder the second longest river in Poland, where 89% of its catchment is located. The Lower Oder Valley National Park (LOVNP) is located ~60 km NE of Berlin, Germany, and comprises a large polder system along ~50 km of river length (Figure 1).

The meteorological conditions are relatively constant across the whole LOVNP, which covers an area of 72 km². Mean annual precipitation in the National Park is 561 mm/year (since 2005), and summer tends to be wettest with some high-intensity convectional events reaching ≥40 mm/day (Deutsher Wetterdienst, 2023). Local average daily temperature (1990–2021) is 17.3 and 0.1°C in summer (June to August) and winter (December to February), respectively (Deutsher Wetterdienst, 2023). Mean annual potential evapotranspiration (PET) is 643 mm/year (period 1980–2022).

There is limited topographic variation in the LOVNP’s floodplain, and a network of raised embankments (dykes) subdivide the region into polders and regulate the interactions between the floodplain and the Oder River (Figure 2a). The general landscape structure in the LOVNP was formed at the end of the last ice age (~12,000 years ago), with the floodplain fringed by elevated areas of ground moraines (Ministerium für Landwirtschaft, 2023). The valley floor is dominated by a mixture of sand and clay differentiating former channels and areas of overbank flows, with peat soils in the North and moors formed along the floodplain edge (Ministerium für Landwirtschaft, 2023).

Until the LOVNP was established with increased emphasis on the conservation of the floodplain landscape since 1995, land in the Lower Oder Valley was used for agricultural production (Ministerium für Landwirtschaft, 2023). The river-floodplain system has been extensively engineered for over 100 years for agricultural drainage and flood protection, as well as improvement of navigation in the Oder channel. As part of this process, embankments have been built to create seven polders within the floodplain (Figure 1). Several floodgates can regulate flow of the Oder River into the floodplain. The annual discharge volume can reach 17.3 km³, while the station upstream of the LOVNP showed mean daily discharge variations between 132 and 1620 m³/s from 2015 to 2021 (Figure S2).

About 60% and 20% of the area in the LOVNP are grassland and woodland, respectively, with less than one third of grassland used for grazing. The remaining 20% consists of lakes, canals, and other open...
water bodies (Ministerium für Landwirtschaft, 2023). This creates a rich diversity of wetland habitats reflecting subtle hydraulic gradients, sustaining rich biodiversity, which underpins conservation and eco-tourism in the National Park.

In this work, we selected two polders—covering different characteristics of the polder systems (see more details below)—as main study areas: Polder A and Polder 10, which cover 14.4 and 17.7 km², respectively. Both are located on the west bank of the Oder River, that is, in Germany (Figure 1; Table 1). Both polders have a narrow, elongated configuration, where the longer side runs parallel to the Oder River, with 9.2 and 8.5 km in length, respectively.

The local topography is flat with elevations of Polder A and 10 varying from –1.6 to 7.8 and from –1.5 to 6.5 m.a.s.l, respectively (Figure 2a). Both polders are predominantly covered by pasture (79.8% and 85.8%, in Polder A and 10, respectively) and some forest areas (6.4%) are sporadically distributed in Polder A (Figure 2b).

Stream and river bank deposits comprise the main surface geology in both polders, while a bog formed in the North-West of Polder 10, and moors and mires exist nearby the western border (Figure 2c). The soils reflect extensively distributed loamy clay in both polders, but they are more abundant in Polder 10 (Figure 2d).

FIGURE 2 Characteristics of Polders A and 10: (a) Elevation with locations for measurements of precipitation, water levels, groundwater levels and floodgates (GW7, 8, 20–23 located nearby Polder 10); (b) Landuse; (c) Superficial geology; (d) Soils.
controlling the direct connection between the polders and the Oder River in winter but transient pluvial flooding is possible in high rainfall events outside winter. Additionally, there is a pumping system in Polder A to pump water inside the polder out into the navigation channel that runs to the East of the floodplain. After pumping, mowing is conducted.

### DATA AND METHODS

#### 3.1 Hydroclimatic and GIS data

Given the increased availability of remote sensing data at 10–30 m spatial resolution following the launch of Sentinel 2 and a corresponding range of basic hydrometric parameters, which were monitored on the river and floodplain of the Oder during the period, we chose 8 years for our study period (2015–2022). Daily precipitation and air temperature data were obtained from two weather stations of German Weather Service (Deutscher Wetterdienst, 2023), which are located 2 and 16 km NW of Polder A, respectively (Figure 2a). Daily river water level data were recorded by two stations near Polder A and 10 (WL4 and WL8) from 2015 to 2022 (Deutscher Wetterdienst, 2023; IMGW-PIB, 2023). Discharge was only available from two stations: D4 is at WL 4 (Figure 2a) and UD1 is located 15 km upstream from WL8. Groundwater levels were monitored at two stations the LOVNP (Figure 2a). The temporal resolutions range from weekly to monthly (Brandenburg, 2023). PET was calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998), with meteorological data (i.e. net radiation, air temperature, wind speed, actual vapour pressure, altitude) acquired from a DWD station, 16 km west of Polder A (Deutscher Wetterdienst, 2023). GIS data (i.e. DEM, land use, geology, and soil type) were provided by the Landesamt für Umwelt Brandenburg (Brandenburg, 2023).

#### 3.2 Remotely sensed data

We used all available Landsat and Sentinel-2 images acquired between 01/01/2015 and 16/08/2022 with a cloud coverage of less than 75% for our analyses. Landsat and Sentinel-2 images were downloaded as Level 1 products from the USGS and the Copernicus Open Access Hub archives. Preprocessing to Level 2 reflectance data ARD was based on the Framework for Operational Radiometric Correction for Environmental monitoring (FORCE), which is an all-in-one processing engine for medium-resolution Earth Observation image archives, enabling large area and time series applications and supporting the integrated processing of Landsat and Sentinel-2 data (Frantz, 2019). The preprocessing included corrections for atmospheric, topographic, adjacency, and directional reflectance effects (Buchner et al., 2020; Frantz et al., 2016; Roy et al., 2017), cloud and cloud shadow masking (Frantz et al., 2018; Zhu et al., 2015; Zhu & Woodcock, 2012), and spatial co-registration of Sentinel-2 to Landsat (Rufin et al., 2020). The FORCE Time Series Analysis submodule was subsequently used to derive combined Landsat and Sentinel-2 time series of the NDWI (Normalized Difference Water Index) and the NDVI (Normalized Difference Vegetation Index) with an interpolated equidistance of 16 days and a spatial resolution of 30 m. Interpolation was based on a RBF (Radial Basis Function) kernel following Schwieder et al. (2016).

The NDWI was calculated based on green and the near-infrared bands. This NDWI ranges from –1 to 1, with water pixels generally showing higher values than land pixels. The NDVI was calculated based on red and the near-infrared bands. This NDVI ranges from –1 to 1, with higher values denoting greater vegetation productivity. An overview of data availability is provided in Table 2.

#### 3.3 Water area classification

The workflow for classifying water inundated area was summarized in Figure S1. The total water inundation area of each imagery date was

<table>
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<th>Table 2 Overview of data used for each polder.</th>
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<td>Polder A</td>
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<td>RS imagery</td>
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<td>WL4</td>
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<td>WL8</td>
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<th>Table 1 Physiographic characteristics of Polders A and 10.</th>
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<td>Area km²</td>
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calculated based on the number of classified water pixels multiplied by pixel size. The classification of water and land was achieved by the Otsu method (an unsupervised classification method separating pixels into two classes and determining the threshold by minimizing intra-class variance) based on NDWI (Otsu, 1979). A threshold was calculated using this method, and pixels with values higher than this threshold were classified as “water.” Different proportions of water and land will affect the Otsu-based threshold: The water area estimates are strongly affected when a large number of pixels are close to the threshold value. An accurate threshold detection usually requires that the number of pixels in each class reaches at least 10% of total number of pixels (Bazi et al., 2007).

In order to evaluate the uncertainty of water area estimation in relation to the Otsu-based threshold, we created virtual maps for each original imagery by reorganizing the proportions of the number of pixels in water and land classes. Each map satisfied the accurate detection requirements. The water inundated area estimates of the original imagery determined by the new Otsu-based threshold from these virtual maps were regarded as the “uncertainty” of the original imagery.

The detailed steps were as follows: For each original imagery, the initial water and land classes were determined by the Otsu method. We then created virtual maps by randomly selecting the pixels from each initial class according to a prefixed proportion ensuring that each virtual map had the same number of pixels as the original imagery. We created two virtual maps with 20% and 80% of water proportion, which indicated the upper and lower limits for the final water inundated area uncertainty (20% water proportion means small numbers of pixels with high values exist in the virtual map, representing a low Otsu-based threshold, and more pixels in the original imagery were classified as water class based on this threshold). The Otsu method was then used again to determine the new thresholds of the two virtual maps. These two new thresholds were used in the original imagery to determine the higher and lower limits of water inundated area estimates indicating the uncertainty of these estimates.

Water storage of each Polder was calculated according to classified water pixels and the DEM map. The inundated water level was assumed as the level, of which the elevation of 80% of classified water pixels are below. The water storage of each classified water pixels was calculated by multiplying pixel area (30 x 30) and level difference between inundated water level and pixel elevation.

### 3.4 Validation and assessment

In order to validate the estimated water inundation area, visual interpretation of the water area on very high-resolution imagery from Google Earth was used as reference. Considering the limited numbers of images on Google Earth, four dates were selected, which captured high and low inundation situations (1 February 2018 and 24 March 2017 for high inundation; 5 December 2018 and 30 September 2017 for low inundation). Referenced pixels were randomly selected ensuring coverage of 80% of clear water area, with an equal number of land and water pixels. Edge areas between water and land and unclear pixels were excluded (which are the mixed feature in a pixel). Overall, accuracy (OA), user accuracy (UA), producer accuracy (PA) and kappa coefficient (k) were calculated to evaluate the performance of classification (see equations in supplementary material). OA (EQ1) represents the percentage of total correctly classified pixels (including water and land). PA (EQ2) represents the percentage of the correctly classified feature (water) in the classified sites. K (EQ4; EQ5) shows the classification performance compared with random classification, and ranges from −1 to 1. As closer the value is to 1, the better the performance.

### 3.5 Wavelet analysis

Continuous wavelet transformation (CWT) was used to identify temporal dynamics in terms of periodic signals of different hydrological variables (i.e., water level, water inundation area, groundwater level and precipitation). The Morlet wavelet function (Equation 1) was applied to calculate the wavelet coefficient (Equation 2) by convolution between the time series data (xₙ) (Labat, 2005):

$$Wₙ^ω(s) = \sqrt{\frac{\Delta t}{s}} \sum_{n=1}^{N} x_n \Psi_0 \left( \frac{n'-n}{\Delta t/2} \right)$$

$$\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}$$

where $\omega_0$ and $\eta$ are the dimensionless parameters frequency and time, respectively, $\Delta t$ is time step and $s$ is the wavelet scale.

The wavelet power value was given by the square of the wavelet coefficient ($|Wₙ^ω(s)|^2$), which is an indicator of how the energy of a signal is distributed in a time-frequency domain (Labat, 2005), and was shown as 2D time-frequency plot in this study. Importantly, the CWT will be influenced by missing information at the start or end of limited time series; therefore, the cone of influence (COI) zone, which is the influenced region, was discarded to avoid such edge effects (Torrence & Compo, 1998).

Wavelet coherency (WTC) was calculated via CWT to investigate the relationship between timeseries of water inundated area estimates and other hydrological variables, that is, water level in Oder, groundwater level and precipitation:

$$R_s^2(s) = \frac{|S_x(s^{-1}(X^ω(s)))|^2}{S_x(s^{-1}(X^ω(s))) \cdot S_y(s^{-1}(Y^ω(s)))}$$

where $W^n ω(s)$ is the complex conjugation of $W^n ω(s)$ and $W^n ω(s)$, and $S_x$ is a smoothing operator.

WTC showed the time and scale positions where two signals exhibited comparable cyclic patterns, and their phase difference. The power values of CWT that exceeded a certain level were regarded as
statistically significant. This level was determined as 95% confidence levels assuming the time series followed a lag-1 autoregressive process and a power value with a chi-square distribution (Torrence & Compo, 1998). The Monte Carlo method was used to evaluate the 95% confidence level for WTC (Grinsted et al., 2004). Wavelet analysis was realized with the Python package “PyCWT” (Krieger et al., 2023). The hydrological variables used in WTC were resampled to the same temporal resolution as processed imagery. Precipitation was resampled by accumulating the previous 16 days daily values, water levels were averaged by a 16 days neighbourhood range, and groundwater levels were linearly interpolated.

4 | RESULTS

4.1 | Hydroclimate and hydrology

Local hydroclimate shows strong seasonality at LOVNP (Figure 3a). Whilst rainfall is fairly evenly distributed, low intensity frontal rain dominates in winter, whilst summer is characterized by heavier convectional rainstorms. PET is highest between April and September reflecting summer radiation input.

The water level regime of the Oder—which reflects the larger climatic footprint of its entire catchment—shows generally winter peaks and summer low flows (Figure 3b). Elevated summer flows can occur—such as higher baseflows in 2017 and the marked summer events in 2020 and 2021, which were caused by higher rainfall. Station WL4 is located downstream of WL8, with WL8 showing stronger seasonality and greater intra-annual variability than WL4, most likely mainly reflecting the moderating effect of the upstream polders flood storage. Discharge data of stations D4 and UD1 are shown in Figure S2. There was a high co-varying trend between the discharge at UD1 and D4, and the differences were mostly within 10% showing a similar magnitude and variability during the study period.

Groundwater levels (Figure 3c) reflect both the seasonality of river flow and local climate. Station GW15 (Polder A) showed stronger seasonality compared to GW 22 (Polder 10), especially in drier years (e.g., 2016, 2019, and 2020). GW 22 exhibited less intra-annual variability and high intra-annual oscillations. The peaks and troughs in groundwater and water levels in the Oder were in general similar, with a slight time lag, while being inversely out of phase with PET in terms of timing of troughs and peaks.

Overall, the hydrological variables from stations nearby Polder A (i.e., WL8 and GW15), exhibited strong connections throughout the period, as their peaks and troughs were very close in time. Peaks of GW15 appeared prior to WL8 in dry years (e.g., 2016, 2019, and 2020), while this time lag decreased in wet years (e.g., 2017, 2018). Connections between GW22 and WL4 (Polder 10) were less obvious, though they showed higher intra-annual oscillations.

4.2 | Patterns of floodplain inundation and water storage

The overall performance of the classifications for water inundation area for both Polder A and 10 was good, reaching at least 85% though sometimes producer accuracy (the accuracy of true water pixels on the ground classified as water pixels, low value means underestimation or high omission error) and user accuracy (the accuracy of classified water pixels, low value means overestimation or high commission error) reached only 70% (Table 3). Spatially, most of the water pixels were located nearby channels with some differences between summer and winter flooding in Polder A, reflected by slightly higher portions of water pixels in summer located far away from channels (Figure S3a,b). Moreover, high winter flooding reflected by NDWI generally corresponded well with sinks in the DEM (Figure S3c,d). Polder A generally had more extensive flooding in winter and appeared less productive from the longer periods of water cover (i.e., lower NDVI) than Polder 10 (Figure 4). Moreover, floodwater in Polder A mainly accumulated in the downstream area of the polder, reflected by the higher NDWIs at times of high inundation. In contrast, no clear inundation was detected in Polder 10, which had lower spatial variability of NDWI than Polder A.

Temporally, both polders experienced extensive inundation by river water in winter after the floodgates were opened (Table S1), though to differing degrees (Figure 5a,b). In wet years, the inundated
The relationship between estimated inundation and the uncertainty interval during winter inundation of Polder A was similar to summer inundation in Polder A, but there were generally narrow uncertainty bands during the winter inundation of Polder A (Figure 5b,c). High-water inundation also lasted longer in Polder A with varying water inundation being more strongly linked to water level variations in the Oder than in Polder 10. These differences between the two polders likely stem from contrasting polder characteristics and management regimes, as Polder A is more extensively controlled by embankments with only two floodgates and widespread mowing of grassland in the summer, while an extended channel system and 10 floodgates reduce water residence times in Polder 10.

Additionally, water storage in Polder A can reach 2–3 hm³ in wet years (2017, 2018, and 2021) and about 1 hm³ in dry years (2016, 2019, and 2020) (Figure 6a), while Polder 10 show less storage volume with only 0.8–1 and below 0.3 hm³ in wet and dry years (Figure 6c), respectively. During wet years, the high storage volume persists longer, corresponding to the most extensive, protracted inundation in both polders. The steep variation in Polder 10 (2018, 2021) is consistent with transient, marked flooding, though this wasn’t evidence in Polder A. The base storage (storage level in non-inundation period) period accounted for 50% of time in Polder A, and it reached 60% in Polder 10 (Figure 6c,d). And the high storage duration was about 40% and 20% of time in Polder A and 10 (Figure 6c,d), respectively.

### 4.3 Wavelet analysis of inundation patterns

Figure 7 shows the periodicities in wavelet power spectra of different hydrological variables with periodicities reflecting cycled signals, which can be weekly, monthly, or yearly (seasonal signals). Water levels at WL8 and WL4 (Figure 7a) exhibited high and consistent power values in 1-year cycles (between 256 and 512 days) throughout the study, which reflects strong seasonality. In addition, WL8 presented some local wavelet ridges in the 1–4 months cycles (between 32 and 128 days, mainly in 2017, 2019, 2020, and 2021), reflecting that flooding is varying within seasons.

Both WL stations displayed periodic signals for <1 month, which show several short-term floods. More significant low periodicities...
were found in WL4 compared to WL8, indicating that WL4 experienced more frequent short-term flooding. Considering the timing when such signals appeared, significant periodicities and variabilities mainly occurred in winter for both WL stations (2 to 64 days).

For the estimated water inundation area of Polder A, annual (1-year) cycle signals were present during most of the study, reflecting the strong seasonality (Figure 7c,d). In the half-year frequency domain, the power values were greater than the higher frequency domain (i.e., monthly or weekly), as sometimes two peaks in summer or winter occurred. Particularly in 2015–2017, obvious periodicities from 1 to 4 months (i.e., high frequent fluctuations) occurred.

In Polder 10, noticeable periodicities for all frequencies (i.e., weekly, monthly, or yearly fluctuations) only occurred in winter during high inundation and the higher frequencies (weekly, monthly)

were more pronounced than in Polder A. This corresponded to the more short-term fluctuations in inundation of Polder 10.

For the groundwater stations near the polders, significant 1-year cycles persisted in GW15, with only local high power values in GW22 (Figure 7e,f). In other words, clear seasonality was apparent in GW15, but not in GW22 (see also Figure 3). However, in the high frequency domain, higher periodicities occurred in GW22. These monthly fluctuations were observed both in summer and winter in GW22, while they were mostly concentrated in summer for GW15. Overall, the power values were more evenly distributed along the entire frequency spectrum in GW22 and the oscillations in the time series were more evenly distributed at the entire frequency scale, rather than showing a distinct seasonality as in GW15.

For the climate variables, significant 1-year cycles were persistent in the power spectrum of PET reflecting expected strong seasona,
though this was only evident for precipitation in 2017 (Figure 7g,h). These cycles were manifested in seasonal peaks and troughs at summer and winter, respectively. Both precipitation and PET showed high frequency cycles in summer, but the periodic signals were more regular in PET. At high frequencies, daily and weekly fluctuations were observed both in PET and precipitation, with monthly fluctuations being only common in precipitation. Overall, power values were more evenly distributed along the entire frequency scale in precipitation, with no fluctuations of mid-range frequency occurring in PET.

4.4 Coherence of wavelets in inundation extent and controlling factors

Statistically significant coherency between water inundation area in Polder A and all other variables in 1-year cycles occurred throughout the study period (Figure 8a–c), reflecting the strong co-varying character between seasonal variations. Water level showed the highest coherencies in 1-year periods, with the strongest co-varying properties with the inundation area in Polder A (Figure 8a). In this frequency scale, the phase differences between water inundation area and river water or groundwater level were small (small time lags). However, the greater phase difference for groundwater means that signals between water level and inundation were transferred faster (Figure 8a,b).

Between water inundation area and precipitation for the 1-year period, a large phase difference was apparent (Figure 8c). Precipitation also had an anti-phase (time lag of half a year) trend.

In the higher frequency spectrum of Polder A, coherence ridges only sporadically occurred in periods from 1-month to 8-months for water level and precipitation, and from 2-months to 4-months for groundwater level. This reflects that the inundation fluctuations are restricted to these shorter periods showing dependence on river water level, groundwater level, precipitation at different time and scale positions. Precipitation showed comparatively high coherency values in periods from 4-months to 8-months (Figure 8c), which suggests a potential contribution for such intermediate periods, though this was not statistically significant. Further, water level and groundwater showed unstable phase differences (Figure 8a–c). These instabilities reflect high uncertainty at high frequencies, as significant

FIGURE 7 Wavelet power spectrum (with wavelet basis of Morlet) of hydrological variables. (a, b) Water level in the Oder River at WL8 and WL4 (daily data); (c, d) Water inundation area in Polder A and Polder 10 (16-days data); (e, f) Groundwater level at GW15 and GW22 (16-days data); (g, h) Precipitation at P3 and PET (daily data). A higher value in the power spectrum indicates a greater likelihood of the presence of a periodic signal with a corresponding period and time. The black circles in the heat map show the significant regions (95% confidence level). The crossed-out shaded areas were not considered because of edge effects.
co-varying parts could be captured, but how long the time lag was between the variables often remains unclear.

In the 1-year period for Polder 10, only precipitation showed significant coherency with water inundation area (i.e., a strong inter-annual co-varying trend, Figure 8f), which was similar to Polder A. However, almost all other domains of the frequency spectrum showed low power values (Figure 8c,f). The phase difference for precipitation was similar to Polder A with an asynchronous appearance, an anti-phase trend for precipitation (Figure 8c,f). The phase difference between water level and inundations was also similar in both polders, however, the seasonal variations were not as relevant in Polder 10, while groundwater showed a more unstable time lag across the study period.

In the higher frequency spectrum (1–8 months), significant coherency occurred for water level in Polder 10, indicating stronger river-floodplain links, while groundwater is less connected to the inundation in this frequency spectrum (Figure 8d,e). The phase differences at higher frequency for water and groundwater levels was unstable along the time scale for both polders. These results again reflect the uncertain linkages at high frequencies, though Polder 10 showed more stochastic behaviour.

5 | DISCUSSION

5.1 | Spatial–temporal dynamics of floodplain inundation

In this study, remote sensing products based on NDWI and NDVI were integrated with empirical data and analysed using wavelet analysis to better characterize and understand the spatial–temporal patterns of river-floodplain inundation in contrasting polders in the LOVNP along the river Oder in Germany. Previous studies have also used topography and DEMs in remote sensing-based analysis to estimate flood inundation (Liu et al., 2020b; Munasinghe et al., 2018; Rosser et al., 2017). These typically show patterns of inundation being more likely distributed adjacent to channels and low-lying areas, with connectivity between flooded areas increasing with increasing water levels. However, in our work in the Oder floodplain, the very different inundation patterns between the two polders studied were mainly related to differences in their floodplain structure and management.

The winter inundation and water storage were generally much greater in extent and more prolonged in Polder A than Polder 10, which being upstream had a first order influence on flood...
system and high number of floodgates, contributed to a strong river-topographic depressions in the DEM. However, in Polder 10, the winter inundation, the flooded areas corresponded well with the attenuation of the main annual flow peaks. During periods of high inundation, the flooded areas corresponded well with the topographic depressions in the DEM. However, in Polder 10, the upstream flood storage, together with the well-connected channel system and high number of floodgates, contributed to a strong river-floodplain connectivity and thus, the polder was less extensively inundated as it drained more rapidly. Czuba et al. (2019) similarly found that channel orientation inside a floodplain plays an important role in river-floodplain exchange in their modelling results.

Although summer flooding was occasionally evident in Polder A, it was rarely detected in Polder 10, which has greater coverage of permanent open water bodies and well-connected channels. Usually, summer flooding is pluvial in origin as the flood gates are closed, limiting river-floodplain connectivity. Thus, in part, these differences reflect the more extensive dry areas in Polder A that are prone to flooding. In addition, inundation in the polders likely reflected methodological uncertainties associated with high vegetation surrounding the channels. Consequently, some inundation was probably undetected due to mixed pixels of water and land. Such mixed pixels were also proportionally more important during times of low inundation. Similar vegetation effects on classification have also identified in other inundation estimations, especially in wetland areas (Leblanc et al., 2011).

The wavelet analysis allowed a more systematic assessment of the contrasting inundation patterns of the two polders, as well as a basis for comparing intra- and inter-annual variability. The 1-year periodicity (i.e., seasonality) was strongest in Polder A reflecting the annual pattern of floodplain inundation in response to high water levels in the Oder. In contrast, in Polder 10 monthly-scaled fluctuations were more pronounced, reflecting the upstream floodplain storage in Polder A and the subsequent pulses of higher connectivity in response to increases in river levels in winter. Similar temporal variations in floodplain inundation have been shown to reflect dominant hydrological processes in river-floodplain systems and differ in contrasting geographical regions (Scott et al., 2019). For example, strong inter-annual variability of maximum inundation extent has also been identified in floodplains in South American (Hamilton et al., 2002) where the duration of the inundation period was linearly related to the maximum extent of the inundation area.

These inferences were derived from analysis for the RS imagery and highlight some of the potential as well as limitations of such approaches. Detection of inundation was extracted from RS optical imagery; a technique which has been widely applied and validated for larger scale assessments of soil moisture and vegetation dynamics (Huang et al., 2018). RS provides global long-term and spatially extensive distributed earth surface observations, which is particularly useful in places where ground observations are difficult (Schmugge et al., 2002). Due to the variations in clear sky observations resulting from cloud coverage, we combined observations from multiple satellite sensors and employed an interpolation algorithm to achieve temporal continuity of the data series as in Frantz (2019). From direct comparison with time series of aerial photographs, we found acceptable accuracies in our validation of the Otsu-based water inundated area classification and the use of the informal uncertainty indicators provided qualitative insight into potential errors in estimated inundated states.

Our approach based on indices is straightforward and consistent through time and overall showed good results. However, to account for observed limitations, such as the inability to detect for small water proportions in a pixel or water hidden by vegetation, spectral unmixing techniques or the additional use of Synthetic Aperture Radar (SAR) data would be helpful. For example, wetland inundation classification by SAR imagery were examined by using multi-temporal RADARSAT-2 C-band SAR intensity and showed good performance (Canisius et al., 2019). Similarly, spectral unmixing techniques for evaluating water bodies in sub-Landsat pixels were also applied in eight imageries from southern Arizona, USA by Sall et al. (2021), and showed accurate result compared with digitized surface water area.

5.2 | Disentangling the influence of river connectivity, groundwater and climatic variability on floodplain inundation with wavelets

Due to the physical structure of floodplains and their interactions with local and catchment-scale drivers, river-floodplain systems are complex hydrological interfaces (Alaghmand et al., 2014; Li et al., 2019). Continuous wavelet transformation allowed us to extract both the frequency and temporal position of coherent signals in concurrent timeseries, allowing more insight than, for example, Fourier transformation (Cheng et al., 2021). Via wavelet coherency, the co-varying tendency and phase difference of two timeseries could be used to indicate their relationship in frequency-time scale (Cheng et al., 2021). Therefore, wavelet analysis has been widely used in hydrology for decomposition, de-noising, complexity description and hydrological forecasting (Sang, 2013).

Even so, overlapping signals meant that it was difficult to fully disentangle the contributions of floodplain structure, river flow regime and other drivers on inundation patterns. In general, the analysis showed that the dominant influences of river levels in the Oder and local rainfall on inundation was, respectively, pronounced in winter and summer, and stronger in Polder A. River-floodplain connectivity varied predominantly at an inter-annual scale in both polders, but Polder 10 also showed more pronounced connectivity at the monthly scale.

In the wavelet coherency spectrum, the limited monthly co-varying links during winter between the Oder and Polder A suggest that the rapid fluctuations of water levels in the Oder do correspond to varying inundation in Polder A. In contrast, the numerous monthly co-varying links between the Oder and Polder 10 highlight the importance of the polders structure with the more limited inundation in the well-connected and freely-opened Polder 10 responding rapidly to water level changes in the river and channels.

Local climatic variables, that is, snowmelt, rainfall intensity, have been shown to play an important role in the temporal variation of floodplain inundation (Scott et al., 2019). Effects due to wetter climate
conditions and disruption by flow regulation on river-floodplain connectivity are amongst such influences identified by others (e.g., Karim et al., 2015; Ward & Stanford, 1995). For Polder A, the apparent inter-annual linkages between rainfall and inundation are suggested by the high coherency values, but the large time lag between these two time series are physically implausible (i.e., local summer rainfall cannot affect winter inundation directly). Hence, this apparent linkage is just an artefact of the mathematical similarity between rainfall and inundation inter-annually, with no physical connection. The monthly-scale co-ly vary links in Polder A in summer highlight the short-term nature of pluvial flooding there. Although the linkages between rainfall and inundation are not frequent in our analysis, undoubtedly antecedent rainfall reduced floodplain’s storage capacity, affecting the water residence time inside polders (Tull et al., 2022), and subsequently reducing the time lag between water level in the Oder river and inundation in the polders (Tull et al., 2022). Overall, the limited contribution of local rainfall to inundation in both polders during winter is reflected by its low coherency values in the high-frequency domain.

Subsurface water storage in floodplain soils and groundwater can act as buffers to precipitation or input signals (Liu, Yu, et al., 2020), and could be recharged by different sources. For example, groundwater levels showed less periodic signals than precipitation or water levels in the Oder river, and the lagged response of groundwater to inundation in Polder A suggests that groundwater was mainly recharged by flood water. In contrast, weaker linkages in Polder 10 may be evidence that the groundwater was also recharged by local rainfall as well as flood water.

Polder A showed a greater low-pass filtering effect for signals transferring from precipitation or river water to inundation, compared with Polder 10, with high-frequency signals rarely apparent in the inundation of Polder A. The differences of the water levels between WL8 (upstream) and WL4 (downstream) also show the polder’s buffering effects of flood storage as the mid-frequency signals (1–4 months) in the water level of the Oder at WL8 were not detected at WL4, although high frequency signals (<1 month) were strengthened in winter. It is likely that the confluence of the navigation canals in the west of the Oder river help transmit some high frequency disturbances downstream.

Again, whilst the wavelet analysis proved useful; capturing and localizing multiple periodicities as well as illustrating the oscillations in various temporal scale, limitations were also apparent. For example, the identification of relationships between two variables is highly mathematical and sometimes can produce artefacts that lack a physical basis (Sang, 2013). This can lead to misleading results such as the high coherency values depicting the inter-annual link between precipitation and inundation in both polders. In addition, the wavelet analysis was also limited by data availability and some of the locally high—but statistically insignificant—relationships may have become clearer with finer temporal resolutions in the time series. Despite this, the wavelet analysis allowed us to detect the multi-temporal scale and non-stationary characteristics of many hydrological variables.

Further limitations in the wavelet analysis stem from the quality of the estimated inundation timeseries derived from RS. Errors here can affect the assessment of where significant regions in the wavelet spectrum appear, and the inconsistent duration and gaps of the timeseries confined the analysis to a limited time-frequency region (Torrence & Compo, 1998). The high but insignificant values in the wavelet spectrum may suggest some potential periodicities, but they may also be the result of intermodulation or subharmonics and may not have a physical meaning (Cheng et al., 2021).

5.3 | Wider implications for floodplain management

Better understanding the controls of the spatial extent and longevity of the two Polders has important process-based implications for management of land and water in the National Park. This is particularly the case for the future as climate change in eastern Europe and changing management of the Oder upstream in Poland may affect future patterns of inundation (Anders et al., 2014). Whilst the main driver of annual floodplain inundation is the flow regime of the Oder river, operation of the floodgates in the polders contributed to quite different flood responses in Polder A and Polder 10. Moreover, the pumping in Polder A had an important influence on the recession of flooding, whereas Polder 10 drained along pre-existing channels. Consequently, there are many possibilities for floodplain management that could be used to develop resilient strategies in the face of future climate and environmental change.

In this regard, the analysis presented here provides a framework for better conceptual understanding of the characteristics and causes of inundation and flood storage that have two obvious uses. Firstly, such spatial-temporal information has potential utility in providing readily communicable information for various stakeholders (e.g., regulatory agencies, land owners, farmers, conservationists, etc.) as an evidence base that could be used for discussing potential management changes in the face of climate and other threats (e.g., Smith et al., 2021; Smith et al., 2022). Secondly, and linked to the first point, this conceptual understanding is an essential prerequisite for numerical model development that could characterize the water balance of river-floodplain dynamics in a quantitative manner (Tull et al., 2022). Again, such quantification, with acknowledgement of associated uncertainty is important evidence in option appraisal.

From a conservation perspective the variability of inundation across the floodplain creates a rich mosaic of wetland habitats that sustains a high degree of biodiversity. And, although the relationship between flooding duration and fish production has been globally documented (Arthington & Balcombe, 2011), for many wetland species and communities the habitat requirements in terms of timing, extent and longevity of saturation are not well-known (Drayer & Richter, 2016). Polder A and 10 have different land use distributions and contrasting flora or fauna assemblages due to their distinct inundation variability. For example, the high hydrological heterogeneity resulting from the short-term inundation in Polder 10 may offer...
greater refuge opportunities for species at risk of flooding (Zmihorski et al., 2016). In summer, Polder 10, with its widely connected channels, provides better aquatic habitat compared to the more isolated ponds in the drier Polder A, and overall, such high physical habitat diversity and hydrological connectivity contributes to the survival of aquatic organisms (Arthington & Balcombe, 2011). In addition, it is important to note that the closed floodgates in summer disconnect the river-floodplain system, and subsequently, water quality gradually becomes the dominant factor contributing to the habitat quality of aquatic organisms (Arthington et al., 2010). Thus, assessing the water quality regimes of the floodplain wetlands of the Oder is a major priority for future work.

As most of the polders are managed for some sort of farming, other management practices include patterns of mowing and grazing on grasslands, which can affect wetland habitats. For example, different wetland bird species have different vegetation requirements, with short-term flooding in Polder 10 and unmowed areas appearing to benefit birds nesting and foraging (Ahlen et al., 2023). Similarly, areas of forestry are likely to have higher evapotranspiration and may create more buffering against summer floods by contributing to soil moisture deficits. Likewise, pumping operations can have a strong influence on inundation variability, thus playing an important role for manipulating habitats to the benefit of particular species in the floodplains. Whilst these anthropogenic management practices, (i.e., floodgate operation, pumping system operation and land use) can be adjusted to maintain certain habitat conditions (Gumiero et al., 2013), conceptual and quantitative understanding of inundation dynamics and their controls as provided in this study will be essential to evidence-based decision making.

6 | CONCLUSIONS

Our study investigated the inundation area in two polders in the Lower Oder Valley National Park by classification of NDWI imagery from FORCE Time Series Analysis submodule (combined Landsat and Sentinel-2 images) and employed wavelet analysis to investigate the spatial-temporal variation of wetland inundation and associated controlling factors. We further analysed spatial differences of inundation patterns using a DEM in relation to management practices and their effects on wetland habitat. Overall, seasonality was well-captured in the wavelet power spectrum of most variables, showing marked inter-annual variation of wetland inundation, though the influence was weaker for inundation of Polder 10 due to its shorter duration and the effects of floodplain storage upstream in Polder A. Water levels in the Oder river showed the strongest influence on winter inundation in the polders, with short-term variations more pronounced in Polder 10, compared with Polder A. Inter-annual variations in extent and longevity of inundation could be marked. Linkages between inundation and local precipitation were only detected in Polder A during summer. These were transient and spatially localized compared with winter inundation from the Oder. Groundwater showed delayed response to inundation in polder A, likely reflecting induced recharge during flooding.

Weaker linkages in Polder 10 (between groundwater and inundation) are consistent with a greater influence of local rainfall-driven recharge. The well-connected Polder 10 (with 10 flood gates) responds more rapidly to water input signals (i.e., water level in Oder river, precipitation), as evidenced by greater coherence between inundation patterns and other hydrological variables.

RS techniques provided direct evidence of how wetland habitat varied over extensive areas and wavelet analysis proved useful in disentangling the linkages between inundation dynamics and potential driving variables in this complex river-floodplain system. Using these techniques in an integrated way, this study provided conceptual understanding of how wetland habitat was influenced by hydrological processes that are currently highly controlled in managed polder systems. As well as providing a framework for future quantitative modelling, the study provides an evidence base for relevant stakeholders to assess whether future changes in management are needed to maintain habitats in the face of projected climate change in eastern Europe and flow regulation upstream in the Oder catchment.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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