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WETLAND RESTORATION

Assessment of Restoration Effects in Riparian Wetlands using Satellite Imagery. Case Study on the Lower Danube River

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Abstract

To better understand the outcomes of river restoration, our paper analyzes the variability of the water content in a restored riparian wetland. We focused our demonstration on the case study of the Babina Islet located in the northern Danube Delta. This site was restored in 1994 by opening levees to regain the pristine hydrological regime with both flooding and dry phases depending on the water level of the Danube River. We monitored the wetland by using the Normal Difference Water Index (NDWI) estimated on Landsat scenes for the period 1984–2020. When compared to pre-restoration conditions, we found an increase of the surface-water area. The maximum surface-water area corresponded to the restoration works. Post-implementation of the restoration solution in 1994, the surface-water area is decreasing. The surface-water area pre-restoration is smaller than the surface-water area in present-day conditions, similar to the control site (Small Islet of Brăila), thus confirming the role of hydrology in maintaining the effects of restoration works. Moreover, we detected the increase of drought area since 1984 on both the restored and the control site. This finding appears to be a new challenge for restoring the riparian wetlands of the Lower Danube River. Our paper recommends the use of standardized indicators via satellite remote sensing to understand riparian wetlands functioning at large scale, which could help to design a coherent strategy of river restoration.

Keywords Wetlands · Surface-water · Drought · Time series · Landsat · Danube

Introduction

Floodplain wetlands are one of the world's most extensive wetland types (Hamilton 2009), but are under threat worldwide (Li et al. 2015). The formation and maintenance of seasonally flooded wetlands strongly depend on the extreme hydrological variability expressed by spatial and temporal variation of inundation (Li et al. 2015; Perennou et al. 2018). The relation between the river and its floodplain is possible through hydrological connectivity (Meng et al. 2020). Humans have altered floodplains' longitudinal, lateral, and vertical connectivity through the construction of dams and dikes, modification of river channels, drainage, and other land use changes (Hamilton 2009). Such anthropogenic alterations may strongly affect water and sediment connectivity and thus ecosystem functioning through a cascade of effects resulting a reduced material, energy, and biological flux in the wetland (Reid et al. 2016). As example, numerous wetlands require restoration due to the disruption or change of their hydrological connectivity by the reinforcement of levees over many centuries (Finlayson et al. 2013), where reference conditions are lacking (Otte et al. 2021). Or the maintenance of the lateral connectivity should be considered the primary goal of large-scale recovery projects (Besacier-Monbertrand et al. 2014). Thus, to better understand human-induced changes in floodplains, it is important to monitor wetlands' inundation (Li et al. 2015; Perennou et al. 2018).

The monitoring of inundation at spatio-temporal large scale on a regular basis can rely on satellite remote sensing (Smith 1997), which could support managers in terms of where to focus cost intensive in situ monitoring (Carvalho et al. 2019). Moreover, while gauge measurements provide key data on the wetland hydrology, they may offer little information about spatial patterns of hydrologically-relevant variables like

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inundation status (Alsdorf et al. 2007; Huang et al. 2014). Consequently, the Landsat imagery is the most used remote sensing data in wetlands research (Guo et al., 2017): not expensive, not limited in time, therefore long time series can be extracted and further analyzed (e.g., Perennou et al. 2018). Indices to detect the water content (Huang et al. 2018) are standardized and generally used to identify changes (e.g., Li et al. 2015). Good results were obtained in terms of wetland extension and hydroperiod (e.g., Díaz-Delgado et al. 2016; Hopkinson et al. 2020; Kissel et al. 2020). More precisely, monitoring wetlands by satellite imagery is recommended to follow up restoration projects (Cordell et al. 2016; Hausner et al. 2018) and assess restoration success (Dawson et al. 2016).

Understanding the success of recovery actions in hydrosystems has a crucial interest – it contributes to scientific knowledge and provides feedback and guidance for future restoration projects towards more effective results (Morandi et al. 2014). Despite the increasing concern and funding for river restoration, the information on the success or failure of such actions is still limited (Castillo et al. 2016; Angelopoulos et al. 2017). This is due to the poorness of monitoring data based on in situ surveys (González et al. 2015; Wyżga et al. 2020). Moreover, the majority of projects conducts the assessment based on non-standardized indicators, depending on the demands of actors and financing sources (Castillo et al. 2016), as well as other political drivers (Morandi et al. 2017). Moreover, the effectiveness of the restoration solution should be compared to some references, either relative (e.g., pre-restoration), absolute (e.g., good ecological status) or pre-established (e.g., historic baseline, desired image) (Morandi et al. 2014; Wohl et al. 2015), while using similar metrics (Lisenby et al. 2016). Both spatial and temporal scales should be considered in evaluating effects of restoration works (Kondolf et al. 2006).

Our paper aimed at detecting changes related to restoration of seasonal floodplain wetlands by monitoring via satellite-based data. More precisely, we hypothesized on finding statistical changes in time series of the water content of seasonal floodplain wetlands and further interpret them as effects of river restoration. We focused on the Lower Danube River prone to river restoration at large scale by lateral reconnection with the floodplain (Constantinescu et al. 2015) after losing more than half of its floodplain and delta wetlands due mostly to embankments (Habersack et al. 2016).

Study Area

The Danube River Basin with an area of 801,100 km^2 is located in the central part of Europe (Fig. 1a). The Danube River has 2800 km in length and a discharge of approximately 6500 m^{3}s^{-1} at the entrance in the Danube delta at Ceatal Izmail (Fig. 1b). It crosses 15 countries from its origin in southern Germany to its confluence with the Black Sea (Romania). Human culture and development have greatly affected the Danube River Basin that is among the most pressurized large river catchments in the world (Tockner et al. 2008). The increasing demands for land for settlement and agriculture have resulted in large-scale river regulation measures for flood protection. About 39% of the entire Danube length were impounded by a total of 78 dams and more than 68% of the active floodplains of the Danube River and its tributaries, which were in frequent exchange with the main river channel, were embanked and, therefore, lost (citations of Hein et al. 2016).

The Lower Danube River or the last 38% of its length, corresponding to the river course in Romania, drains the Romania-Bulgarian Lowlands via the Danube delta to the Black Sea. After passing the Carpathians, the Danube forms a lowland river system with formally wide floodplains (Stagl and Hattermann 2015). The dams on the Lower Danube River are Iron Gates I and II constructed in 1972 and 1984, respectively, with a volume of 2.1 km^3. Compared to the mean annual inflow, the degree of regulation (storage capacity/mean annual inflow) by this dams is less than 2% per year (Stagl and Hattermann 2015).

Similar to the upper and middle courses, the lateral connectivity of the Lower Danube River was limited mostly due to the levees that were built along the river for farming the floodplain and to protect the riparian settlements against floods. Nowadays, about 84% of the floodplain area along the Romanian Danube are embanked (Fig. 1c) and about 70% are affected by desiccation and drainage (citations of Hein et al 2016). Consequently, the floodplain shows clear signs of ongoing terrestrialization and a reduction of its former functions (Hein et al. 2016). The lateral connectivity strongly depends on local topographic features, therefore the historical floods of spring 2006 submerged some areas in the floodplain by overflowing or breaching levees, while other areas were not flooded (Gâștescu and Țuchiu 2012). Consequently, each enclosure of the Danube floodplain requires special attention and specific actions for river restoration. So far, only small-scale projects (mean area of ~ 24 km^2) were implemented (Ioana-Toroimac and Zaharia, 2016). All the projects reported good results, but only few post-restoration data were published and the scientific literature lacks of a critical analysis of their effects and effectiveness.

Case Study

We focused our demonstration on the case study of the Babina Islet. The main reason for choosing this site is the age of the project (i.e., date of implemented restoration solution at local scale). It is the first river restoration project implemented on the Lower Danube River in the 1990s. The age of the project allows the analysis of river restoration

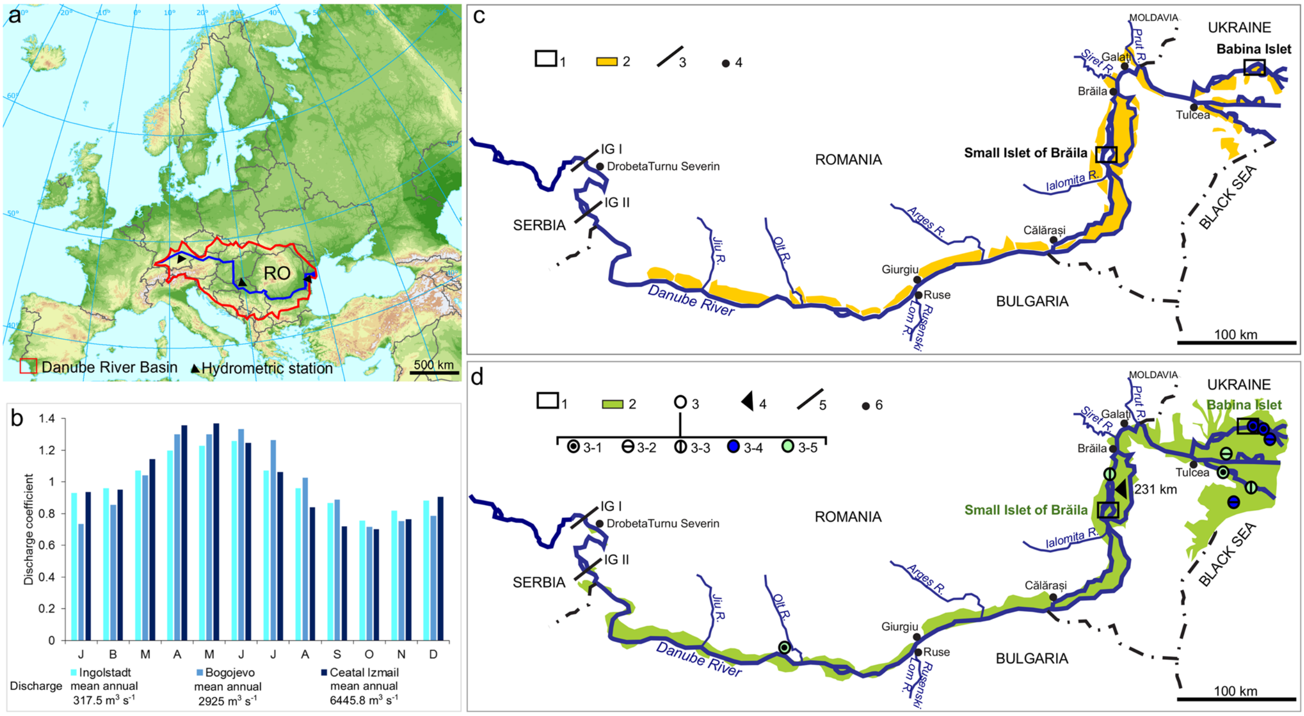

Fig. 1 Study area: **a**) geographical position in Europe of the Danube River Basin (hydrometric stations from West to East: Ingolstadt on the upper course, Bogojevo on the middle course, and Ceatal Izmail on the lower course); the Lower Danube corresponds to Romanian (RO) river course; **b**) variations of the monthly discharge coefficient (ratio between mean monthly discharge and mean annual discharge) of the Danube at Ingolstadt (1931–2019), Bogojevo (1931–2003), and Ceatal Izmail (1931–2010) (according to data downloaded from Global Runoff Database Center 2021); **c**) embankments along the Romanian bank of the Lower Danube River floodplain and delta (redrawn from to Știucă et al. 2007): 1 – case study in this paper; 2 – enclosure; 3 – dam (IG I – Iron Gates I; IG II – Iron Gates II); 4 – city > 50,000 inhabitants; **d**) river restoration actions: 1 – case study in this paper; 2 – project of the Lower Danube Green Corridor (based on WWF, 2016); 3 – river restoration completed project; 3–1 – agriculture as driver for pressure; 3–2 – fishing as driver for pressure; 3–3 – navigation as driver for pressure; 3–4 – opening levees as restoration solution; 3–5 – reshaping canals as restoration solution; 4 – hydrologic observations by remote sensing at km 231; 5 – dam (IG I – Iron Gates I; IG II – Iron Gates II); 6 – city > 50,000 inhabitants

effects on long term. The project of Babina Islet is also demonstrative for improving the lateral connectivity of the Danube and its riparian wetlands. Figure 1d also showed the uniqueness of the Babina project in terms of drivers for pressures and restoration solution (i.e., agriculture as driver for pressure and opening levees as restoration solution).

The Babina Islet is located in the northern part of the Danube Delta, on Chilia arm (Fig. 1c, d), at 35–45 km from the Danube exit in the Black Sea, and with an area of approximately 22 km^2. It is part of a reach of anabranching channels along with two other islands. The Babina Islet was embanked and transformed into a rice field in 1985 that was never productive (Dorondel et al. 2021). Then, in 1990, it became part of the protected area of Danube Delta at international level (Man and Biosphere programme). The restoration project started in May 1994 and was completed in 2003, with the aim of extending wetlands by restoring the pristine hydrological regime with both flooding and dry phases depending on the water level of the Danube (Gâștescu and Știucă 2008; Schneider et al. 2008). In addition, the basic ecological functions, such as recycling and storage of nutrients, should be re-established and previously damaged or destroyed habitats reinstated (citations of Hein et al. 2016). Therefore, the levees were locally opened in order to let the Danube flood the site. The position of opened levees corresponds to previous drainage canals through which the (re)flooding was foreseen (Fig. 3). The project declared a performance timescale of 1–4 years, a restored area of 21 km^2, and a life span of 50 years (Natural Water Retention Measures 2015).

A previous evaluation of the project results published in 2008 showed: the increase of lateral connectivity; the increase of surface and subsurface water levels, as well as of lotic habitats; the decrease of terrestrialization; the recolonization with rheophilic species from Danube; and the sedimentation with fine sediments (Schneider et al. 2008; Hein et al. 2016). Overall, the project of Babina was presented as an ecological success.

To better understand the effectiveness of the river restoration project, we propose the comparison with a site demonstrative for present-day reference conditions considered as control site. The Small Islet of Brăila is part of larger wetland islands between anabranched channels of the Danube River (Fig. 1c, d). The Small Islet of Brăila is considered to be one of the areas in relatively pristine hydromorphological conditions (Staras 2001). Despite the quasi-natural features of the area, without local interventions, it suffered adjustments due to feedbacks such as the lowering of the groundwater level as a consequence of channel incision, therefore it has a moderate potential for restoration (Funk et al. 2019). In our study, we delimited a part of the Small Islet of Brăila, which corresponds to the protected zone with the most valuable natural heritage (50.9 km^2) of the southern part of the natural protected area.

Concerning the comparison between the two sites, the Small Islet of Brăila is located upstream and it is hydrologically influenced mostly by one of the Danube anabranches. The Babina Islet is located downstream and it is hydrologically influenced mostly by a Danube branch in the delta and backwaters upstream the exit in the Black Sea (Mikhailova et al. 2020). Between the two sites, the Danube flows into a single branch and receives two large tributaries – the Siret and Prut rivers contributing with 5% of the Danube discharge. The analyzed gauging station of Ceatal Izmail is located between the two sites, at the end of the single-branch reach of the Danube River, downstream the two confluences. The chosen gauging station is moderately demonstrative for the two sites. Therefore, the analysis of the Lower Danube River discharge is used only to give an overall picture of the hydrological variability in the studied sites. The station at km 231 have only water level data based on satellite remote sensing (Fig. 1d); we used it to underline the position of the Landsat scenes in our study when compared to the hydrological regime of the Danube River.

The Hydrological Variability of the Lower Danube River

The Lower Danube River has a mean annual discharge of 6554.8 m^3s^{-1} at Ceatal Izmail gauging station at the entrance in the Danube Delta (period 1931–2010) according to data downloaded from Global Runoff Database Center (2021). The high flow occurs in spring and early summer (March-June), with a peak in May due to snow melt and thaw in the river basin. The low flow occurs in late summer and autumn (August-November), with the lowest value in October due to the lack of precipitation and high temperatures and evapotranspiration over summer. This is a common characteristic all over the Danube River Basin in the temperate climate, with small variations from the upper (western) basin to the lower (eastern) basin due to altitude decrease. The highest flow occurs in June at Ingolstadt on the upper course and Bogojevo on the middle course (Fig. 1b) and the lowest flow in October.

Concerning the hydrological impact under climate change, according to statistical analysis conducted by Pekárová et al. (2019), since mid-1980s, the peak discharge occurs earlier, in April instead of May. The number of ice cover days has decreased considerably mainly due to an increase in the winter mean temperature in the Lower Danube Basin (Ionita et al. 2018). More distinctly, the summer runoff is reduced and the low flow in autumn are less distinct compared to those of the early twentieth century (Stagl and Hattermann 2015). Models simulated a general trend towards a decrease in summer runoff for the whole Danube basin and, additionally, in autumn runoff for Lower Danube basin, aggravating the existing low flow periods. For the winter and early spring seasons, mainly January-March, an increase in river runoff is projected (Stagl and Hattermann 2015).

The impact of river damming translates by minor monthly deviations between the natural and regulated regimes at the Iron Gates I dam, with a slight increase in discharges during low flow periods (of + 2%) and a minimal decrease (of – 1%) during high flow periods (Zaharia 2010). Despite the large storage volume, the Iron Gates I dam are not significantly influencing the runoff regime on a monthly basis at the multiannual scale (Stagl and Hattermann 2015). At multiannual scale, Pekárová et al. (2019) found a generally less variable flow. Large floods increased in terms of peak and duration, while small floods decreased (Pekárová et al. 2016).

Consequently, despite damming, the Danube River recorded the historical flood in April 2006 (Fig. 2, mean daily discharge > 16,000 m^3s^{-1}). Other major floods occurred in June-July 2010 and April 2005 along the Lower Danube River, but also on its tributaries in southern Romania (Grecu et al. 2017). During these floods high amounts of sediment load were transported (Grecu et al. 2017). The lowest mean daily discharges (< 2000 m^3s^{-1}) occurred in September 2003, October 1992, and October 1985.

Methodology

Monitoring the Water Content

In our study, the monitoring of wetlands relied on the Normal Difference Water Index (NDWI). The NDWI had as original purpose the open water detection (McFeeters 1996) and was computed based on the Eq. 1.

$$\mathrm{NDWI} = (\mathrm{Green} - \mathrm{NIR})(\mathrm{Green} + \mathrm{NIR})^{-1} \tag{1}$$

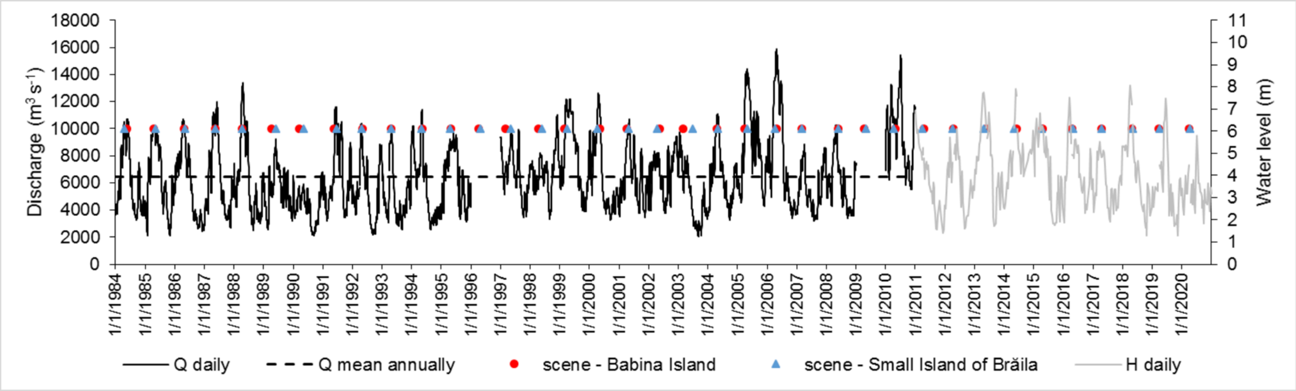

Fig. 2 Variations of the Danube River discharge (Q) at Ceatal Izmail gauging station (1984–2010), prolonged by the water level (H) at km 231 (2011–2020), as well as the date of the selected Landsat scenes in this paper (discharge data downloaded from the GRDC Global Runoff Database Center 2021; water level data downloaded from Theia-land 2021)

where green and near infrared (NIR) correspond to certain wavelengths ranges.

The NDWI was successfully used in previous studies to delineate land from open water, as well as to identify non-urban surface-water associated with wetlands (e.g., McFeeters 1996, 2013; Eid et al. 2020).

To monitor the water content in riparian wetlands, we considered the four classes of the NDWI as proposed by EOS (Earth Observing System 2020): water surface ($0.3 < \text{NDWI}$); flooding/humidity ($0 < \text{NDWI} < 0.3$); moderate drought/non-aqueous surfaces ($-0.3 < \text{NDWI} < 0$); and drought/non-aqueous surfaces ($-1 < \text{NDWI} < -0.3$) (Fig. 3). The threshold of $\text{NDWI} > 0.3$ to detect the surface-water was also used by McFeeters (2013).

Creating Time Series Data *via* Satellite Imagery

To test the relevance of NDWI for the seasonal character of wetlands, we employed Landsat scenes selected on the EOS website. The Landsat scenes have a spatial resolution of 30 m and a temporal resolution of 15 days. For testing, we considered years with mean values of the discharge (e.g., 1994, 1999). The years with highest discharges (e.g., 2006) are characterized by cloudy conditions in spring, therefore a lower number of scenes could be interpreted. Meanwhile, years with lower discharges are not demonstrative for the surface-water extension inside the wetland. Therefore, overall, we analyzed 14 scenes in 1994 for the Babina Island and 13 scenes in 1999 for the Small Islet of Brăila. On each scene, we detected the area corresponding to each NDWI class.

To analyze the variability of the water content, we created time series of NDWI for the time interval 1984–2020, therefore the longest period available by Landsat missions (TM 5, TM 7, and 8 OLI + TIRS) for this region. To create time series, we selected one Landsat scene/year in spring or early summer (March-June) during the high water levels of the Danube River (Fig. 2). We aimed at finding the maximum extent of the surface-water area. Hence, our aim was probably not completely achieved in some years due to unavailable scenes (i.e., clouds, technical issues of satellite missions). Over the period of 37 years, we analyzed: 32 scenes for the Babina Islet, and 35 scenes for the Small Islet of Brăila.

Statistical Analysis of the Time Series of NDWI

To analyze the long-term spatial and temporal variability of the water content, first, we completed the time series by replacing missing values with their mean and median: 13.5% values for the Babina Islet and 5.4% for the Small Islet of Brăila. Statistically similar results were obtain for these protocols (according to the Mann–Whitney test at $p < 0.05$). In this paper, we presented results obtained by replacing missing values by their mean and attributing them to the middle of April.

To interpret results, we used standardized values (%) for areas of the four classes. We further employed statistical tests that already proved their efficacy in the analysis of various time series of environmental parameters. To compare the situation pre- versus post-restoration or beginning versus end of the studied time interval, we used the non-parametric test of Mann–Whitney (Mann and Whitney 1947). We worked at a time scale of 10 years, which is the duration of maintenance works of the Babina Islet project. To identify changing points in the time series, we used the non-parametric test of Pettitt (Pettitt 1979). To detect monotonic trends in the time series, we used the non-parametric test of Mann–Kendall (Mann 1945; Kendall 1975; Gilbert 1987). As these tests are non-parametric, the normality of the time series was not verified.

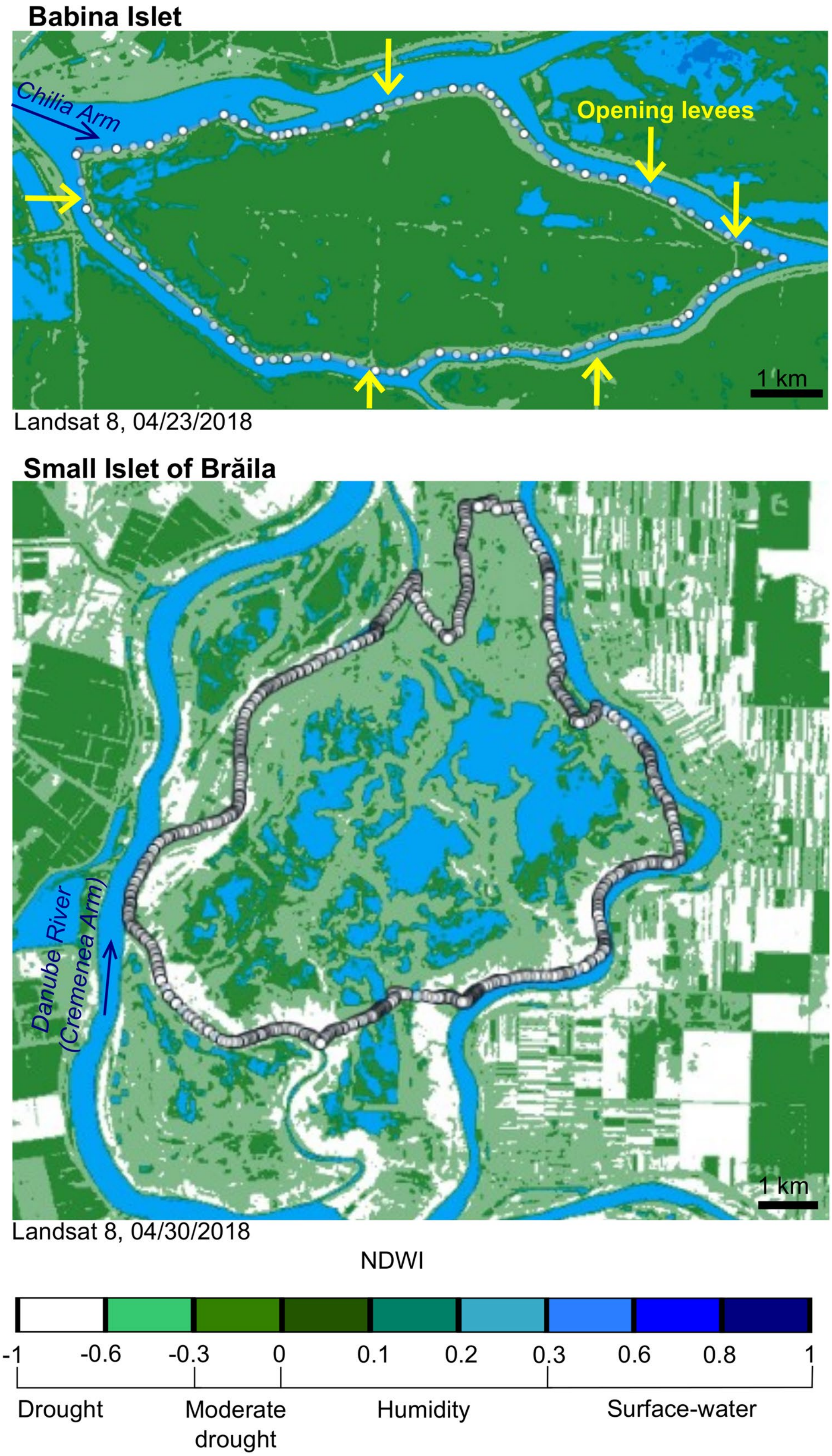

Fig. 3 Example of classes of Normalized Water Difference Index (NDWI, according to Earth Observing System 2020) on a Landsat scene for case studies in this paper (sites delimited by dotted line)

Results

Hydroperiod on the islets

For selected years, the maximum surface-water area corresponded to the high flow phase of the Danube River in spring and early summer (Fig. 4). The surface-water lasted until May–June. A slight increase was also noticed in the end of the year. The hydroperiod appears to be continuous in winter on the Small Islet of Brăila.

Figure 4 also showed a pattern of evolution of flooded lands: the surface-water transformed into humid areas by water content decrease; the latter class became lands in moderate drought status, which further transformed in drought status. The rest of the investigation is based on scenes corresponding to the maximum extension of the surface-water area.

The surface-water was absent during the high flow phase of some years (i.e., 5 years on the Babina Islet and 4 years on the Small Islet of Brăila) (Fig. 5). This suggests that the "annual" flood does not occur every spring along the Lower Danube River. The years without surface-water differ from one site to another (i.e., 1984, 1987, 1989, 1993, 2014 on Babina Islet and 1990, 1992, 1998, 2008 on Small Islet of Brăila), indicating the role of local tributaries to the Danube

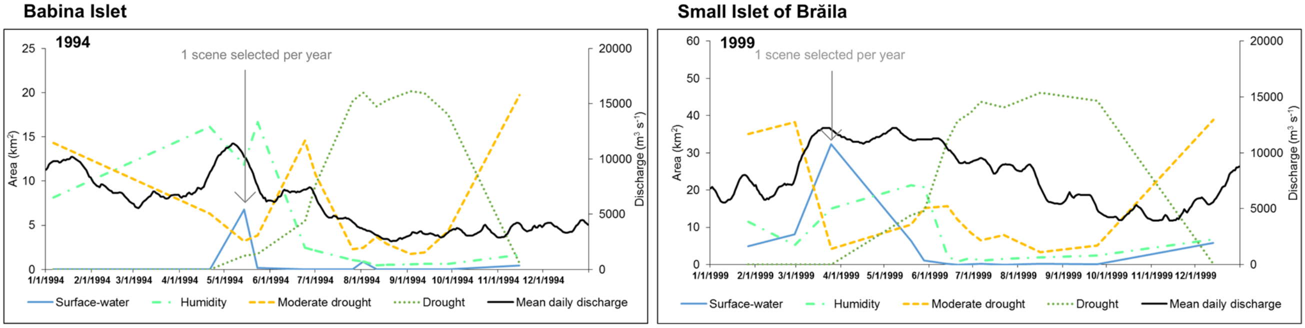

Fig. 4 Variations of the water content on studied islets and Danube River discharge at Ceatal Izmail during selected years

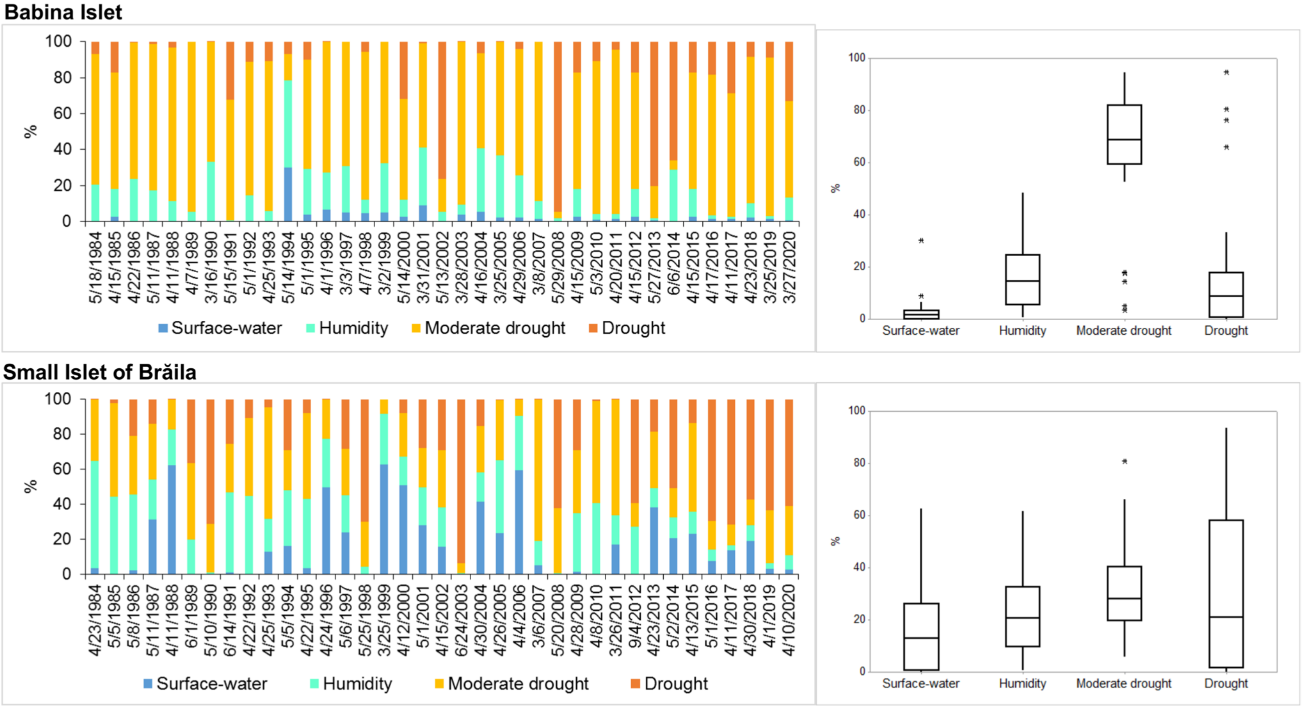

Fig. 5 Variations corresponding to the maximum water content in the studied sites (spring-early summer 1984–2020). The boxplots contain the minimum, quartile 1, median, quartile 3, and maximum values

Table 1 Water content variability in the studied sites: changing point by Pettitt test and trend by Mann–Kendall test (results in bold are statistically significant at $p < 0.05$; the rest of the results are statistically significant at $0.05 < p < 0.10$)

Case study	Water content	Changing point	Trend
Babina Islet	Surface-water	**1993**	-
	Humidity	**2006**	↓
	Moderate drought	-	-
	Drought	**2007**	↑
Small Islet of Brăila	Surface-water	-	-
	Humidity	**1997**	↓
	Moderate drought	-	-
	Drought	-	↑

water volume and level. In the case of the Babina Islet, most of the years without "annual" flood occurred before the restoration works.

Temporal Variability of Wetland Area

On Babina Islet, the surface-water area covered only 2.8% of the islet. The humidity, moderate drought, and drought areas represented 15.3%, 64.8%, and 17.1% of the islet. The highest surface-water area occurred in 1994 (30.2%), simultaneous to the restoration works. The highest drought area occurred in 2008 (94.7%). Except for a few outliners, the four water content classes recorded a low variability, with relatively low interquartile ranges (3% – 23%) (Fig. 5).

On the Small Islet of Brăila, the surface-water area represented 17.3% of the island. The humidity, moderate drought, and drought areas represented respectively 22.3%, 32.0%, and 28.4% of the islet. The maximum surface-water extent occurred in 1999 (62.7%), followed closely by 2006 (59.3%) during the historic flood. The highest drought area was registered in 2003 (93.6%). The four water content classes characterized by a relatively high variability, with interquartile ranges from 20% to 56% (Fig. 5).

Changing Points in the Temporal Variability of Wetland Area

On the Babina Islet, the surface-water area recorded a changing point in 1993 right before the restoration actions and the occurrence of its maximum extension (Table 1). The mean value of surface-water area before the changing point was of 0.4%, while post-restoration it was about 3.7%. No changing point was detected for the surface-water area on the Small Islet of Brăila during the studied period.

For humidity and drought areas, the changing points corresponded to hydrological events, i.e., floods. On the Babina Islet, the humidity area recorded a changing point in 2006 while the drought area in 2007 (Table 1). These changing points corresponded to high discharges of 2005 and 2006. The humid lands had a higher area before the changing point while the drought area became more extended since. On the Small Islet of Brăila, the humidity area recorded a changing point in 1997, with higher values before.

Trends in The Temporal Variability of Wetland Area

The surface-water area did not record a statistical trend for the entire studied period and on both sites (Table 1). Yet, a negative trend was measured after the changing point of 1993 on Babina Islet. This finding confirmed the effective and simultaneous role of restoration works in extending the surface-water area on this islet.

The humidity and drought areas registered opposite statistical trends for the entire studied period and on all the sites. The humidity area had a negative trend, which was more obvious on the Small Islet of Brăila ($p < 0.05$) then on the Babina Islet ($p < 0.10$). The drought area recorded a positive trend, which was also more obvious on the Small Islet of Brăila ($p < 0.05$ and Sen slope $= +0.92$) than on the Babina Islet ($p < 0.05$, Sen slope $= +0.36$). Thus, any processes triggering these trends were more intense on the Small Islet of Brăila.

Temporal Variability of Wetland Area Pre- and Post-Restoration of the Babina Islet

The analysis comprised two types of comparisons. (i) First, to detect changes due to the restoration works of 1994 and maintenance of 2003 on the Babina Islet, we compared the decade of restoration (1994–2003) with the decade pre-restoration (1984–1993) and with the decade post-restoration (2004–2013). (ii) Then, to understand the overall results, we compared the first decade of the analysis (1984–1993) with the last decade (2011–2020). The analysis was applied to both sites (Table 2). Any results for the Small Islet of Brăila could confirm or infirm the effects of the restoration works of the Babina Islet.

(i) The Babina Islet recorded the increase of the surface-water area during the decade of restoration when compared with the decade pre-restoration and with the decade post-restoration ($p < 0.05$). In lack of restoration works on the Small Islet of Brăila, the surface-water area had slightly higher values during the decade of restoration then during the decade pre-restoration, at $p < 0.10$. The moderate drought area had lower values during the decade of restoration then during the previous decade on both islands and also during the next decade on the Small Islet of Brăila.

Table 2 Water content variability in the studied sites: comparisons of mean areas (in km^2) at decade scale by Mann–Whitney test (results in bold are statistically significant at $p < 0.05$; the rest of the results are statistically significant at $0.05 < p < 0.10$)

Case study	Water content	1984–1993	1994–2003	1994–2003	2004–2013	1984–1993	2011–2020
Babina Islet	Surface-water	**0.05 < 4.8**		**4.8 > 1.8**		**0.05 < 1.4**	
	Humidity	-		-		14.9 > 5.2	
	Moderate drought	**75.1 > 64.0**		-		-	
	Drought	-		-		**5.2 < 17.7**	
Small Islet of Brăila	Surface-water	1.7 < 15.3		-		1.7 < 14.6	
	Humidity	-		-		32.9 > 9.8	
	Moderate drought	**34.4 > 23.7**		**23.7 < 35.2**		34.4 > 22.4	
	Drought	-		-		**12.3 < 58.2**	

(ii) The islets recorded lower surface-water area in the first decade of the analysis when compared with the last decade of the analysis, with higher statistical significance for the Babina Islet. The decrease of humidity area and the increase of drought area was confirmed by comparing the first decade with the last decade of the studied period on both islands.

We found some similarities between the two sites. When concerned the surface-water, the decade of restoration and the last decade appeared to be more humid than the first decade of the analysis. Therefore, we conclude that the effects of restoration were probably supported by the river's hydrology.

Discussion

The analysis of the variability of the water content on the restored islet allowed to develop three ideas to be discussed. Was the restoration of the Babina Islet effective? What contribution of the method used in our paper to detect the effects of wetlands' reinundation? What lessons learned to improve river restoration?

Effectiveness of Reinundating Wetlands on the Babina Islet

We concluded on modest results concerning the extension of wetlands on the Babina Islet. The surface-water area extended on maximum 6.6 km^2 (30.2% of the islet) simultaneous to the restoration works in 1994. Then, the surface-water area reach a maximum of 2 km^2 in 2001. Since 2005, the surface-water area rarely exceeded 0.5 km^2. The official documents reported the restoration of the entire island (according to Natural Water Retention Measures 2015). In practice, the surface-water is larger by a mean value of 0.7 km^2 post-restoration than pre-restoration. Our findings are demonstrative for the maximum inundation of the wetland or the highest peak of the hydroperiod knowing that wetland extension was the aim of the restoration project of the Babina Islet.

In the years post-restoration, the canals that were supposed to bring water to the interior clogged and certain parts the islet were rarely flooded (Dorondel et al. 2021). The de-clogging process was hindered by institutional issues (Dorondel et al. 2021). Later, the historical floods of 2005 and 2006 in southern Romania and on the Danube River had mostly a negative impact on restoration effects, which characterized by lower extent of humidity area and higher extent of drought area since these historic hydrological events. This evolution was probably due to siltation that was the prevailing post-restoration process on the Babina Islet (Hein et al. 2016), as well as in the majority of restored sites on the Lower Danube River (Ioana-Toroimac and Salit 2016), and was also detected on other Danube islands (Hachemi et al. 2021). As hypothesis, the clogging may be more intense on the Babina Islet in relation to backwaters that were identified for this arm on approx. 50 km inside the Danube Delta by Mikhailova et al (2020). When compared to the control site of the Small Islet of Brăila, we found similarities in terms of water content variability at decade scale. This suggests that the favorable hydrological context supported the restoration effectiveness.

So far, the Small Islet of Brăila continue to be the most demonstrative case study for river connectivity concept under present-day conditions of the Danube flow and channel. In the Small Islet of Brăila, riparian processes could be further investigated in detail to better understand the nestedness and interdependence of hydrological, geomorphic, ecological, and biogeochemical processes (sensu Polvi et al. 2020) and find the right solution for floodplain restoration along the Lower Danube River. Pristine areas in the Danube Delta, including the Babina Islet, have specific conditions and could be under the influence of backwaters – less variability at monthly scale (Mikhailova et al. 2020), which complicates the relation between hydrology and other environmental factors, and make them specific case studies.

Our vision of the Lower Danube River restoration is strictly nature-oriented, with a preference for water flux, which is restrained when compared to the overall objectives of river restoration. River restoration has also a human-oriented foundation (Wohl et al. 2015). In the case of the Babina Islet, the project expunged local ecological knowledge, triggered an ominous series of restrictions for the locals, and it is considered a social failure (Dorondel et al. 2021).

Contribution to Better Understanding the Effectiveness of River Restoration

Our case study was demonstrative for river lateral reconnection by opening levees. Setting back, opening, and removing levees was highly recommended for the restoration of freedom space and floodplain (Gumiero et al. 2013). Yet, our modest results of self-sustainability of wetlands questioned these recommendations. Moreover, it confirmed previous studies showing that lateral reconnection may be followed by an increase in the fine sediment deposition in the floodplain (Maaß and Schüttrumpf 2019) and even further euthrophication (Klaus et al. 2011). Therefore, in lack of maintainance works, lateral reconnection to extend wetlands may have little success. Consequently, there is a need to rethink riparian wetlands restoration towards more self-sustainable solutions.

As methodological issues, our paper enforced certain directions of evaluating the effectiveness of river restoration.

- Our paper contributed at understanding the physical habitat of the restored site, comprising a small part of indicators to monitor and evaluate the success of river restoration (Marttunen et al. 2019), including also the political and social support (Morandi et al. 2014).
- Our paper analyzed the effects of river restoration by statistic means. We borrowed methods, i.e., tests of changes and trends in time series, from statistical hydrology (e.g., Birsan et al. 2014) and adapted them to the parameters used in our study. We highlighted the effects of river restoration on long term to the detriment of the mechanisms responsible for this evolution as suggested by Pasternack (2020).
- Our paper took into account different baseline conditions as recommended by Morandi et al. (2014): pre- versus post-restoration status, as well as present-day reference conditions. We concluded that restoration effects were detected when compared to pre-restoration conditions. The comparison with present-day reference conditions confirmed or invalidated certain variability issues.
- Our paper relied on standardized indicators (i.e., NDWI) which could be used for other sites therefore obtain comparable results as recommended by Castillo et al. (2016).
- We believe that not only will the outcomes from the monitoring are of considerable scientific interest, but they will also contribute to better adapt restoration solution towards improving the functioning of rivers similar to previous studies (e.g., Wyżga et al. 2020).

Challenges for River Restoration on the Lower Danube River

On both studied islets, during the high flow phase of the hydrological regime, the humidity area decreased, while the drought area increased. We conclude that drought affected the islets of the Lower Danube River during the last decades at least in the studied sites. Altered hydrological peaks and water table variations were common consequences of river damming (Petts and Gurnell 2005). The study of hydrological impact of Iron Gates dams on the river flow is in progress.

We conclude that the restoration of the Lower Danube's islets could be un-self-sustainable. The process of drought extension appeared to be dominant and it could prevent wetlands persistence. This finding suggests a new challenge for river restoration and overall river management. Could the Danube's islets maintain wetlands on long-term in present-day conditions characterized by a lower number of small floods lasting less time? This question could be extended to the entire Lower Danube's floodplain. Moreover, hydrological modelling predicted a runoff decrease in spring in the Danube River basin (Stagl and Hattermann 2015), which could further affect wetland extension. More in-depth analysis is required in order to plan for restoring and maintaining the wetness of the Lower Danube's islets and floodplain.

A new strategy of restoring the Lower Danube River should start from reconsidering the objectives. These objectives should rely on the idea that hydrology is the most important constraint of wetland conditions and dynamics, therefore water management is most often the key-driver to wetland restoration (Gumiero et al. 2013). As example, floodplain restoration could be supported also by dam reoperation. If floodplain reconnection creates additional downstream capacity to store and convey floodwaters, dam operators could reduce the reservoir volume reserved for flood control, benefiting the environment (Watts et al. 2011). Floodplain reconnection could allow groundwater recharge (Watts et al. 2011), which could also solve the drought problem. More data and analysis are necessary to conclude on the effectiveness of such a solution in the case of the Lower Danube River.

Conclusions

Our paper analyzed NDWI variability in riparian wetlands to understand challenges for river restoration. We detected changing points that could be related to restoration effects. We determined trends that could be interpreted in terms of new challenges for river restoration. Therefore, we recommend the use of satellite-based indicators to study inundation or drought in large wetland areas for restoration purposes.

In the restored site of Babina Islet in the Danube Delta, our paper showed a slight increase of surface-water area, which persisted after almost three decades. Even if we characterized these effects as being modest in terms of maximum inundated area, we acknowledge the work to plan and implement this project since it was the first one in Romania and therefore was conducted with no previous experience. Surprisingly, the comparison with present-day reference conditions site (i.e., Small Islet of Brăila) revealed another issue of water content variability, independent from restoration works – increasing drought during the high water phase of the hydrological regime.

These challenges of river restoration – modest extension of surface-water area, as well as increasing drought area – should raise awareness on the human impact on hydrosystems. Moreover, in river restoration, there is not a single effective solution to mitigate the impact of similar pressures. Each case study is unique in terms of both nature response and project governance. Unfortunately, despite willigness of the scientific community and civil society (Constantinescu et al. 2015), restoring the lost wet paradise of previous centuries appears to be a myth (Dufour and Piégay 2009) in the case of the Lower Danube River.

Recommendations

During our research on the outcomes of restoring Babina Islet's connectivity with the Danube River and preparation of this manuscript, we encountered some challenges, therefore we make a few recommendations.

- To practitioners: conduct continuous monitoring of restoration sites, because occasional fieldwork campaigns may not capture the integrality of riparian processes; therefore, make use, among other tools, of satellite remote sensing data for continuous survey of restored sites; make the results of the monitoring accessible to help other practitioners and scientists to gain know how and know why.
- To scientists: focus more on post-restoration effects because it could bring fundamental results in understanding riparian processes; when interpreting the results of river restoration, consider other features of the river, which could influence riparian processes; reflect at multicriteria methodologies based on standardized indicators that could help to conclude on the effectiveness of river restoration for a variety of case studies.

Overall, our recommendations underline the importance of gathering data post-restoration at good temporal and spatial scale. They could be later interpreted to understand both the effectiveness of the restoration solution as well as riparian processes in different ecoregions. On the whole, analyzing such post-restoration data could help at enhancing fundamental knowledge on fluvial environments.

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Declarations

Ethics approval All investigations relied on open access data. Landsat scenes were analyzed on Earth Observing System website. Hydrological data were downloaded from Global Runoff Data Center website and Theia-land hydroweb.

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