Science of the Total Environment 609 (2017) 1544–1555

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Controls on anastomosis in lowland river systems: Towards process-based solutions to habitat conservation

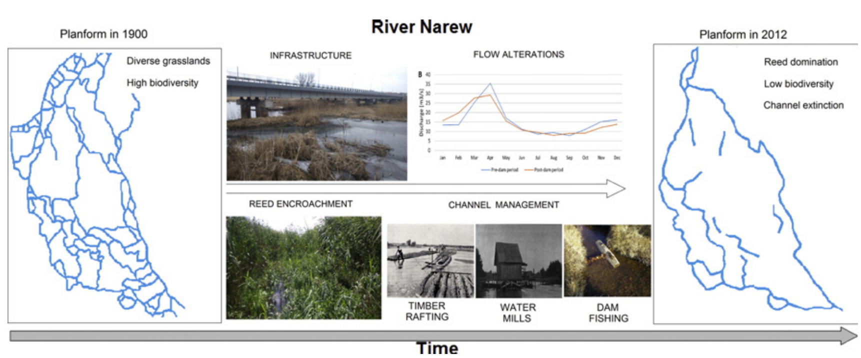
Paweł Marcinkowski [a], Robert C. Grabowski [b,*], Tomasz Okruszko [a]

[a] Department of Water Engineering, Faculty of Civil and Environmental Engineering, Warsaw University of Life Sciences (WULS-SGGW), Nowoursynowska 159 Street, 02-776 Warszawa, Poland
[b] School of Water, Energy, and Environment, Cranfield University, College Road, Cranfield, Bedfordshire MK43 0AL, UK

HIGHLIGHTS

- Controls on anastomosis in lowland rivers are not well understood.
- Anabranch loss in the anastomosing River Narew (110 km since 1900) provides a backdrop to investigate controls.
- River flow alterations, channel management, and floodplain vegetation interact to drive extinction of anabranches.
- Process-based solutions are needed to disrupt anabranch loss pathways and conserve wetland habitat.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 19 July 2017
Accepted 20 July 2017

Editor: Ouyang Wei

Keywords:
Anabranching
Fluvial geomorphology
Floodplains
Hydromorphology
Multithread river

ABSTRACT

Anastomosing rivers were historically common around the world before extensive agricultural and industrial development in river valleys. Few lowland anastomosing rivers remain in temperate zones, and the protection of these river-floodplain systems is an international conservation priority. However, the mechanisms that drive the creation and maintenance of multiple channels, i.e. anabranches, are not well understood, particularly for lowland rivers, making it challenging to identify effective management strategies. This study uses a novel multi-scale, process-based hydro-geomorphological approach to investigate the natural and anthropogenic controls on anastomosis in lowland river reaches. Using a wide range of data (hydrologic, cartographic, remote-sensing, historical), the study (i) quantifies changes in the planform of the River Narew, Poland over the last 100 years, (ii) documents changes in the natural and anthropogenic factors that could be driving the geomorphic change, and (iii) develops a conceptual model of the controls of anastomosis. The results show that 110 km of anabranches have been lost from the Narew National Park (6810 ha), a 42% reduction in total anabranch length since 1900. The rates of anabranch loss have increased as the number of pressures inhibiting anabranch creation and maintenance has multiplied. The cessation of localized water level and channel management (fishing dams, water mills and timber rafting), the loss of traditional floodplain activities (seasonal mowing) and infrastructure construction (embanked roads and an upstream dam) are contributing to low water levels and flows, the deposition of sediment at anabranch inlets, the encroachment of common reed (*Phragmites australis*), and the eventual loss of anabranches. By identifying the processes driving the loss of anabranches, this study provides transferable insights into the controls of anastomosis in lowland rivers and the management solutions needed to preserve the unique anastomosing river pattern and diverse wet grasslands that are central to the conservation value of lowland floodplains.

* Corresponding author.
E-mail addresses: p.marcinkowski@levis.sggw.pl (P. Marcinkowski), r.c.grabowski@cranfield.ac.uk (R.C. Grabowski), t.okruszko@levis.sggw.pl (T. Okruszko).

http://dx.doi.org/10.1016/j.scitotenv.2017.07.183
0048-9697/

1. Introduction

Rivers with natural floodplains and associated wetlands support diverse and productive ecological communities, and their protection is an international conservation priority (Johnson et al., 2016; Kingsford et al., 2016; Tockner and Stanford, 2002). Alluvial rivers are self-forming, adjusting their position, dimensions, planform and geomorphic features in response to changing boundary conditions and extreme events. Through geomorphic processes (e.g. sediment erosion and deposition), a variety of landforms are created in floodplains (e.g. multiple channels, backswamps, ridges/swales, backwaters, oxbow lakes) that, with the added complexity of sedimentological, topographical and hydrological variations, produce a diversity of mesohabitats across the aquatic and terrestrial ecotone (Fryirs and Brierley, 2013; Ward et al., 2002). However, this geomorphological richness has been lost from most temperate lowland floodplains because of direct and indirect human activities. Lowland rivers with multiple channels separated by vegetated, floodplain islands, i.e. anastomosing rivers, while once common in temperate zones (Lewin, 2010; Walter and Merritts, 2008), are now rare in the developed world, placing an even greater importance on conservation for those that remain. The challenge for conservationists is that the controls on river anastomosis are not fully understood, making it difficult to develop sustainable management solutions.

Anastomosing rivers occur in a variety of environments and climatic conditions: mountainous or lowland areas and in temperate, subartic, humid tropical or arid regions (Makaske, 2001; Nanson and Croke, 1992; Nanson and Knighton, 1996). One of the best studied anastomosing reaches is the upper Columbia River in the Rocky Mountains of Canada (Kleinhans et al., 2012; Makaske et al., 2017). There is continual debate among geomorphologists about the classification of river planform (Carling et al., 2014), but generally anastomosis is distinguished from braiding, the other main type of multi-channel planform, by the stability of the channels, vegetated islands, and their location on low-gradient floodplains. From a process-based perspective, anastomosing rivers are believed to form via avulsion, in which new channels (i.e. anabranches) are created when water breaks through the erosion-resistant riverbank sediment and begins to incise into the floodplain (Gradziński et al., 2003; Makaske et al., 2017; McCarthy et al., 1992; Schumann, 1989; Smith and Smith, 1980; Smith et al., 1989).

For an anastomosing planform to persist in a floodplain, either anabranch formation is promoted through avulsions or anabranch extinction suppressed (Makaske, 2001). Kleinhans et al. (2012) proposed four hypotheses to explain anastomosing in the confined Columbia River valley, which are more widely applicable; it may form because of a rise in downstream base level, high sediment inputs from upstream, the increased flow efficiency of multiple channels, or as an evolution from deltaic formations in lakes. For the Columbia River, high sediment input from upstream appears to be the most likely hypothesis (Makaske et al., 2017). The confined mountainous floodplain receives a large input of sediment from the hillslopes that results in bed aggradation and overbank flooding. Other controls on anastomosis have been proposed for rivers in different environmental and climatic settings, but generally anastomosis is believed to persist because of erosion-resistant banks and high water levels (Nanson and Huang, 1999; Tooth and Nanson, 1999, 2000). An inability of channels to alter their capacity after frequent or high-magnitude flooding is a precondition for avulsion and the eventual formation of new channels elsewhere on the floodplain. A highly variable flood-prone flow regime characterized by the occurrence of seasonal high water stages is postulated as another crucial factor in most anastomosing rivers worldwide (Nanson and Knighton, 1996; Schumann, 1989). However, localized blockages (e.g. wood, vegetation, ice jams) have been hypothesized to be equally important for the formation of multiple channels (Ettema and Muste, 2001; Gradziński et al., 2003; McCarthy et al., 1992).

Most studies on anastomosing rivers have focused on natural systems that have had limited direct impact from human activity. However, lowland rivers with their numerous human pressures represent how anastomosis responds to different direct and indirect factors. The list of human interventions that impact lowland rivers and floodplains is long (mills, fishing dams, land cover change, timber rafting, reservoirs, bank protection, channel realignment, channel sectioning), but a structured process-based investigation of geomorphic change over time in response to these interventions can provide insight into the controls (Downs et al., 2013; Grabowski and Gurnell, 2016a, 2016b; Gurnell et al., 2016b).

Against this background, this study investigates the controls on anastomosis in a lowland river floodplain specifically including both natural and anthropogenic factors. The study area is the Narew National Park (NNP), which is home to one of the best-preserved stretches of anastomosing river in Europe. Yet the anastomosed planform is disappearing from the River Narew, causing concern among park managers and conservationists. Using a hierarchical, hydro-geomorphic process-based assessment, the study (i) quantifies changes in the planform of the River Narew over the last 100 years, (ii) documents changes in the natural and anthropogenic factors that could be driving the geomorphic change, and (iii) develops a conceptual model of the controls of anastomosis for the River Narew. By understanding what factors are responsible for the loss of anabranches in the NNP, we improve our mechanistic understanding of anastomosis in lowland river floodplains and facilitate the development of sustainable conservation strategies for these important habitats.

2. Materials & methods

2.1. Study area

Presently the longest example of a cohesive sediment anastomosing type river in Europe is in the upper River Narew, NE Poland (Fig. 1). The uniqueness of the river planform and its important wetland habitats were the driving factors to formally protect the full length of the anastomosing section and the adjacent valley as a national park and a Natura 2000 site (EU Birds and Habitats Directives). The River Narew is a lowland, low-gradient (0.0002 mm^{-1}) river, a right-hand tributary of the River Vistula, with a total drainage area of ca. 75,000 km^2 (Fig. 1). The catchment is in a temperate zone in which marine and continental air masses collide. The region is characterized by moderately warm summers (mean temperature in July 18 °C) and cool winters (mean temperature in January −2 °C). The annual average precipitation in the catchment is ca. 600 mm. The catchment is entirely covered by glacial tills and the dominant types of soil are pure and loamy sands with high permeability. The main valley bottoms are filled with peat deposits from the Holocene. The land cover in the Upper Narew catchment is predominantly agricultural (53%) with arable lands composing 39% and pastures the remaining 14% (Banaszuk et al., 2004). The second most important land use by area is forest (39%). Urban areas cover less than 3% of the catchment.

The study focuses on the anastomosing section between Suraż and Rzędziany (ca. 35 km) that forms the NNP (6810 ha) (Fig. 1). Within the NNP, the river is characterized by a network of small interconnected, unconfined channels within a wide valley (1–4 km wide) bounded by low hills of glacial tills. The channels have a low width/depth ratio, a mobile sand bed and erosion-resistant peat banks (Gradziński et al., 2003). Vegetation cover within the NNP is predominantly early growth reed and sedge communities, which have long been managed for reed harvesting (Banaszuk et al., 2004). Peat deposition has occurred throughout the Holocene and peat deposits within the valley can reach 4 m in thickness (Gradziński et al., 2003).

Human modification of the Narew floodplain system dates back centuries. Activities, such as timber rafting, fish weirs, and water mills, impacted directly and indirectly on water levels, water velocities, longitudinal continuity and sediment transport, and channel dimensions. Large-scale engineering projects are more recent on the River

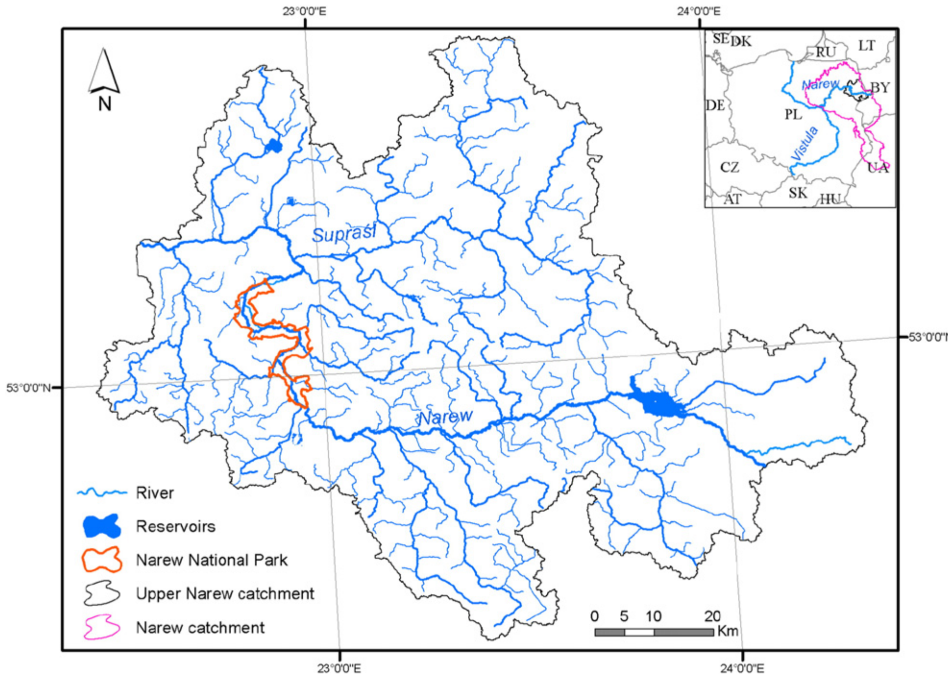


Fig. 1. Study location: the anastomosing section of the River Narew is located in the Narew National Park, NE Poland. (Data sources: The Map of Hydrographic Division of Poland 2010 from National Water Management Authority).

Narew, with bridges and embankments beginning to be built at the end of the 19th century and construction of a large reservoir in the upper catchment in the late 20th century. The Siemianówka Reservoir located upstream from the NNP was completed in 1992. Further details of these activities and their potential impacts on the anastomosing pattern of the Narew are provided in the results section.

2.2. Hierarchical framework

The study applied a hierarchical hydromorphological assessment framework developed in the REFORM project (Gurnell et al., 2016a). The multi-scale approach examines the hydrological and geomorphological processes from catchment down to reach scale that influence the character and dynamics of river channels and their floodplains. The upper Narew catchment was a case study for the REFORM project and more information on the delineation and characterization of the catchment can be found in Blamauer et al. (2014). The framework states explicitly that the hydromorphological character of river reach depends not only on interventions and processes within the reach but also on those upstream and sometimes downstream of the reach. Furthermore, the methodology accepts that river reaches often respond in a delayed way to processes and interventions within the catchment; time lags must be considered.

2.3. Channel planform changes

Historical maps and aerial photographs were used to examine changes in channel planform and width over time. The oldest map used in the study dates to 1900 and comes from the Map Archive of the Military Institute of Geography (http://polski.mapywig.org). With a resolution of 1:100,000, it provides the earliest reliable record of the number and position of anabranches within the NNP. Additionally, aerial photographs (1:10,000 resolution) for 1966, 1997 and 2013 were acquired from the Main Geodetic and Cartographic Documentation Centre (CODGIK) in TIFF format. The historical map was manually georeferenced in ArcGIS based on common landmarks (i.e. streets, railways) (Grabowski and Gurnell, 2016a). Afterwards, all channels of the River Narew within NNP were digitized for each time point. Channel area and length were quantified and used to calculate average channel width separately for the main channel and anabranches. To evaluate the development of the system, the anabranching index (Ai - the number of active channels at baseflow separated by vegetated islands) was calculated for each time period.

2.4. Drivers of geomorphic change

In this study, the natural and anthropogenic factors that could be driving channel change were investigated. Precipitation, snow cover and river discharge records were investigated to establish if there has been any change to the hydrological regime. No data were available on sediment loads in the River Narew. Given the lowland, low gradient setting of the river, bed material is presumed to originate from the underlying glacial till geology, which is mobilized during bank erosion, though input from the forested headwaters is possible. Land cover data does not suggest any substantial anthropogenic change in land cover in the valley or catchment that might affect fine sediment generation or delivery, and are not presented here. Importantly, potential anthropogenic drivers of channel change since the beginning of the 20th century were researched. Changes in anabranch number and width and the natural and anthropogenic factors are incorporated into a chronology to facilitate a process-based assessment of the controls on anastomosis in lowland river systems.

2.4.1. Precipitation and snow cover changes

Historical precipitation and snow thickness records were acquired from the Institute of Meteorology and Water Management – National Research Institute. Rainfall statistics were based on the time period 1951–2012 from 20 rainfall gauging stations located in the Upper Narew Catchment. To assess the significance level of precipitation and snow cover thickness trends, the non-parametric Pettitt's test was applied, with the significance level set at 0.05 (Pettitt, 1979). The null hypothesis is that data are homogeneous throughout the period of observation.

2.4.2. Flow regime analysis

The historical flow records from the river gauging station at Suraż, located at the upstream end of the NNP, were used to analyze the flow regime of the River Narew. Average daily discharge records for time period 1950–2012 were acquired from the Institute of Meteorology and Water Management – National Research Institute. Two periods were considered: 1950–1991 (pre-dam period) and 1992–2012 (post-dam period). A flow duration analysis was conducted, yielding mean median discharge for both periods. In addition, the number of flooding days was calculated based on bankfull discharge, which for the Suraż gauging station is ca. 50 m^3/s. Statistical analysis of flow data homogeneity was conducted to indicate significant break-points and trends in timescale to assess the impact of dam construction on flow regime. For this purpose, the non-parametric Pettitt's test was applied for min, max and mean annual discharge and for number of days with flood occurrence, with the significance level set at 0.05.

2.4.3. Management changes

To investigate the direct anthropogenic influences on anastomosis, archival research was conducted on the history and habits of local inhabitants. The Podlaska Digital Library was researched to find books, maps and documents that described the historical, socioeconomic and ethnographic setting for the River Narew region. From this research, several key activities were identified that likely impacted river form, directly or indirectly. These activities are: bridge construction, timber rafting, fishing dams, water mills, reservoir construction and realignment of the channel downstream of the NNP. Sources are listed in the Results section.

3. Results

3.1. Channel planform changes

The anastomosing section of the River Narew in the NNP has changed significantly over the last 100 years (Fig. 2). Over 110 km of anabranches have disappeared from the river network. However, the response is not uniform across the anastomosing section. Higher rates of channel extinction are evident in the southern part of the system (near the upstream border of the NNP), with lower rates of loss observed in the central and northern parts of the NNP. Differences in extinction rates are also evident over time, with an increasing trend noted. In the first time period (1900–1966) the loss equaled 0.53 km/year, increasing in 1966–1997 to 1.45 km/year and increasing yet again in 1997–2013 (2.26 km/year) (Table 1). The analysis of channel width indicates that the width of the main channel relative to the total in each cross section has increased from 31% in 1966 to 61% in 2012. Unfortunately, reliable data on channel depths were not available. Nevertheless, the width analysis suggests that the main channel has increased in capacity concurrently as anabranches become dominant.

3.2. Drivers of geomorphic change

3.2.1. Precipitation and snow cover alteration

Rainfall statistics indicate a slight increasing trend over the last 60 years, with some wetter and drier periods (Fig. 3). Total annual precipitation is higher from 1970 to 1980 than from either 1951 to 1969 or 1981 to 2012 (Fig. 3A). This pattern was broken in 2010 by an extremely wet year with flooding across Poland, but recent years appear to be framed within the pre-2010 trend. For snow cover thickness, the statistical analyses indicate a break point in 1990 when the average thickness decreased from ca. 24 cm to 12 cm (Fig. 3B).

3.2.2. Flow regime changes

Since the reservoir became operational in 1992, no significant changes in average daily flows have been observed (Fig. 4A), but there have been significant alterations in minimum flow, maximum flow and flood duration (Fig. 5). The annual hydrograph has changed, with lower average flows in April but higher in February and March (Fig. 4B). This change is due most likely to decreasing snow thickness and dam operations, in which water is released from the reservoir in advance of the spring thaw to prevent flooding in municipalities close to the reservoir.

Pettitt's test for minimal yearly discharges indicated two characteristic break points (Fig. 5A). The first, in 1971, correlates with an increase in precipitation (Fig. 3A) and the second, in 1992, correlates with the construction of the Siemianówka reservoir dam. Regarding the mean annual flow, two break points are also detected (Fig. 5B), but these correlate with the precipitation fluctuations (Fig. 3A). Maximum annual flow and the number of days of flooding are significantly lower after 1990 (Fig. 5C, D), which is around the time of dam construction as well as the observed reduction in snow cover thickness (Fig. 3B).

3.2.3. Management changes

3.2.3.1. Bridge construction. The first major change in the floodplain within the time period of this study (1900–2013) was the construction of three embanked roadways across the floodplain. Cartographic evidence from several sources shows these 50-meter wide earthen ridges appearing in the late 19th century. Bridges spanned the main channel, but anabranches were artificially buried with sand and entirely cut-off from the river system. Construction of the embanked roadways caused permanent artificial redirection of stream flow into the main channel leaving the anabranches either completely unsourced or partially contributed. This intervention resulted in a narrowing of the floodplain locally by 60–80% and altered the distribution of flows across the anabranches. Other studies have shown that large earthworks in low gradient rivers with wide floodplains cause a discontinuity in the floodplain and a loss of anabranches (Steinfeld and Kingsford, 2013). Therefore, the construction of the embanked roadways and bridges is hypothesized to have a negative impact on anastomosis (Fig. 6).

3.2.3.2. Timber rafting. The River Narew was the main river used for rafting timber from the Białowieża forest to other parts of the country (first reference reported in 1447 in royal chronicles, Chętnik, 1935). Timber was rafted on the River Narew for most of the year. Historical publications state clearly that the rafting season was closed only for a few weeks in winter because of ice jams. Within the NNP, where the stream network consisted of many splitting and rejoining channels, timber rafters often faced the problem of sandbars, especially at the channel junctions. This required the local deepening of anabranch inlets by rafters using hand tools or the placement of rafts at both sides of the channel to narrow flow and induce scour (Chętnik, 1935). By removing sediment accumulations, rafters would have reduced the likelihood of inlet closure for the smaller anabranches. As such, timber rafting is hypothesized to have a positive influence on the maintenance of anastomosis, but was abandoned officially after 2nd World War around 1950 (Fig. 7).

3.2.3.3. Fishing dams. In the past, fishing was one of the main professions for the population living in the area. Among the many fishing techniques of the time, one of the most popular was the fishing dam. Small wooden dowels were struck into the river bed and braided with wicker, leaving a hole, called a “window”, with a trap attached to its end. Beside their main purpose of catching fish, these structures cause a local impoundment effect that would have affected the distribution of water flowing to anabranches, and even activating smaller channels overgrown with vegetation. Although these structures were technically forbidden because of their impacts on boating and timber rafting, Gloger (1881) indicated that dams were the most common fishing technique in the region and over 100 fishing dams could be found in a 10 km stretch. The large number of fishing dams in the area had a significant impact on flooding in the NNP; spring floods are reported to have lasted longer,

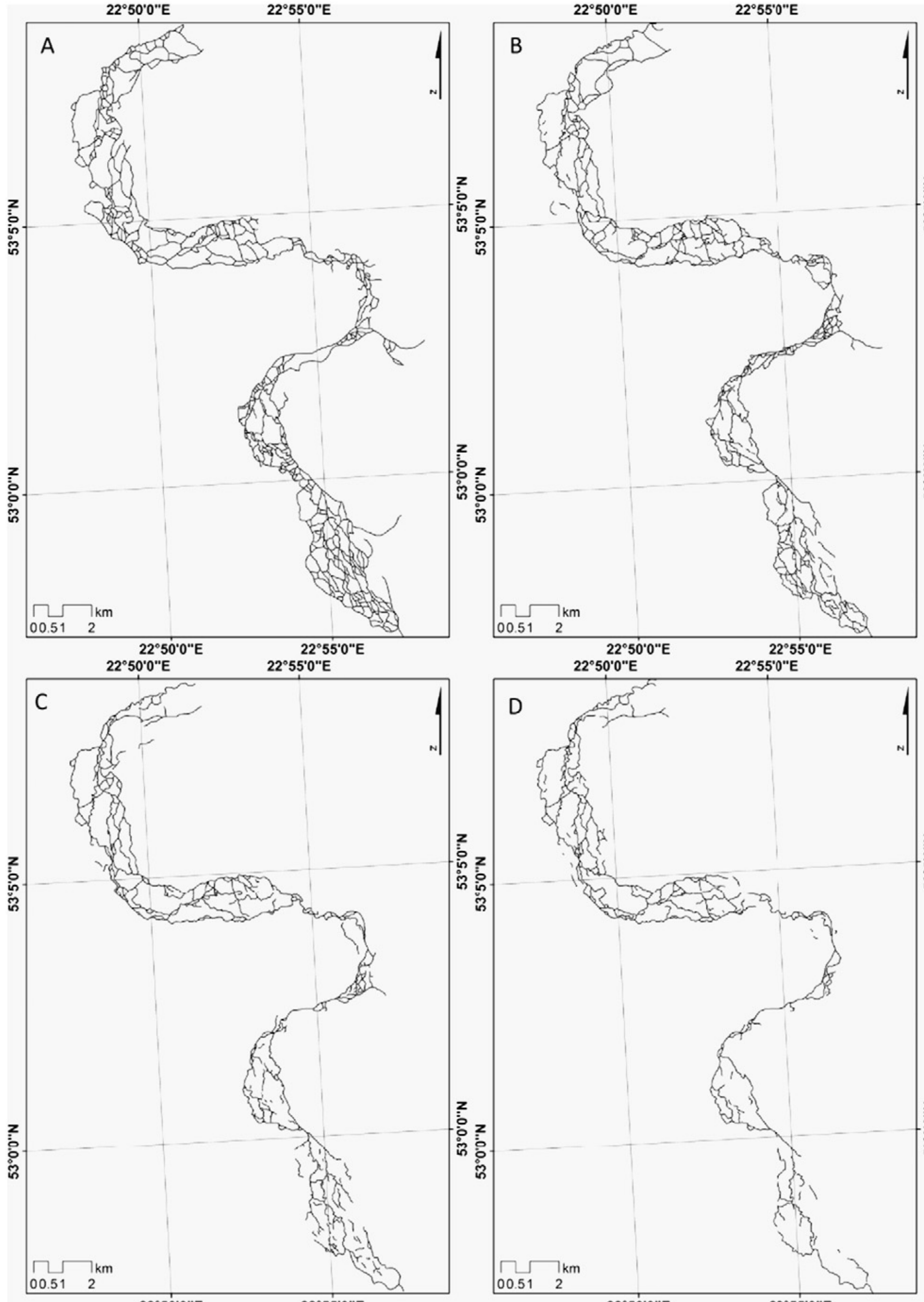


Fig. 2. Changes in the channel network of the River Narew in the Narew National Park over time: (A) 1900, (B) 1966, (C) 1997, and (D) 2012.

sometimes as late as June, when fishing dams were in use (Chętnik, 1911; Gloger, 1881). This way of fishing was completely abandoned before World War II, perhaps around 1930, and now only a few wooden dowels remain in parts of the river as evidence of their existence. Because of the increases in water levels they caused, fishing dams are hypothesized to have a positive influence on anastomosis (Fig. 7).

3.2.3.4. Water mills. Water mills were once found along the main channel of the River Narew (Chętnik, 1914). It was easy to redirect the flow between the multiple low energy channels, which was a considerable advantage from a milling perspective. The mill weir produced a damming effect on the main channel and a constant redirection of water to anabranches upstream of the mill. The higher water flows in the

Table 1
Descriptive statistics of planform evolution in the River Narew, Narew National Park.

Year	Mean width [m] (main channel)	Mean width [m] (anabranches)	Share of main ch. width in tot. width	Anabranching index	Length [km]	Loss of stream/year [km]
1900	No data	No data	No data	5.54	274.7	
1966	22.9	51.3	31%	4.81	239.8	0.53
1997	24.1	31.4	43%	4.05	194.1	1.45
2012	24.6	16	61%	3.08	160.2	2.26

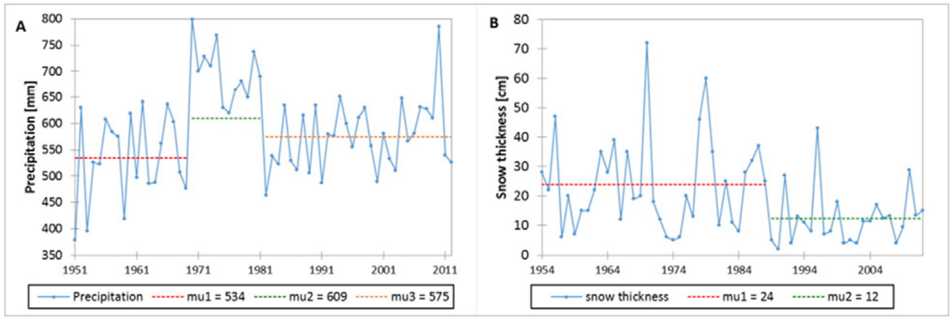


Fig. 3. Changes in (A) mean annual precipitation and (B) snow thickness over time. Mu represents the average value per period.

anabranches would have prevented the encroachment of vegetation that could have facilitated their gradual closure. Lewin (2010) argues that even newly created channels would have persisted in lowland floodplains, as most of the low-flow summer discharge could have been diverted into the anabranches by temporarily damming other anabranches or the main channel. Thus multiple anabranches could have been maintained or widened through mill weirs and the associated selective temporary damming of channels. Therefore, similar to the effect of wicker dams for fishing, water mills in the NNP would have raised water levels and redirected flow across the floodplain, and are hypothesized to have had a positive influence on anastomosis. The last two water mills in the NNP were destroyed during World War II, around 1940, and it is hypothesized that the cessation of water milling would have caused a gradual concentration of flow into the main channel at the expense of anabranches (Fig. 7).

3.2.3.5. Seasonal mowing. In the past, the floodplain was covered predominately with sedges that were seasonally mown to provide roofing material. The regular maintenance prevented the expansion of shrubs and forests, which would have naturally succeeded sedges and grass in this climate and setting (Banaszuk et al., 2004; Próchnicki, 2005). Following cessation of mowing in the 1980s, common reed (*Phragmites australis*) has expanded its distribution in the NNP (Próchnicki, 2005; Banaszuk and Kamocki, 2008). It is a large, perennial grass with the widest geographical distribution of any flowering plant (Kettenring et al., 2011). It is native to Europe and is not considered invasive, though its distribution is believed to have increased, particularly in wet grasslands where grazing pressure has been reduced. The expansion of *P. australis* is a concern for conservationists due to the associated decrease in species richness associated with reed beds. *P. australis* is a very efficient colonizer because it seeds profusely and spreads by a vigorous system of rhizomes and stolons (Best et al., 1981). In addition, *P. australis* has a physiological adaptation that enables it to inhabit a broad range of the aquatic terrestrial ecotone; aerenchyma (tissue responsible for internal gas exchange) is abundant in the stems, rhizomes, and roots and, hence, the grass has a much more efficient pathway for providing oxygen to its underground structures than any other emergent marsh vegetation. These features facilitate considerably the ability of *P. australis* to colonize anabranches of the anastomosing system. The cessation of mowing, combined with lower water levels, has favored reed growth and expansion. Próchnicki (2005) reports that 35% of the NNP is covered in *P. australis*, an increase from a historical cover of

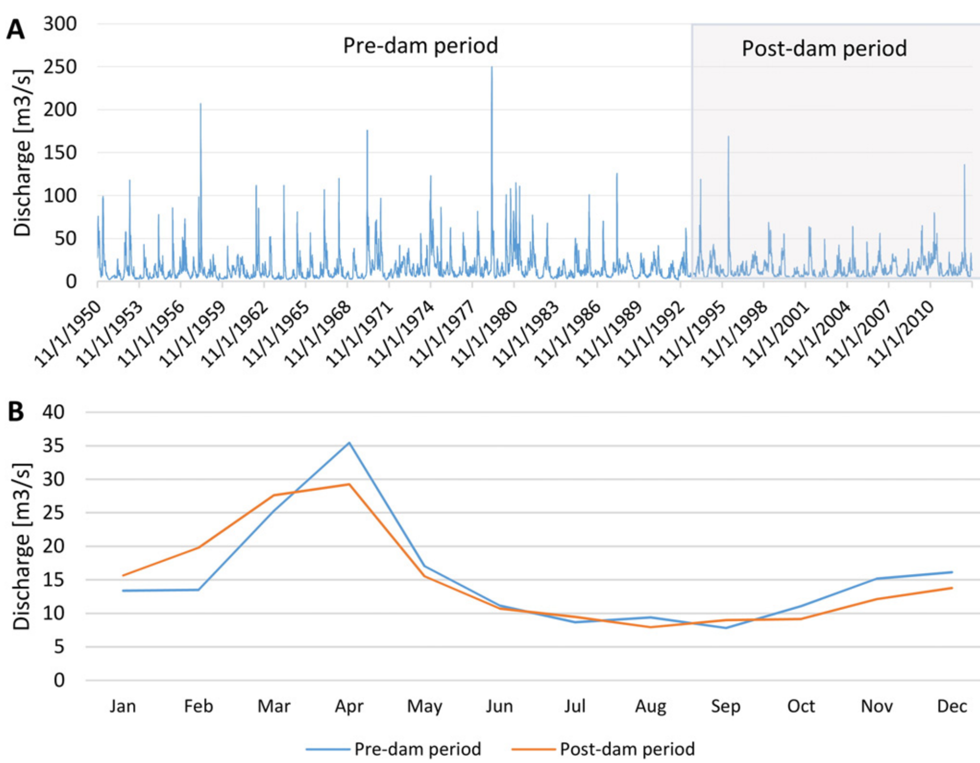


Fig. 4. Flow regime of the River Narew at the Suraż gauging station: (A) average daily discharge and (B) median monthly discharge.

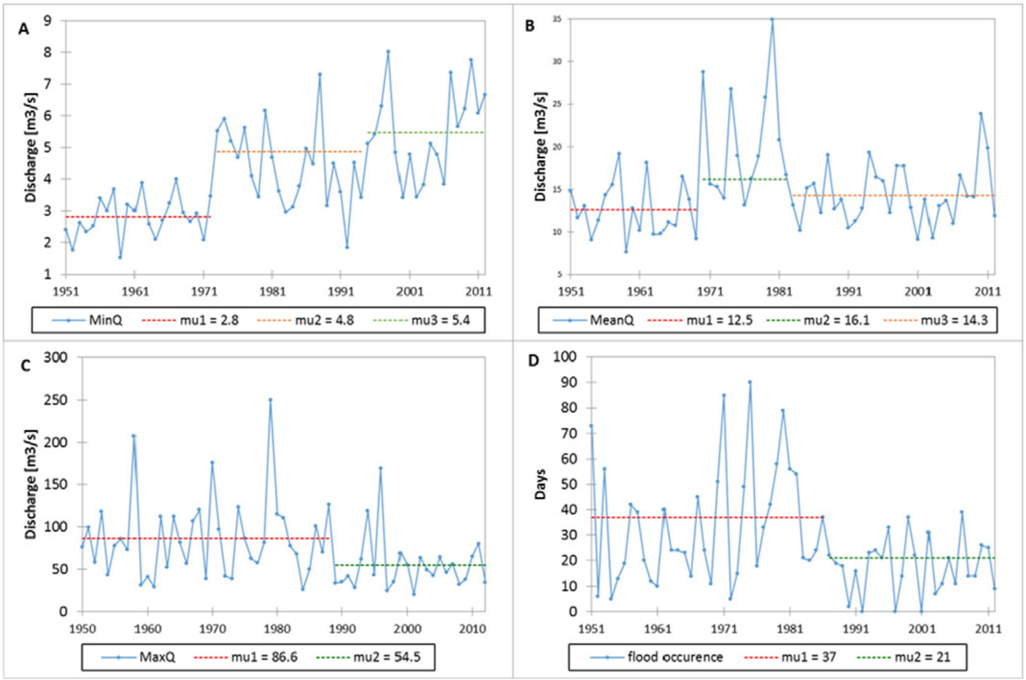


Fig. 5. River discharge variations over time for the River Narew at the Suraż gauging station: (A) minimum annual flow for each period, (B) average annual flow, (C) maximum annual flow, and (D) number of flooding days. Mu represents the average value per time period.

10%. Moreover, *P. australis* lines over 73% of the banks of the stream network and is found growing in shallow anabranches, most likely establishing during low water stages. Anecdotal evidence from park rangers and aerial imagery suggests that the vegetation leads to anabranch blockages and eventual extinction. Consequently, seasonal mowing of the floodplain is hypothesized to have had a positive influence on anastomosis through its suppression of reed growth and expansion (Fig. 7). Mowing was partly reintroduced in the NNP in 2010.

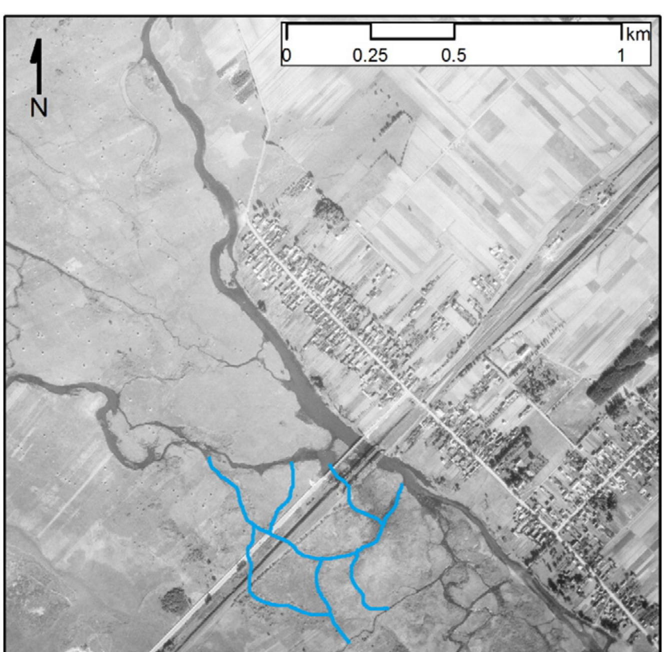


Fig. 6. Aerial photograph of the bridge at the upstream NNP boundary (1966). Blue line represents the historical river planform before channel burial.

3.2.3.6. Reservoir. As stated in the methods, a dam was constructed on the River Narew in the upper catchment in 1992, creating the Siemianówka reservoir. The geomorphological impacts of dams have been well-studied; the alterations in flow and sediment supply caused by dams significantly affect downstream reaches (Zahar et al., 2008; Chen et al., 2010; Fu et al., 2010). The reservoir and dam have multiple purposes: (1) local tourism and recreation, (2) energy production, (3) flood protection, and (4) fishing (Mioduszewski, 1999). According to the reservoir management instructions (BIPROMEL, 1999), high flows during the spring thaw must be mitigated to reduce flood risk in the valley, while low flows during the summer months must be sufficient high to maintain biological life. Environmental flow limits (i.e. the minimum discharge in a river) are regulated nationally in Poland, and thus are in effect on the River Narew. Water stored over the winter is released in the spring, but only for ca. 20 days with a maximum discharge of 60 m^3/s, which is significantly lower than historical floods that occurred during the spring thaw.

As shown in Figs. 4 and 5, the dam affected the water regime significantly, with a decrease in peak annual discharge, a decrease in the number of inundation days, and an increase in minimum monthly discharge. The decrease in peak annual discharges and inundation days is hypothesized to have a negative impact on anastomosis by decreasing overbank flooding and avulsions, and reducing stream power, sediment transport, and the removal of sediment and vegetation patches within anabranches (Fig. 7; Smith et al., 2016). The small increase in baseflow in summer is hypothesized to have a minimal impact on anastomosis, and is not presented in Fig. 7.

3.2.3.7. Channel realignment. Finally, a significant change in channel planform downstream of the NNP may have had an impact on anastomosis. In 1970, a channel realignment and land reclamation project was undertaken on a ca. 50 km long stretch of the River Narew. The purpose of this work was to expand the agricultural use of the floodplain by changing the multi-channel planform into a single-channel (Banaszuk et al., 2004). The river straightening increased the channel gradient, accelerating the flow of water out of the NNP and lowering water levels within, decreasing flood extent magnitude and duration. As such, the channel realignment is hypothesized to have had a negative impact on

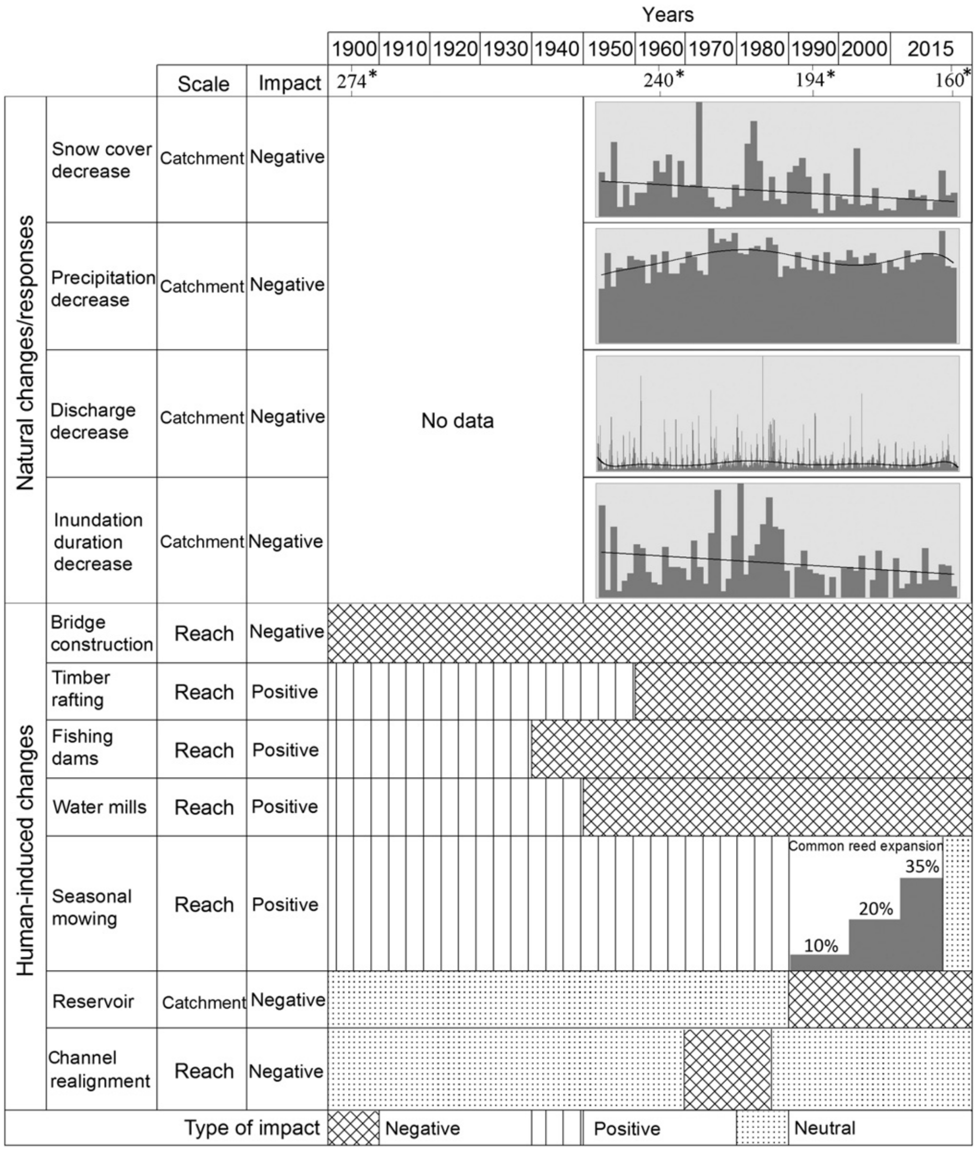


Fig. 7. A chronology of channel change, represented by total channel length* (km), and natural and anthropogenic factors that may be driving anabranch loss in the Narew National Park.

anastomosis (Fig. 7); however, a weir was constructed at the downstream end of the NNP in 1985 to mitigate against the negative consequences of channel realignment.

4. Discussion

This study investigated the natural and anthropogenic mechanisms that create and maintain multiple river channels in lowland anastomosing rivers. Following a hierarchical approach to hydro-geomorphological assessment, analyses were conducted at different spatial scales (reach and catchment) on one of the last remaining anastomosing rivers of Europe, the River Narew. Through a combination of land cover mapping, analysis of channel planform change from historical maps and aerial photos, flow regime analysis, and a catalogue of human activities, the study found several likely mechanisms for anabranch loss. While precipitation has varied over the last half century, suggesting potential natural and indirect anthropogenic (i.e. climate change) contributing factors, the most substantial influences on anabranch formation and maintenance are related to direct management of the river network. In particular, this study found that there are five possible anthropogenic factors that continue to disrupt anabranch creation and maintenance processes resulting in ongoing anabranch loss: construction of embanked roadways across the floodplain, cessation of timber rafting, cessation of localized damming activities (fishing dams and water mills), cessation of seasonal mowing, and reservoir construction and operation.

4.1. Extinction causes

A locally persistent anastomosing planform requires that either anabranch formation through avulsions is active or anabranch loss suppressed (Makaske, 2001). In the NNP, the substantial loss of anabranches over the last 100 years (110 km, Fig. 2) provides strong evidence that neither of these are happening in an appreciable manner. No substantial new anabranches have formed, and the number (and overall width) of anabranches has declined at an increasing rate (Table 1). Of the four mechanisms proposed by Kleinhans et al. (2012) to control anastomose formation, only three are relevant to the River Narew: a rise in downstream base level, high sediment inputs from upstream, and the increased flow efficiency of multiple channels. Mechanisms that suppress anabranch loss could be considered to be the contrary of these mechanisms, and would also include factors that drive geomorphic change more generally, such as high river discharges. In this section, we explore the likelihood that natural and anthropogenic factors, individually and in combination, are inhibiting the maintenance of the anastomose pattern in the NPP by considering their impact on water levels, flow efficiency, sediment loads and geomorphological-relevant flows.

The chronology of natural and anthropogenic changes in the River Narew suggests that multiple factors are responsible for the loss in anabranches (Fig. 7). However, the evidence does not suggest that natural or indirect anthropogenic changes (i.e. climate change) in the hydrological regime are contributing. Generally, the increase in precipitation seen over the period of record should promote greater river flows and higher water levels, but the decrease in snow cover should reduce the peak annual flood magnitude that typically occurs during the spring thaw (Fig. 3). Yet, maximum annual flows and days of inundation are unchanged until 1992 when the dam was constructed (Fig. 5). Therefore, the discussion will focus on direct anthropogenic factors.

To facilitate the interpretation of anthropogenic and channel anastomosis changes in the NNP, a simplified chronology was produced to summarize the positive and negative influences of direct anthropogenic factors for the time periods of the historical map analysis (Fig. 8). In the first time period (1900 to 1966), bridge construction had the earliest and most immediate impact on the continuity of anabranches (i.e. decrease in flow efficiency) and flooding (i.e. localized decreased extent and frequency of overtopping). Towards the end of this period, timber rafting, dam fishing and water milling ceased to take place in the NNP. The removal of these activities from the floodplain would have reduced water levels and the frequency and extent of overtopping, both of which would have suppressed anabranch formation by avulsion. The cessation of direct channel maintenance by timber rafters would have reduced the redirection of flow into anabranches, decreasing flow rates that would have mobilized sediment and reduced the potential for vegetation encroachment. The anabranch extinction rate over this period was 0.53 km/year. While we do not have cartographic evidence to document the impact of bridge construction alone, the slow rates of change predicted in the low-gradient river would suggest that the impacts of timber rafting, dam fishing and water milling would be lagged in time, with a more pronounced impact in the second time period.

In the second time period, channel realignment downstream of the NNP would have accelerated anabranch loss, by further reducing water levels and the frequency and duration of flooding (Fig. 8). Furthermore, seasonal mowing, which had controlled the expansion of common reed, ceased in the 1980s. During low water stages, reed colonizes anabranches, slowing water flows and trapping sediment, which leads to a permanent blockage of the anabranch in only a few seasons (Jones et al., 2012; Rooth et al., 2003). Interestingly, the process of vegetation encroachment appears to be initiated at the inlets to anabranches where flow velocity rapidly decreases compared with the main channel and there is often an accumulation of bed sediment (Fig. 9). The newly established vegetation impedes flow from entering the anabranch, reducing the flow efficiency of the anabranch and providing ideal conditions for further vegetation growth along its length (Tal and Paola, 2010). The rate of anabranch loss increased to 1.45 km/year in this period.

In the most recent time period, negative pressures on anastomose maintenance increased generally with the construction of the Siemianówka reservoir and the further expansion of reed. The dam reduced peak flows, decreasing the frequency and magnitude of flood events and the number of days of flooding (Figs. 4 and 5). This alteration to the flow regime decreased the likelihood of new anabranches forming by avulsion, and would have decreased stream power that would have mobilized the bed sediment and flushed fine sediment and vegetation. The large upstream reservoir would have also reduced bedload inputs to the NNP. If the river and floodplain in the NNP was previously aggrading by bed material, this might cause the cessation of anastomosis alone. However, there is no evidence that channels were aggrading prior to dam construction; the lowland low energy river has no significant sources of bed material, and floodplain aggradation is primarily by deposition of organic material from the floodplain vegetation and fine sediment from overbank flooding. While sediment supply is unlikely to be a factor, further research should investigate the possibility. Changes that promote channel anastomosis have occurred during this period as well. The impact of channel realignment was reduced with the construction of a weir at the downstream end of the NNP in 1995, and seasonal mowing was resumed in 2010. However, this period had a large number of pressures acting to suppress anabranch formation and facilitate loss, and anabranch extinction rates increased further to 2.26 km/year (Fig. 8).

The process-based assessment approach used in the study allows the generalization of pressures and their impacts on anastomosis in the NNP. Analysis of the cause-effect relationships presented in the previous section suggests that numerous factors interact to reduce the probability of anabranch formation and increase the likelihood of anabranch loss. While natural anabranch formation via avulsion is suppressed with lower water levels, anabranch loss appears to be accelerated greatly by lower water levels, decreased high flows, and vegetation encroachment in the river channels (Fig. 10). The process of anabranch extinction appears to start at the inlets to anabranches where bed sediment deposits naturally (Fig. 9). Most riverbanks in the NNP are now lined with reed (75%; Próchnicki, 2005) which can extend laterally from the floodplain into the channel and root into sediment deposits

Factor		1900–1966	1966–1997	1997–2012
Construction of Bridges		↓	↓	↓
Construction of reservoir		---	---	↓
Channel maintenance by human	Water damming	↑	↓	↓
	Mowing and dredging	↑	↓	↓
Seasonal mowing of floodplain		↑	↓	↓
Channel realignment		---	↓	---
Summary		↑↑	↓↓↓↓↓	↓↓↓↓↓
Actual extinction pace (km/year)		0.53	1.45	2.26

(↑ - channel maintenance, --- -no influence, ↓ – channel extinction)

Fig. 8. Cumulative impacts of anthropogenic changes on anastomosis in the Narew National Park. Note: water damming includes fishing dams and water mills, and mowing and dredging relate to the management of channel vegetation and sediment for timber rafting.

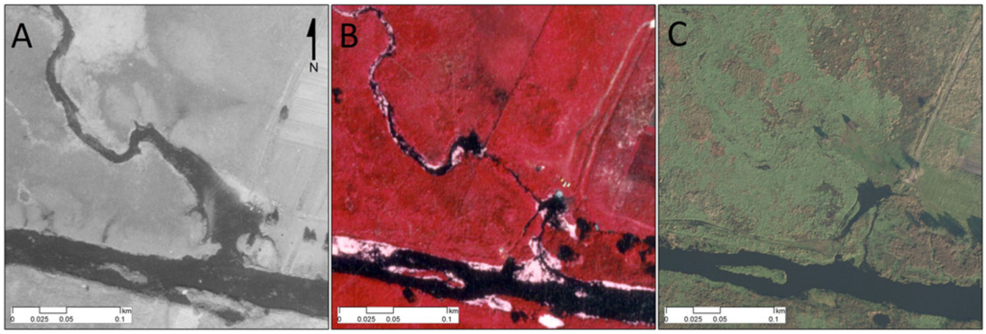


Fig. 9. Evidence of anabranch loss initiated by inlet closure, from remote sensing imagery: (A) 1966, (B) 1997, and (C) 2012. (Data sources: CODGIK, NNP, Google Earth).

(Best et al., 1981). The aquatic vegetation blocks the channel physically and increases flow resistance (Nepf et al., 2007; Gibbs et al., 2014; Gurnell, 2014). This in turn results in turbulent energy dissipation, creating zones of low velocity and low bed shear stress that encourages deposition of fine organic and inorganic particles. The geomorphic impacts of aquatic vegetation in lowland rivers have been shown in several recent studies, in which vegetation encroachment and fine sediment deposition lead to channel narrowing and an increase in sinuosity (Gurnell et al., 2016b; Gurnell and Grabowski, 2016). In the NNP, though, the story is slightly different. Low water levels facilitate sediment deposition and the colonization of reed, and reduced high river flows minimize sediment and vegetation mobilization. This process of vegetation encroachment and sedimentation reduces flow efficiency in the anabranches and results in the eventual closure of the inlet, at which time the anabranch becomes effectively a long backwater that only receives flow (and fine sediment) during periods of flooding (Fig. 9B). This in turn creates perfect conditions for further reed colonization (Jones et al., 2012). After a few years, the former anabranch is overgrown by reeds and disappears completely (Fig. 9C). The importance of reed in the extinction process is highlighted by the accelerated anabranch extinction rates since reed has expanded in the floodplain, however the other anthropogenic factors also contribute to the expansion of reed beds and extinction of anabranches.

4.2. Evolutionary trajectory

The temporal analysis of river response to changing conditions at both catchment and reach scales (Figs. 7 and 8) allows a prediction of possible trajectories of future river channel change. At present, the anastomosing planform of the River Narew in the NNP is protected primarily by a list of restrictions on activities within the borders of the national park, with the expectation that natural hydro-geomorphic processes will maintain anabranches. However, given the lower water levels and decreased frequency of flood inundation in the park, it is highly unlikely that new anabranches will form via avulsion. The loss of anabranches in the NNP is effectively irreversible under the current boundary conditions. Furthermore, the hands-off approach to direct channel management will likely result in a further loss of anabranches via reed expansion and sedimentation, switching the river from a multi- to single-thread river in the coming decades. The park authorities have recently restarted seasonal mowing to suppress reed and encourage sedge growth, but this is only done in limited areas of the park.

As the River Narew is protected specifically for its planform and wetland habitat, more active management of water levels and vegetation is needed in the NNP. The anastomosing planform was invariably created through natural processes, but it has been developed and preserved through a long history of human use and modification of the river system. To prevent further loss of anabranches, process-based preservation of form should be prioritized, not only for their geomorphological importance but to actively preserve the species rich wet grasslands. We would argue that the best starting point for solutions is to propose measures that disrupt the anabranch extinction pathways shown in Fig. 10, and encourage the activation of recently abandoned anabranches.

Numerous process-based solutions can be envisioned and a sensible course of action is to pursue multiple complementary measures to address different anabranch extinction pathways (Fig. 10). Some measures would benefit the system more widely. For example, the renaturalization

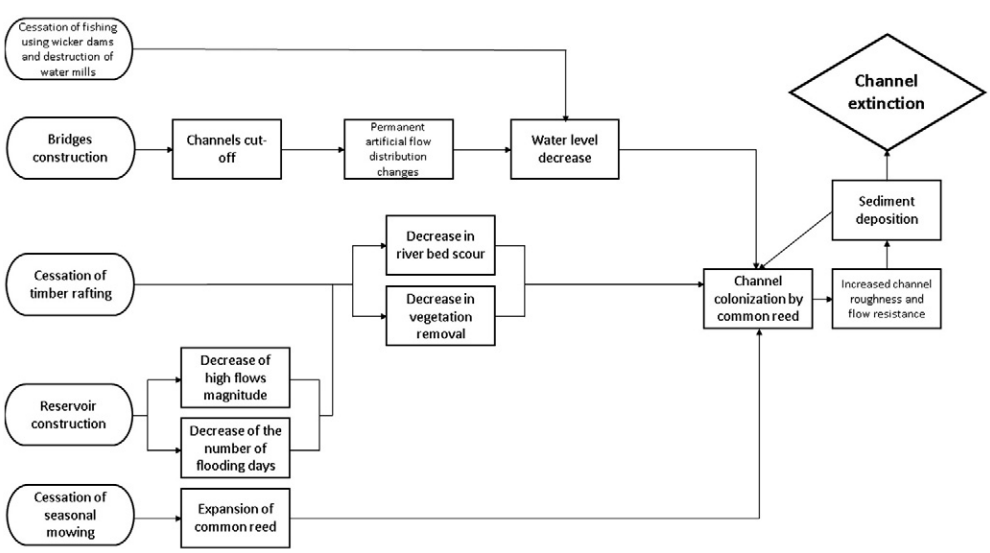


Fig. 10. Cause-effect relationships of the anthropogenic factors and mechanisms of channel extinction.

of dam flows would increase water levels and discharges during the peak flow period of the spring thaw (Poff and Schmidt, 2016). This solution would have the most widespread impact, but must be considered along with measures to ensure that the multiple functions of the reservoir are not impacted (e.g. flood risk does not increase for communities near the river and reservoir). Localized actions in the NNP may be equally effective at promoting anabranch formation and maintenance, and have less potential negative impact on neighboring communities. Culverts could be placed within the road embankments, vegetation removed from anabranch inlets, and small dams or woody debris structures used to locally increase water levels and divert flows. To make the process more cost-effective and sustainable, trees could be allowed to grow around inlets. This would ensure a long-term supply of large woody debris to act as jams and dams that would locally increase water levels, activating side channels and promoting avulsions (Wohl, 2017). If this was done in combination with more widespread mowing, then reeds would be suppressed, sedge growth encouraged, and the overall character and conservation value of the NNP would be preserved.

5. Conclusion

This study found that the River Narew in the Narew National Park is increasingly losing the anastomosing pattern for which it is protected. Using a process-based hydro-geomorphological assessment method and a range of data sources, the study documented the rate of anabranch loss and related it to natural and anthropogenic factors operating at the reach and catchment scales. The cessation of traditional channel and land management activities and the construction of infrastructure in the park and further upstream resulted in lower water levels and reduced high river flows, and created favorable conditions for vegetation encroachment of the anabranches. The current approach to habitat conservation in the park is unlikely to prevent further anabranch loss, and the results of the process-based assessment were used to propose management solutions that will preserve the unique anastomosing river pattern and diverse wet grasslands that are fundamental to the park's conservation value. Moreover, the examination of factors responsible for the loss of anabranches on the River Narew provides new evidence on the mechanisms of anabranch formation and maintenance in lowland rivers. The study demonstrates the importance of high water levels to drive avulsions and maintain flows in anabranches, as well as the significant interactions between water levels, sediment deposition, and vegetation encroachment that determine flow efficiency and control anabranch loss.

Acknowledgments

We would like to thank two anonymous reviewers their comments and suggestions which helped to improve the manuscript. This paper is a product of research conducted within the REFORM collaborative project funded by the European Union Seventh Framework Programme under grant agreement 282656. Part of the research was financed by the National Science Centre, Poland under grant agreement 2015/19/N/ST10/01629.

References

Banaszuk, P., Kamocki, A., 2008. Effects of climatic fluctuations and land-use changes on the hydrology of temperate fluviogenous mire. Ecol. Eng. 32:133–146. http://dx.doi.org/10.1016/j.ecoleng.2007.10.002.

Banaszuk, H., Banaszuk, P., Gradziński, R., Kamocki, A.K., Mioduszewski, W., Okruszko, T., Próchnicki, P., Szewczyk, M., 2004. Przyroda Podlasia: Narwiański Park Narodowy. [Nature of Podlasie: Narew National Park] (Białystok: Narwiański Park Narodowy).

Best, E.P.H., Zippin, M., Dassen, J.H.A., 1981. Growth and production of *Phragmites australis* in Lake Vechten (The Netherlands). Hydrobiol. Bull. 15 (3), 165–174 (Netherlands Hydrobiological Society).

BIPROMEL, 1999. Siemianówka reservoir – water management rules. Technical Report. Bipromel, Warszawa.

Blamauer, B., Belletti, B., García De Jalón, D., González Del Tánago, M., Grabowski, R.C., Gurnell, A.M., Habersack, H., Klösch, M., Marcinkowski, P., Martínez-Fernández, V., Nardi, L., Okruszko, T., Rinaldi, M., 2014. Catchment Case Studies: Full Applications of the Hierarchical Multi-scale Framework. Deliverable 2.1, Part 3, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative Project (Large-scale Integrating Project) Funded by the European Commission Within the 7th Framework Programme Under Grant Agreement 282656.

Carling, P., Jansen, J., Meshkova, L., 2014. Multichannel rivers: their definition and classification. Earth Surf. Process. Landf. 39:26–37. http://dx.doi.org/10.1002/esp.3419.

Chen, Z.Y., Wang, Z.H., Finlayson, B., Chen, J., Yin, D.W., 2010. Implications of flow control by the Three Gorges Dam on sediment and channel dynamics of the middle Yangtze (Changjiang) River, China. Geology 38, 1043–1046.

Chętnik, A., 1911. Ziemia [Earth]. Polskie Towarzystwo Krajoznawcze. Year 2 No3 36–39.

Chętnik, A., 1914. Ziemia [Earth]. Polskie Towarzystwo Krajoznawcze. Year 5 No3 39–42.

Chętnik, A., 1935. Spław na Narwi [Rafting on Narew]. Wydawnictwo Kasy im. Mianowskiego, Warszawa.

Downs, P.W., Dusterhoff, S.R., Sears, W.A., 2013. Reach-scale channel sensitivity to multiple human activities and natural events: lower Santa Clara River, California, USA. Geomorphology 189, 121–134 (1 May 2013).

Ettema, R., Muste, M., 2001. Laboratory observations of ice jams in channel confluences. J. Cold Reg. Eng. 15, 34–58.

Fryirs, K.A., Brierley, G.J., 2013. Geomorphic Analysis of River Systems: An Approach to Reading the Landscape. Wiley-Blackwell.

Fu, B., Wu, B.F., Lu, Y.H., Xu, Z.H., Cao, J.H., Niu, D., Yang, G.S., Zhou, Y.M., 2010. Three Gorges project: efforts and challenges for the environment. Prog. Phys. Geogr. 34, 741–754.

Gibbs, H.M., Gurnell, A.M., Heppell, C.M., Spencer, K.L., 2014. The role of vegetation in the retention of fine sediment and associated metal contaminants in London's rivers. Earth Surf. Process. Landf. 39:1115–1127. http://dx.doi.org/10.1002/esp.3575.

Gloger, Z., 1881. Wędrowiec [Traveller] (Warszawa).

Grabowski, R.C., Gurnell, A.M., 2016a. Using historical data in fluvial geomorphology. In: Kondolf, G.M., Piegay, H. (Eds.), Tools in Fluvial Geomorphology. J. Wiley, pp. 56–74.

Grabowski, R.C., Gurnell, A.M., 2016b. Diagnosing problems of fine sediment delivery and transfer in a lowland catchment. Aquat. Sci. 78:95–106. http://dx.doi.org/10.1007/s00027-015-0426-3.

Gradziński, R., Baryła, J., Doktor, M., Gmur, D., Gradziński, M., Kędzior, A., Paszkowski, M., Soja, R., Zieliński, T., Żurek, S., 2003. Vegetation-controlled modern anastomosing system of the upper Narew River (NE Poland) and its sediments. Sediment. Geol. 157 (3):253–276. http://dx.doi.org/10.1016/S0037-0738(02)00236-1.

Gurnell, A., 2014. Plants as river system engineers: further comments. Earth Surf. Process. Landf. 40:135–137. http://dx.doi.org/10.1002/esp.3671.

Gurnell, A.M., Grabowski, R.C., 2016. Vegetation–hydrogeomorphology interactions in a low-energy, human-impacted river. River Res. Appl. 32:202–215. http://dx.doi.org/10.1002/rra.2922.

Gurnell, A.M., Corenblit, D., García de Jalón, D., González del Tánago, M., Grabowski, R.C., O'Hare, M.T., Szewczyk, M., 2016a. A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. River Res. Appl. 32: 142–163. http://dx.doi.org/10.1002/rra.2928.

Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, T., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García de Jalón, D., González del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A.J., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016b. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat. Sci. 78:1. http://dx.doi.org/10.1007/s00027-015-0424-5.

Johnson, S.E., Amatangelo, K.K., Townsend, P.A., Waller, D.M., 2016. Large, connected floodplain forests prone to flooding best sustain plant diversity. Ecology 97 (11): 3019–3030. http://dx.doi.org/10.1002/ecy.1556.

Jones, J.I., Collins, A.L., Nadenc, P.S., Seard, D.A., 2012. The relationship between fine sediment and macrophytes in rivers. River Res. Appl. 28, 1006–1018.

Kettenring, K.M., McCormick, M.K., Baron, H.M., Whigham, D.F., 2011. Mechanisms of *Phragmites australis* invasion: feedbacks among genetic diversity, nutrients, and sexual reproduction. J. Appl. Ecol. 2011 (48), 1305–1313.

Kingsford, R.T., Basset, A., Jackson, L., 2016. Wetlands: conservation's poor cousins. Aquat. Conserv. Mar. Freshwat. Ecosyst. 26:892–916. http://dx.doi.org/10.1002/aqc.2709.

Kleinhans, M.G., de Haas, T., Lavooi, E., Makaske, B., 2012. Evaluating competing hypotheses for the origin and dynamics of river anastomosis. Earth Surf. Process. Landf. 37: 1337–1351. http://dx.doi.org/10.1002/esp.3282.

Lewin, J., 2010. Medieval environmental impacts and feedbacks: the lowland floodplains of England and Wales. Geoarchaeology 25:267–311. http://dx.doi.org/10.1002/Gea.20308.

Makaske, B., 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth Sci. Rev. 53, 149–196.

Makaske, B., Lavooi, E., de Haas, T., Kleinhans, M.G., Smith, D.G., 2017. Upstream control of river anastomosis by sediment overloading, upper Columbia River, British Columbia, Canada. Sedimentology. http://dx.doi.org/10.1111/sed.12361.

McCarthy, T.S., Ellery, W.N., Stanistreet, I.G., 1992. Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. Sedimentology 39, 779–795.

Mioduszewski, W., 1999. Monography of the Siemianówka water reservoir. WZMiUW Białystok.

Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology 4, 459–486.

Nanson, G.C., Huang, H.Q., 1999. Anabranching rivers: divided efficiency leading to fluvial diversity. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form, pp. 477–494.

Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: their cause. Character and classification. Earth Surf. Process. Landf. 21, 217–239.

Nepf, H., Ghisalberti, M., White, B., Murphy, E., 2007. Retention time and dispersion associated with submerged aquatic canopies. Water Resour. Res. 43:10. http://dx.doi.org/10.1029/2006wr005362.

Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. Appl. Stat. 28, 126–135.
Poff, N.L., Schmidt, J.C., 2016. How dams can go with the flow. Science 353 (6304): 1099–1100. http://dx.doi.org/10.1126/science.aah4926.
Próchnicki, P., 2005. The expansion of common reed (*Phragmites australis* (cav.) trin. ex steud.) in the anastomosing river valley after cessation of agriculture use (narew river valley, NE Poland). Pol. J. Ecol. 53, 353–364.
Rooth, J.E., Stevenson, J.C., Cornwell, J.C., 2003. Increased sediment accretion rates following invasion by *Phragmites australis*: the role of litter. Estuaries 26 (2B), 475–483.
Schumann, R.R., 1989. Morphology of Red Creek, Wyoming, an arid-region anastomosing channel system. Earth Surf. Process. Landf. 14, 277–288.
Smith, D.G., Smith, N.D., 1980. Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta. J. Sediment. Petrol. 50, 157–164.
Smith, N.D., Cross, T.A., Dufficy, J., Clough, S.R., 1989. Anatomy of avulsion. Sedimentology 36, 1–23.
Smith, N.D., Morozova, G.S., Pérez-Arlucea, M., Gibling, M.R., 2016. Dam-induced and natural channel changes in the Saskatchewan River below the E.B. Campbell Dam, Canada. Geomorphology 269:186–202. http://dx.doi.org/10.1016/j.geomorph.2016.06.041.
Steinfeld, C.M.M., Kingsford, R.T., 2013. Disconnecting the floodplain: earthworks and their ecological effect on a dryland floodplain in the Murray–Darling basin, Australia. River Res. Appl. 29, 206–218.
Tal, M., Paola, C., 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. Earth Surf. Process. Landf. 35, 1014–1028.
Tockner, K., Stanford, J.a., 2002. Riverine flood plains: present state and future trends. Environ. Conserv. 29:308–330. http://dx.doi.org/10.1017/S037689290200022X.
Tooth, S., Nanson, G.C., 1999. Anabranching rivers on the Northern Plains of arid central Australia. Geomorphology 29, 211–233.
Tooth, S., Nanson, G.C., 2000. The role of vegetation in the formation of anabranching channels in an ephemeral river, Northern Plains, arid central Australia. Hydrol. Process. 14, 3099–3117.
Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319:299–304. http://dx.doi.org/10.1126/science.1151716 (80-.).
Ward, J.V., Tockner, K., Arscott, D.B., Claret, C., 2002. Riverine landscape diversity. Freshw. Biol. 47:517–539. http://dx.doi.org/10.1046/j.1365-2427.2002.00893.x.
Wohl, E., 2017. Bridging the gaps: an overview of wood across time and space in diverse rivers. Geomorphology 279:3–26. http://dx.doi.org/10.1016/j.geomorph.2016.04.014.
Zahar, Y., Ghorbel, A., Albergel, G., 2008. Impacts of large dams on downstream flow conditions of rivers: aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). J. Hydrol. 351 (2008), 318–330.