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Original Research

Estimation of Environmental Flows in Semi-Natural Lowland Rivers – the Narew Basin Case Study

Mikołaj Piniewski[1]*, Michael C. Acreman[2], Charles J. Stratford[2], Tomasz Okruszko[1], Marek Giełczewski[1], Mariusz Teodorowicz[3], Marek Rycharski[4], Zuzanna Oświecimska-Piasko[4]

[1]Department of Hydraulic Engineering, Warsaw University of Life Sciences, Nowoursynowska 159, 02-787 Warszawa, Poland
[2]Centre for Ecology and Hydrology, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, United Kingdom
[3]Department of Environment Protection Engineering, University of Warmia and Mazury in Olsztyn, Oczapowskiego 5, 10-957 Olsztyn, Poland
[4]Insitute of Technology and Life Sciences, Falenty, Hrabska 3, 05-090 Raszyn, Poland

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Abstract

This paper discusses a new environmental flow method based on the adapted building block approach. A four-step procedure is outlined in this paper:

(1) selecting biota of interest and organizing a team of specialists
(2) selecting river reaches of interest
(3) defining flow requirements of selected biota
(4) defining environmental flow indicators

The focus is placed on two elements of river and wetland ecosystems: fish and floodplain wetland vegetation. The method is applied to identify changes in the environmental flow indicators between 1976-83 ("past") and 2001-08 ("present") in 16 selected river reaches of the Narew basin, a large semi-natural lowland catchment situated in northeastern Poland. The results indicate that hydrological conditions for fish and floodplain wetland vegetation were significantly better in the past period compared to the present.

Keywords: environmental flows, Narew, building block method, fish, floodplain wetlands

Introduction

Achieving environmental flows will be a key measure for restoring and managing river ecosystems for implementation of the Water Framework Directive (WFD) in the European Union [1]. In Poland, the term "environmental flows" is very often understood as a single value, the minimum flow requirement, below which biological life in the river is threatened ("hydrobiological criterion") or fish survival is at risk ("fishing criterion"). Witowski et al. [2] reported that many environmental flow methods used in everyday practice by the Regional Water Management Board in Kraków produced thresholds equal to one half of the absolute minimum flow. These methods disregard the fact that average flows and floods may be crucial for ecosystem health, e.g. effective breeding of numerous fish species. In particular, good status of valuable, protected hydrogenic floodplain habitats is reliant on frequent inun-

*e-mail: mpiniewski@levis.sggw.pl

dation of river water [3]. The recently published National Water Policy Project has identified the lack of data and environmental flow methods relevant to habitats and species requirements as one of the problems of Polish water management [4].

Most of the environmental flows studies reported in the literature [e.g. 5, 6] were carried out on impacted rivers, whereas the Narew River system can be seen as a largely un-impacted system in relation to European standards. It can therefore be considered as a reference condition for catchments of similar physical features under higher levels of human pressure.

Various factors determine the health of a river ecosystem [7] and its ability to deliver ecosystem services. These include discharge (flow), the physical structure of the channel and riparian zone, water quality, channel management - such as macrophyte cutting and dredging, the level of exploitation (e.g. fishing) and the presence of physical barriers to connectivity. The Millennium Ecosystem Assessment [8] showed that many ecosystems were being degraded or lost, with aquatic systems suffering particularly from the withdrawal of water for direct human needs for drinking, growing crops, and supporting industry. The quantity of water required to maintain a river ecosystem in its desired state is referred to as environmental flow (http://www.eflownet.org/). The first environmental flows focused on the concept of a minimum flow level; based on the idea that all river health problems are associated with low flows and that, as long as the flow is kept at or above a critical level, the river ecosystem will be conserved. However, it is increasingly recognised that all elements of a flow regime, including floods, medium, and low flows are important [9-11].

The complexity of natural ecosystems makes it difficult to define thresholds at which the flow regime will maintain a desired river condition [11]. Nevertheless, since the mid-1970s, methods have been developed to define just what the environmental flow for a given river should be. Over 200 different methods have been identified [13], but many are similar and a few broad groups of methods can be defined [13]. Each method has advantages and disadvantages, which make it suitable for a particular set of circumstances. Criteria for method selection include the type of issue (abstraction, dam, run-of-river scheme), the management objective (e.g. pristine or working river), expertise, time and money available, and the legislative framework within which the flows must be set.

The approaches developed in various countries around the world to define environmental flow allocations can be divided into four categories.

(1) Look-up Tables

The most commonly applied method has been the use of rules of thumb based on simple indices given in look-up tables. A hydrological index used in France (Freshwater Fishing Law, June 1984) required that residual flows in bypassed sections of river must be a minimum of 1/40 of the mean flow for existing schemes and 1/10 of the mean flow for new schemes [15]. This was largely based on engineering judgement rather than ecological knowledge. Look-up tables are also well established in Poland [2]. The method now in force in Polish water law, known as the Kostrzewa method [16], enables calculation of in-stream flow values for two criteria: hydrobiological and fishing. In the case of the hydrobiological criterion, the in-stream flow is defined as the mean annual minimum flow times at parameter *k*, whose values can be found from a look-up table and range from 0.5 and 1.52 depending on the basic catchment features. For medium and large lowland catchments, this generally leads to very low thresholds that are exceeded almost all the time.

(2) Desktop Analysis

These methods generally focus on analysis of existing, mainly hydrological data. Rather than focusing on specific species or biological communities, it assumes that some part of the ecosystem is adapted to each flow element; thus all elements are needed to maintain a healthy system. Interesting examples of desktop analysis approach include: the Indicators of Hydrological Alteration [IHA: 3] and the Range of Variability Approach [RVA: 16]. The IHA/RVA method assesses the degree of departure of an impacted flow regime from the natural flow regime that is acceptable, i.e. that still conserves the river ecosystem. The degree of departure is indexed by up to 32 parameters, including magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events), duration (indexed by moving average minima and maxima) and rate of change.

(3) Functional Analysis

This type of method relies on explicit understanding of the functional links between aspects of hydrology and ecology of the river system. Perhaps the best known is the Building Block Methodology (BBM) developed in South Africa [5, 18]; its basic premise is that riverine species are reliant on specific elements (building blocks) of the flow regime. For example, low flows provide nursery areas for small fish with limited swimming capacity, medium flows sort river sediments and stimulate fish migration and spawning), whereas floods maintain channel structure and allow movement of species to the floodplain habitats.

(4) Habitat Modelling

This method recognizes that it is not flow itself that creates the appropriate habitat conditions for different species, but rather the interaction of flow and channel geometry (and in many cases aquatic plants) that creates the required depth and velocity of water needed at different life stages. Research in this field started with the introduction of the concept of weighted usable area by Waters [19] which quickly led to development of a computer model, the Physical Habitat Simulation (PHABSIM) system [20], that uses various hydraulic models to simulate cross-sectional velocities. The physical habitat modelling approach has now been adapted in many countries [21], including France [22] and Norway [23]. It has also been tested by Grela and Stochliński [24] in the Polish Carpathians. The method requires field data collection of cross-section geometry and depths and velocity measurements at three flows and is thus expensive and labour-intensive.

Materials and Methods

Study Area

The Narew basin is situated in northeastern Poland. The study area described in this paper is the part of the basin situated upstream from Zambski Kościelne gauging station, between the meridians of longitude 20º21'E and 24º27'E and between the parallels of latitude 52º35'N and 54º16'N (Fig. 1). It covers ca. 28,000 km^2, 5% of which lies in western Belarus.

The flow regime of the Narew is typical of large lowland floodplain rivers in Central Europe. The peak flows occur during spring snowmelt periods, while the low flows take place usually in late summer. The Narew basin is the core part of the region known as "the Green Lungs of Poland." There are three national parks (ca. 750 km^2), protecting wetland and forest ecosystems, and a number of other protected areas. This region has already been studied as part of previous large-scale integrated modelling activities [25].

Environmental Flow Method

BBM has a detailed manual for implementation [5] that includes a series of structured stages to assess available data and model outputs and to involve a team of professional experts to a consensus on the building blocks of the flow regime. Acreman et al. [6] took the basic BBM concept of linking species/communities to specific elements of the flow regime and adapted it for application of the WFD in the UK (Fig. 2).

The use of the building block approach of Acreman et al. [6] was further developed in order to estimate the environmental flows for the major reaches of the Narew system. Adaptation of the method was partly forced by time, human resources, and budget constraints. Another important reason was a different scope of the study: Acreman et al. [6] developed the BBM in order to design an environmental flow release regime from impoundments, while here the method is intended to be used for semi-natural rivers. Therefore, some of the steps mentioned in [6] were partly or fully omitted. The adapted method proposed in this paper can be described in four steps:

(1) Selecting the elements of water/wetland ecosystems (biotic groups/communities/species) relevant for the case study and organizing a team of specialists responsible for finding the links between these elements and flow regime.
(2) Selecting river reaches of interest within the river network of the case study catchment. Analysis of basic

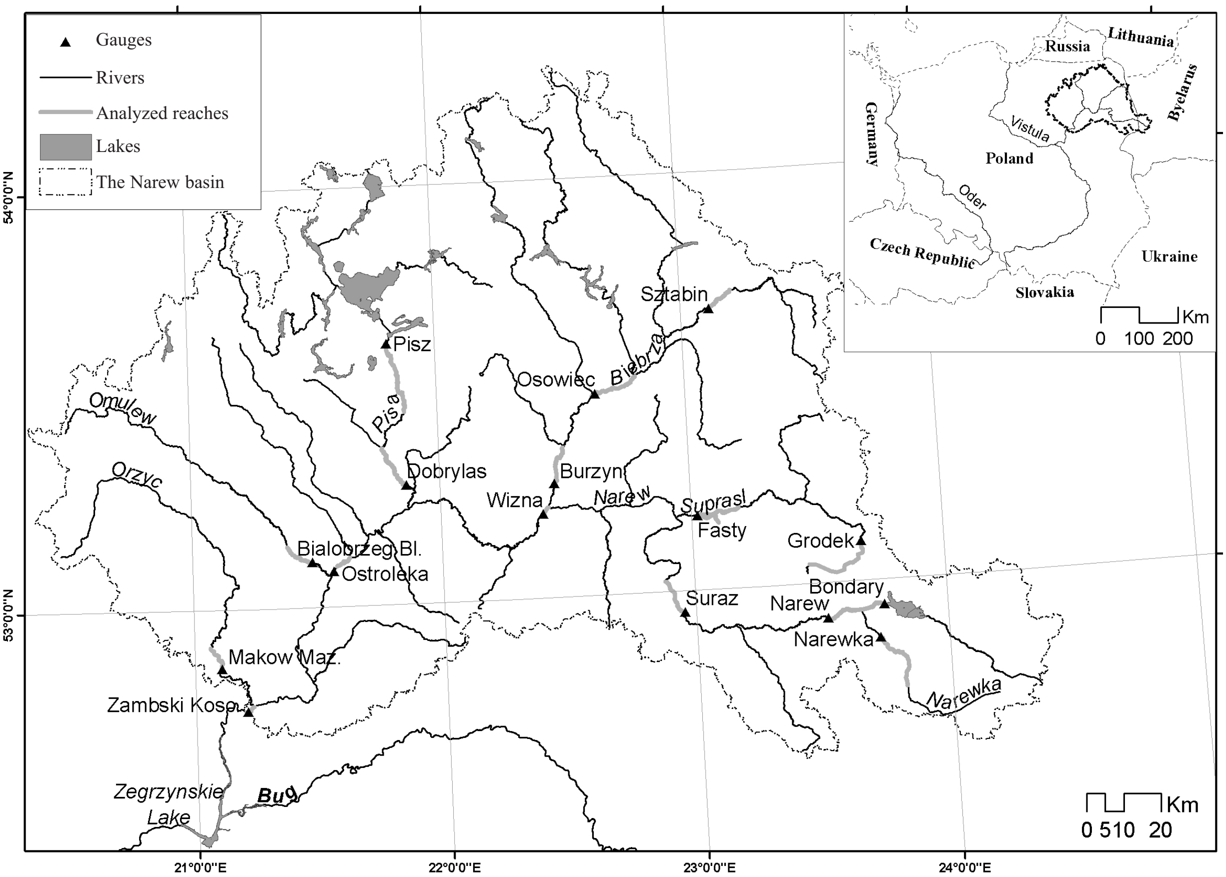


Fig. 1. Map of the Narew basin with analyzed river reaches.

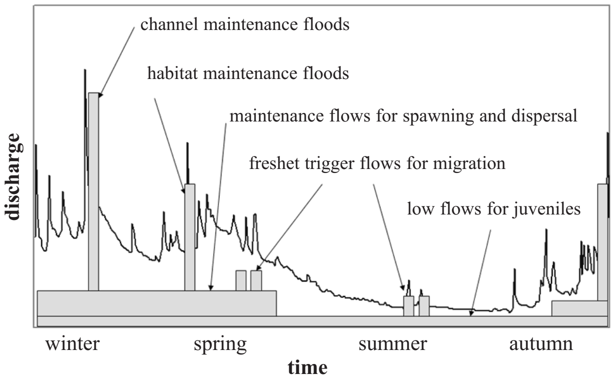


Fig. 2. Building blocks of the flow regime and dependent elements of the river ecosystem [6].

geomorphological features and anthropogenic modifications causing potential hydrograph alterations.

(3) Collecting readily available data on abundance of selected biota/communities/species with emphasis on water-related requirements. Defining environmental flow requirements in the form of the building blocks.

(4) Defining measures of compliance of the actual flow regime with the specified environmental flow requirements (these measures will be referred to hereafter as indicators).

(1) Selection of biota of interest

In the presented approach the emphasis was placed on two elements of the river and wetland ecosystems that were considered the most important and relevant for the study area: fish and floodplain wetland vegetation. The underlying assumption was that healthy fish populations and wetland vegetation reflect wider ecological health. A selection of fish and floodplain wetland vegetation has a few advantages: it includes representatives of both floral and faunal communities, both river and valley ecosystems, and there exists a vast literature concerning both [e.g. 1, 5, 6, 11]. Floodplain wetlands protected in the Biebrza and Narew national parks are amongst the most valuable in Poland and Europe [26, 27], although a lot of valuable habitats, protected by NATURA2000, also exist outside the national parks [28]. The analysis of main hydromorphological pressures on fish in different regions of Poland, carried out within the EFI+ Project[1] [29], proved that the rivers of the Narew basin belong to the least impacted in Poland. All these facts support the idea of selecting only fish and floodplain wetland vegetation as representatives of biotic elements in further analysis.

Instead of organizing a series of structured discussion panels (as in the original BBM), a team of specialists, including three hydrologists, two ecohydrologists, a fish biologist and two wetland ecologists was organized to work on the topic. Also, contrary to the original BBM [5], but in accordance with [6], no field research was carried out (apart from an introductory field visit to selected sites) due to earlier mentioned constraints.

[1]An improved fish population index for European rivers, FP6 project No. 0044096.

(2) Selection of river reaches

Due to the large size of the catchment, it was necessary at the very beginning to define a set of river reaches to be studied in detail. The final selection was based on three criteria:

1. Spatial coverage of the whole length of the River Narew and its six longest tributaries (the rivers of Narewka, Supraśl, Biebrza, Pisa, Omulew, and Orzyc).
2. Availability of sufficiently long (>15 years) daily river flow data from the flow gauging station representative for the particular reach.
3. Reaches should be selected from the 151 reaches that were used in the application of SWAT model in the Narew basin by Piniewski and Okruszko [30].

The last criterion is an artificial one and was used here only because of ongoing modelling activities using the SWAT model. Finally, as a result of compromise between the above criteria, sixteen reaches depicted in Fig. 1. For simplicity, in the following text the reaches will be referred to by the name of the corresponding gauge.

Selected reaches were situated either upstream (13 cases) or downstream from the gauging stations. Mean reach length equalled 14 km, whereas minimum and maximum values were 2.6 and 28.3 km, respectively. Four reaches (Suraż, Narewka, Gródek, Białobrzeg Bl.) were slightly heterogeneous in terms of geomorphology, e.g. an upper part could have a wide valley and meandering channel while the lower part the opposite. River control structures existing along two reaches (Gródek, Fasty) included weirs, which usually operate only in summer in order to drain/irrigate the meadows adjacent to the reaches. In the case of the Gródek reach, the channel was also straightened and deepened. However, the existing examples of anthropogenic modifications do not amount to disqualification and all the reaches may be regarded as being in a natural or semi-natural state.

There was only one large man-made structure, Siemianówka dam situated in the Upper Narew built in the late 1980s, whose operation affects the flow at the reaches of Bondary, Narew, and Suraż [31], the last one situated ca. 80 km downstream from the dam. The second important human impact was on the Pisa River that drains the majority of the Great Mazurian Lakes. The outflow from the lakes was controlled by a system of weirs and locks built in the mid-19th century, which make the flow in 2 reaches, Pisz and Dobrylas, more stable. The next example of flow alteration caused by upstream human impact was the city of Białystok, above the Fasty gauge on the Supraśl River. There was a river water intake upstream as well as a water treatment plant discharging relatively large amounts of water (approximately 0.8 m^3/s).

As mentioned above, analysis of the main hydromorphological pressures on fish for selected regions of Poland, including the Narew basin (sites corresponding to the following reaches analyzed in this paper: Sztabin, Osowiec, Burzyn, Suraż, and Wizna), was carried out in [29]. The most distinctive features of these reaches were: lack of barriers within the analyzed segments, excellent floodplain connectivity, low modification of instream habitats, pres-

Table 1. Key fish species and their spawning characteristics.

Fish species	Reaches	Spawning grounds	Spawning time	Spawning Temperature
Pike (*Esox lucius*)	All apart from Gródek	Submersed plants, often on flooded floodplains, oxbows and shallow backwaters	March-May	5-9ºC
Wels catfish (*Silurus glanis*)	All apart from Gródek, Narewka and Dobrylas		June-July	19-24ºC
Brown trout (*Salmo trutta m. fario*)	Gródek	Gravelly substrate	October-November	5-11ºC

ence of riparian vegetation in good condition, and lack of water abstractions. The only significant pressures were the existence of a barrier downstream (Dębe dam) and modification of a hydrograph due to the existence of a dam on the upstream Narew (Siemianówka dam).

Despite all these examples of human impact, which are few in our view, it has to be stressed that, compared to other river systems in Poland and especially to ones in Western Europe, the rivers of the Narew basin are in a fairly natural state.

(3a) Fish fauna composition and its environmental flow requirements

Detailed identification of the fish fauna composition in selected reaches would require several years of research involving at least a combination of electrofishing and angling information. However, due to limited time and resources, such research could not be carried out. Instead information from literature [32-37] – which described results of complex monitoring of the Narew River fish fauna made between 1986 and 1991 at the request of the Polish Anglers Association – was the main data source in this study. As reported in the later study of Kruk et al. [38] electrofishing was conducted at 331 sites across the river system, excluding the Biebrza River, which was investigated previously by Witkowski [39]. A total of 49,675 individual fish were caught and 36 species were identified. The second number implies a relatively high species diversity and good ecological status of the river. Another source of information was the earlier-mentioned results of the EFI+ project [29]. In this project, electrofishing was carried-out in 50 sampling sites in the Rivers Narew and Biebrza. In total, 28 different species were found, three of which were alien species, and 30,453 specimens were caught. The lower species diversity than in the 1980s could be either due to the fact that the electrofishing was carried out in a smaller number of sites or because there was an overall decrease of fish population in the Narew River system during last 20 years. According to this study, the most common fish species were: roach, pike, perch and white bream (>80%), followed by ide, burbot, rudd, tench, bleak, bitterling, gudgeon, crucian carp, spined loach, loach, and bream. In terms of abundance, fish communities were highly dominated by roach (>45%), followed by pike, white bream, perch, loach, and rudd. Such a fish community structure clearly corresponds to environmental conditions in rivers sampled in this region (mainly large, slowly flowing rivers and their oxbows). Values of river slope in this part of Poland range between 0.7 and 1.8‰, and half of the sites were located in oxbows. This explains the high share of roach, white bream, rudd, pike, and perch in the fish communities.

Fish species may have very different environmental requirements. Even within one species, adults might have other requirements than juveniles. In this study, the focus was on water-related requirements, i.e. those related directly or indirectly (via velocity and depth) to river flow. It was not feasible to take into account all the different requirements of fish, therefore for each reach up to 2 key species were selected from the earlier-found fish-fauna composition. Key species are defined here as the highly valued species due to their usability and importance for the ecosystem's equilibrium, as they control the structure of the fish communities. Selected key species with their occurrence and spawning characteristics [39] are listed in Table 1. Spawning (and first days of growing) is the most critical life history stage for fish in the Narew River and for this reason only the requirements related to spawning were deeper analyzed in this study. This is consistent with findings of King et al. [41] in Australia, Webb et al. [42] in Scotland, and Kondolf et al. [43] in California, who were also looking at flow requirements of fish during the spawning period.

Of lower importance are fish requirements for feeding and wintering, but little is known about them. For both of these life history stages, flow should exceed a certain threshold, but its definition is rather arbitrary. Estimation of this threshold was made here following the well-established (in Poland) Kostrzewa method according to the fishing criterion for lowland fishes [2]. The basic assumption of this method is that fish fauna can survive provided that during its crucial life, history stages flow exceeds the mean minimum flow for a given season (for wintering, which is less crucial, the threshold is the absolute minimum winter flow).

Pike (*Esox lucius*) and wels catfish (*Silurius glanis*) are two phytophilous species, which were selected as key species in the majority of the reaches. Spawning conditions are optimum for these fish if the water level covers the marginal plants, but depth is not too critical. It is more important for the level to remain steady, i.e. if the level is high and then drops before the eggs have hatched, leaving the eggs exposed, they are unlikely to survive; it can also leave fish stranded. The most relevant hydrological characteristics are the timing of flooding and duration of resulting inundation. The requirement for pike is flow above a bankfull for 20 days between March and May, whereas for wels catfish flow above bankfull for 10 days between June and July is needed.

Brown trout (*Salmo trutta m. fario*) was selected as a key species only in one reach. It spawns in October-November in gravel beds. It is critical that there are no extreme low flows during both spawning and egg incubation, i.e. from October to March, as frost can then penetrate the spawning grounds. Flooding in this period can also have a negative consequences since it may lead to erosion and silting up of the spawning grounds. Therefore, the flow in brown trout-inhabited reaches should remain within an optimum range (not too low and not too large) from October to March. Based on expert judgement, the bounds of this optimum range were set as $0.75 \cdot Q_{50}$ and $3 \cdot Q_{50}$, Q_{50} being the median flow.

(3b) Floodplain wetland vegetation and its environmental flow requirements

The second group of biotic communities dependant on river water considered in the selected approach was the floodplain wetland vegetation. This type of vegetation is clearly dependant on frequent inundation of river water and many of its indicator species belong to the most ecologically valuable ones. Therefore, referring to the above considerations about fish, floodplain wetland vegetation communities may be considered as the "key communities" in analyzed reaches.

Due to the different nature of data available for vegetation compared to those for fish, it was easier to perform a fully spatial, GIS-based analysis. The first step in defining environmental flow requirements was the identification of its spatial occurrence. This was achieved using various available GIS and non-GIS data, one of them being especially important: GIS-Mokradła (GIS-Wetlands – a spatial information system about the Polish wetlands based on maps in the scale 1:100,000; http://www.gis-mokradla.info). The following additional data were used:

- Computer Database of the Polish Peatlands (Komputerowa Baza Danych o Torfowiskach Polski "TORF")
- topographic maps in the scale 1:50,000
- geomorphologic map in the scale 1:500,000
- Habitats Directive inventory

Table 2 summarises floodplain wetland vegetation types found in selected reaches (here reach includes both river and adjacent valley). Wetlands occurring in selected reaches are divided as in [44] into peatlands (natural wetlands where peat accumulation takes place) and non-peat wetlands (others). The following five rather broad categories of vegetation communities were distinguished: alder forests, mesic meadows, Molinia meadows, sedges, and rushes. Environmental flow requirements were defined based on one key element: duration of inundation per year. Three categories of optimum inundation requirements were used: 0 days (no inundation), 15-75 (short in.) days and 60-120 days (medium in.). These values are indicative only and due to the environmental tolerance of all vegetation communities; in further analysis the thresholds were fuzzified. Ascribing these categories to reaches was based mainly on vegetation types, while other variables from Table 2 served as supplementary ones.

The building blocks for the floodplain wetlands are thus defined only by the magnitude and duration of the overbank flow for a particular reach. For simplicity timings were not taken into account in this approach. It should also be stressed that the five identified vegetation classes are broad and often composed of various vegetation communities having individually quite different requirements.

(4) Environmental flow indicators

The term *indicator* has ambiguous meaning in environmental sciences [45]. In this paper, an indicator is an observed value representative of a phenomenon to study. In general, indicators quantify information by aggregating different and multiple data. The resulting information is therefore synthesized, which can help to reveal complex phenomena. The role of indicators in the presented approach is to measure a degree of compliance of historical flow data with estimated environmental flow requirements. All the indicators presented below can reach values between 0 (no compliance) and 1 (full compliance).

Three spawning indicators, one for each fish species, have been developed. For pike it is a "spring spawning indicator" (*FISH1a*), for wels catfish a "summer spawning indicator" (*FISH1b*), whereas for brown trout an "autumn and winter spawning indicator" (*FISH1c*). If there was only one key species in a particular reach, then the "Fish spawning indicator" (*FISH1*) equalled *FISH1a*, *b*, or *c*. If there were more than one key species in a particular reach, like pike and wels catfish in 13 sites, *FISH1* was calculated as an average of two respective "seasonal" indicators.

Each indicator was calculated as a mean value of individual scores attributed to each year. Scores measure degree of compliance of observed flows with particular requirements, which were defined in the previous point. In the case of spring and summer spawning indicators, *Score* was calculated as:

$$Score = \min\left\{\frac{Days_{exc}}{Days_{spawn}}, 1\right\}$$

...where $Days_{spawn}$ equals 20 (days) for pike and 10 for wels catfish and $Days_{exc}$ denotes the number of days between the beginning and the end of the analyzed period (i.e. 1 March-31 May for pike and 1 June-31 July for wels catfish), during which flow exceeded the overbank flow Q_{bank}. The interpretation of the meaning of the *Score* variable for these two indicators is shown in Fig. 3a. For instance, in the case of wels catfish, if in a particular year there is no overbank flow between June and July, the *Score* equals zero, if there are at least 10 days of inundation, then *Score* equals 1 and if it is between 0 and 10 *Score* is linearly interpolated between 0 and 1.

In the case of brown trout, flow should remain stable from October to March for effective spawning. The *Score* variable equals the sum of the days during which flow remained in the desired range $[0.75 \cdot Q_{50}, 3 \cdot Q_{50}]$, divided by the number of days between 1 October and 31 March.

It should be stressed that interpretation of all these indicators is relatively simple. They correspond to the frequen-

Table 2. Description of vegetation in selected reaches.

Id	Reach	Dominating wetland type	Sub-dominating wetland type	Topsoil peat type	Dominating vegetation type	Sub-dominating vegetation type	Opt. duration of inundation [days]
1	Bondary	non-peat wetlands	peatlands	sedge	sedges, Molinia meadows	mesic meadows	60-120
2	Narew	non-peat wetlands	peatlands	alder, sedge, rush	sedges, Molinia meadows	rushes	60-120
3	Suraż	peatlands	non-peat wetlands	sedge	sedges, rushes	Molinia meadows	60-120
4	Wizna	non-peat wetlands	peatlands	sedge	Molinia meadows	mesic meadows, sedges	60-120
5	Ostrołęka	non-peat wetlands	peatlands	alder	mesic meadows, alder forests	-	15-75
6	Zambski Kośc.	non-peat wetlands	-	-	mesic meadows, alder forests	-	0
7	Narewka	peatlands	non-peat wetlands	alder, moss	sedges, rushes, mesic meadows	alder forests	15-75
8	Gródek	peatlands	non-peat wetlands	alder, sedge, rush	mesic meadows	Molinia meadows, alder forests	15-75
9	Fasty	peatlands	non-peat wetlands	alder, sedge, rush	mesic meadows	-	0
10	Sztabin	peatlands	-	sedge, moss	sedges	rushes, Molinia meadows, alder forests	60-120
11	Osowiec	non-peat wetlands	peatlands	sedge, moss	sedges	rushes, Molinia and mesic meadows	60-120
12	Burzyn	non-peat wetlands	peatlands	sedge, alder	rushes, sedges	mesic meadows	60-120
13	Pisz	non-peat wetlands	peatlands	alder	mesic meadows, alder forests	sedges	0
14	Dobrylas	non-peat wetlands	-	-	Molinia and mesic meadows	-	15-75
15	Białobrzeg Bl.	non-peat wetlands	peatlands	sedge	Molinia meadows, sedges	-	60-120
16	Maków Maz.	non-peat wetlands	-	-	mesic meadows	-	0

cies of exceeding the overbank flows that were set as threshold values for floodplain inundation. The values close to 1 mean that requirements are almost always fulfilled, values close to 0 to the contrary, and values in-between having intermediate interpretation.

For floodplain wetland vegetation, an indicator called *WETLANDS1* was developed. Yearly *Scores* depend here on inundation requirements of a vegetation class attributed to a particular reach and on two hydrological variables: magnitude and optimum duration of bankfull flow in a reach (Table 2). Duration of inundation was calculated in the simplest way, as the total days per year, time independent. The optimum durations were fuzzified (turned into fuzzy numbers by trapezoidal or triangular membership functions) for each vegetation class (Fig. 3b). For instance, in the case of floodplain wetland vegetation requiring an optimum 15-75 day-long inundation (short in.), if the calculated duration falls between 15 and 75 days, then *Score* equals 1. If it falls between 0 and 15 days or 75 and 120 days, it is linearly interpolated between 0 and 1 (or 1 and 0, respectively). If it falls above 120 days, *Score* equals 0.

Testing of Indicators

A common approach of using indicators in environmental sciences is for detection of changes from the observed state to the predicted future state (usually derived from model simulations; [46]). In this study we used the slightly different approach of using indicators to detect the change between two past time periods: the first one 1976-83, representing more distant in time conditions, and the second one 2001-08, representing present conditions. The 25-year-long time interval between these periods was long enough for conducting such a comparison. Some previous studies reported a decline in the state of wetland habitats in the upper Narew [47, 48] over this

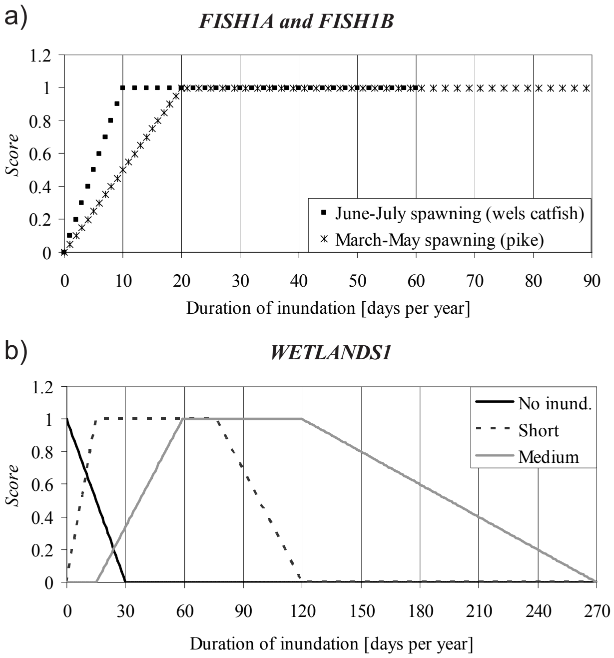


Fig. 3. Calculation of *Scores* for spring and summer spawning indicators (a) and for floodplain wetland vegetation indicator (b).

period. A direct comparison of hydrological, habitat and vegetation conditions between the 1970s, 1980s, and 2000s was conducted by Dembek et al. [49] for a transect crossing the Narew river valley a few kilometres downstream from the Suraż reach. This study revealed a significant decrease of groundwater level and major changes in vegetation, including invasion by alien species such as *Caricetum gracilis* and *Phragmites Australis*. A probable decline in fish population in several sites on the rivers Narew and Biebrza during the last 30 years was earlier discussed (comparison of data from [29] and [38]). This view was also supported by anglers from this region (personal communication).

The selection of 1976-83 as a reference period for the past was motivated by the mentioned studies but was also subject to hydrological data availability. Daily flow data from gauging stations for both time periods were used in the analysis. Flow time series were rescaled using catchment area ratios to represent mean conditions for the particular reaches rather than stations. Bankfull flow values were estimated from the longitudinal profile of the bankfull flow, which is in operational use by the Institute of Meteorology and Water Management in Białystok as a mean value along the reach.

The time period 1976-83 was substantially wetter than 2001-08. Both the magnitude and frequency of floods and low flows are indicative of this. However, the response of the catchment at Zambski Kościelne was significantly different from the response of the sub-catchment at Bondary. This can be explained by the additional effect caused by the operation of Siemianówka dam (Bondary station is situated at the very outflow from reservoir). Mean flow of the Narew at Zambski Kościelne during 1976-83 was approximately 40% higher than during 2001-08, whereas the same characteristic for Bondary was as much as 120% higher in the later period. The influence of the dam can also be observed at Narew and Suraż stations.

Results and Discussion

Spawning Indicators

Fig. 4 illustrates the spatial distribution of the *FISH1a* and *FISH1b* indicators. It is clearly evident that the hydrological conditions for pike spawning are considerably better than wels catfish. The rivers Biebrza and Narew are able to offer the most frequent 20-day-long spring floodplain inundation (even during drier years), and the rivers Pisa (upstream reach), Narewka, and Supraśl the least frequent. In the downstream part of the Biebrza (Burzyn), requirements for pike were satisfied in each of 16 years of analysis. There is a dramatic difference in *FISH1a* values for the upstream Narew (Bondary) between the two time periods. This is certainly due to the previously mentioned effect of Siemianówka dam operation.

In the case of wels catfish, it can be seen that hydrological conditions in the Narew at Zambski Kościelne and the Pisa at Pisz do not favour spawning of this species (*FISH1b* equals zero in both time periods). The requirement for 10-day-long floodplain inundation between June and July, which enhances effective spawning of wels catfish, was rarely satisfied in most of the reaches in the Narew basin, mostly due to the fact that summer flooding seldom occurred. The best conditions were found on the Biebrza at Burzyn and on the Narew at Wizna, where bankfull flows were the most frequently exceeded.

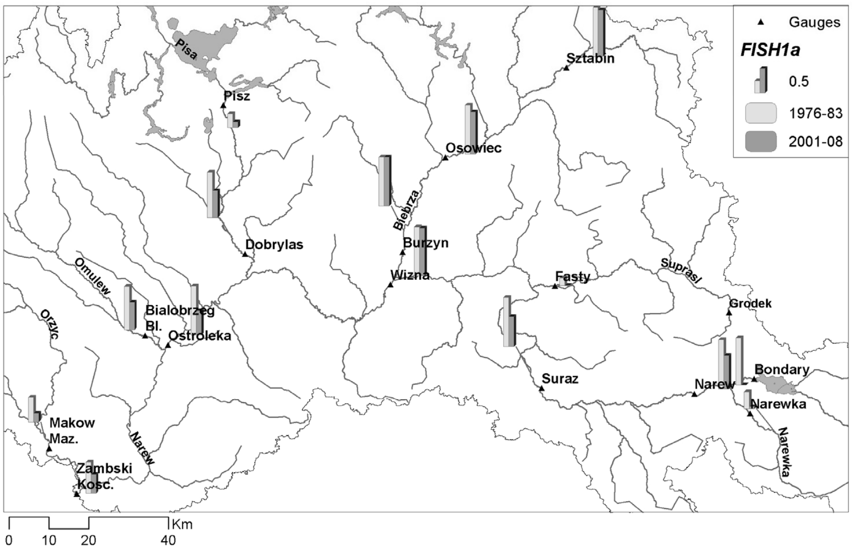
In the case of brown trout, there is only one reach (the Supraśl River at Gródek) for which it has been selected as the key species, therefore it is not illustrated on a map. *FISH1c* (autumn & winter spawning indicator) yielded 0.64 for the time period 1976-83 and 0.59 for 2001-08. This suggests that flow conditions for spawning were only slightly better during the first period.

Floodplain Wetlands Indicator

Fig. 5 illustrates that *WETLANDS1* yielded the highest values at Fasty gauge on the Supraśl (0.9 in average), where floodplain vegetation does not require any inundation. These high values mean that inundation was rare in this reach. In most sites with short (15-75 days optimum) and medium (45-120 days optimum) requirements, *WETLANDS1* yielded quite high values (above 0.5). There was only one river reach with *WETLANDS1* equal to zero. This happened to the most upstream reach on the Narew (Bondary) with medium inundation requirements, for the time period 2001-08. Given that *WETLANDS1* was equal to 0.76 for the time period 1976-83 at Bondary, it is strong confirmation of the negative effect of the operation of Siemianówka dam.

Fig. 6 gives more insight into the interpretation of the *WETLANDS1* indicator i.e. it explains whether low values of *WETLANDS1* resulted from too frequent or too rare

FISH1a indicator (spring spawning, pike)



FISH1b indicator (summer spawning, wels catfish)

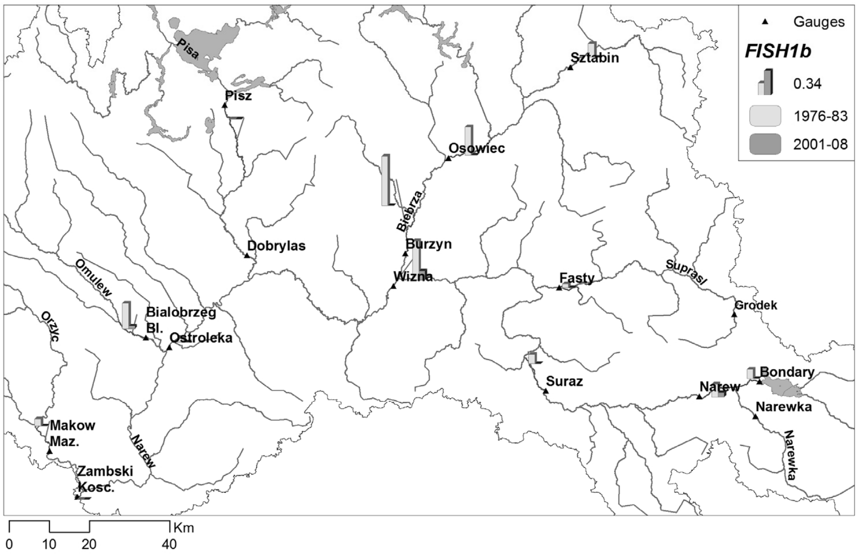


Fig. 4. Spatial distribution of *FISH1a* and *FISH1b* indicators.

WETLANDS1 indicator

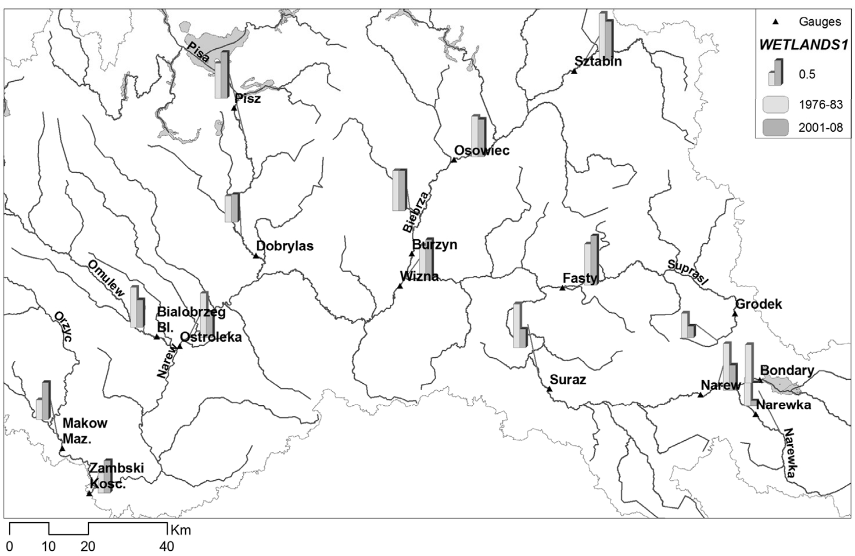


Fig. 5. Spatial distribution of *WETLANDS1* indicator.

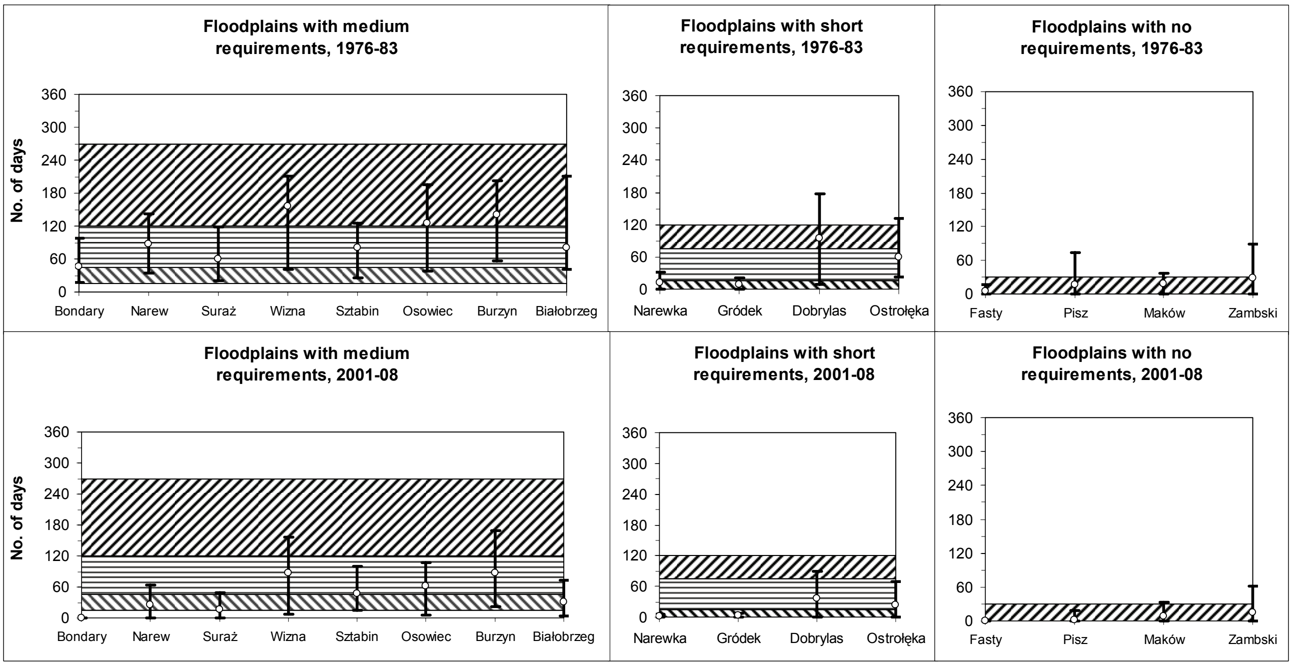


Fig. 6. Mean, minimum, and maximum duration of inundation in days per year for floodplains with different requirements. Patterns correspond to optimal (horizontal pattern), suboptimal (diagonal pattern), or critical (blank) conditions.

inundation. For the most interesting (valuable) floodplains, with medium requirements, it can be seen that during drier years not only Bondary, but also Narew and Suraż on the Narew and Białobrzeg on the Omulew experienced inundation that was too brief. In the case of floodplains with optimum requirements of 15-75-day inundation, two sites, Dobrylas on the Pisa and Ostrołęka on the Narew, experienced inundation that was too long during wet years, whereas Narewka on the Narewka and Gródek on the Supraśl, in contrast, experienced no inundation during dry years. Finally, floodplains with vegetation that does not require inundation are occasionally inundated during wet years (Zambski Kościelne on the Narew). Despite these individual deviations, it can be concluded that the overall picture (i.e. looking at average values and three classes as a whole) is quite consistent, especially given the environmental tolerance of vegetation communities.

Temporal Analysis

Fig. 7 compares the mean values of all the calculated indicators for two analyzed time periods. A large difference between past and present years for *FISH1a* and *FISH1b* confirms that 30 years ago the conditions for effective spawning of phytophilous predatory fish species such as pike and wels catfish were considerably better. This is in accordance with earlier mentioned sources saying that fish population in this region used to be richer in the 1970s than nowadays. However, extremely low values, e.g. of *FISH1b* should be treated carefully, i.e. the requirements used in this study should be seen as optimum rather than minimum. In other words, if any of the indicators is close to zero, it does not necessarily imply (although it may imply) that the respective biotic group is in danger; however, if the indicator values are close to one, it is very likely that the hydrological conditions (but only hydrological, because others were not analyzed) are close to optimum. *FISH1b* equal to 0.02 for the time period 2001-08 does not imply that breeding of wels catfish was ineffective, but it means only that it was less effective than it could have been if the floodplains had been inundated for a few days in June or July in any year between 2001 and 2008.

The calculated values of *WETLANDS1* depend largely on established wetland vegetation groups and thus should be analyzed separately. For the most valuable habitats with vegetation requiring medium or short inundation the difference in favour of the period 1976-83 is distinct. The opposite can be observed for the reaches with no inundation requirements, which is entirely due to the fact that this period was much wetter than the present years. However, for all three groups of vegetation communities the change in indicator values between the analyzed time slices is less pronounced than for selected fish species.

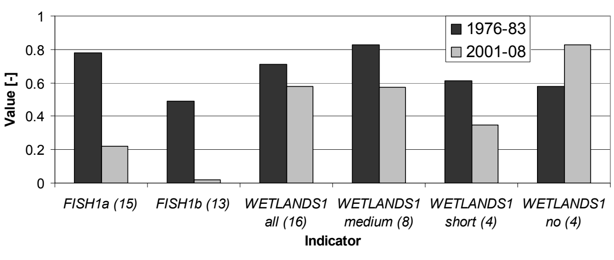


Fig. 7. Comparison of mean values of indicators for two periods (numbers of reaches for which indicators were calculated are written in parenthesis).

Conclusions

A new environmental flow method developed from the building block approach applied by Acreman et al. [6] was discussed in this study. The method was able to capture the most important phenomena occurring in the lowland semi-natural rivers. It enabled both spatial and temporal comparison of the environmental flow indicators. The method was relatively simple and time efficient – its application can occupy from 4 to 12 months, depending on the size of the study area as well as the budget and human resources involved. At the same time, the method was more complex than most methods used for estimation of environmental flows in Poland, which are usually single-value approaches [2]. The developed indicators proved to be sensitive to changes in hydrological conditions and thus can be applied in the modelling studies concerning the impact of climate and land use change in the catchment on river flow, as outlined in [46]. In particular, such studies may be helpful in answering the question of whether the environmental flow regime in semi-natural lowland rivers can potentially be in danger in future scenarios, and what measures can be taken in order to protect it.

Presented results indicate that water conditions for fish and floodplain wetland vegetation were significantly better in 1976-83 compared to 2001-08. It is not evident that such a situation took place in reality, since monitoring of the fish fauna and wetland vegetation was not so common 30 years ago as nowadays. A few sources that directly [49, 50] or indirectly [29, 38, 47, 48] confirm this statement have been mentioned earlier in this paper. The reasons for this negative change may be many:

- construction of the Siemianówka reservoir in the upper Narew clearly influenced the hydrology and, in consequence, the ecology downstream from the dam [47, 48]; this impact affected the following reaches: Bondary, Narew, and Suraż, so it does not explain temporal differences in indicators for other sites
- river regulation downstream from the Narew National Park was mentioned by Dembek et al. [49] as one of the reasons for deterioration of wetland communities in the Park; this could also partly explain the change in the Suraż reach
- as it has been mentioned previously, period 1976-83 was much wetter than 2001-08, which resulted in more frequent floodings and better accordance with environmental flow regime; this may be partly explained by the phenomenon of the observed climatic change; Maksymiuk et al. [51] reported that the most pronounced in northeastern Poland was the increase of mean temperature in winter, which in consequence led to a reduction in the amount of snow cover and further to decrease of the magnitude of spring floodings; this partly explains the temporal difference for the reaches not influenced by the dam.

It should also be stressed that there are other environmental factors than just river flow, which are of great importance to fish and floodplain wetland vegetation. In the case of fish, water temperature and quality can control fish population dynamics. In the case of floodplain wetland vegetation, it is not only the river which can provide a water source; water may also derive from interflow or shallow groundwater recharge. Water quality is also important. All these types of things have not been taken into account in the presented approach.

The environmental flow indicators developed in this paper were built with a basic knowledge about the Narew basin fish fauna and floodplain wetland vegetation. Similar abundance of information can be found elsewhere, therefore the approach can be tested in other river basins as well. Establishing site-specific relationships between the flow regime and dependent elements of the river and wetland ecosystems is a critical condition for the application of this method for other rivers.

Finally, the advantage of indicators developed here is the simplicity of interpretation, but due to long-term averaging some information is clearly lost. Using a sufficiently long (ca. 30 years) and continuous period of analysis could enable the use of additional measures representing also temporal variability of indicators (Fig. 7) or even analysis of the whole statistical distribution. It could potentially give an indication of environmental tolerance of fishes or floodplain vegetation on deviations of hydrological regime.

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