Ecohydrological Functioning
of a Tropical Monsoon and a Temperate River Floodplain

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Cover: Upper - Floodplain of the Narew River, Poland
Lower - Floodplain of the Songkhram River, Thailand
Back cover: Floodplain of the Songkhram River during the flood
Photographs by Tanapipat Walalite

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Ecohydrologie van de overstromingsvlaktes van een tropische moesson rivier en een gematigd klimaat rivier
(met een samenvatting in het Nederlands)

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Contents

Chapter 6

Chapter 1

Introduction

Tanapipat Walalite

1.1 The need for knowledge on floodplain ecosystems in tropical regions

Although river-floodplain ecosystems have been recognized as highly productive compared to terrestrial or aquatic ecosystems, they are severely threatened. Most river floodplains in developed countries, such as in Europe and in North America, are already altered by human activity. In developing countries, especially in Southeast Asia, the remaining natural floodplains disappear quickly. There is thus an urgent need for conservation actions that preserve natural floodplains to prevent further loss of ecological services of these ecosystems (Tockner and Stanford 2002).

Effective conservation strategies require an understanding of the floodplain's ecological function and functioning. While the ecological functioning of river floodplains in the temperate climate zone is well studied, floodplains situated in a tropical climate, especially in the monsoon region of Southeast Asia, are less studied. Moreover, each river floodplain can exhibit different characteristics and ecological processes. Therefore, the knowledge body regarding rivers and floodplain ecosystems in tropical regions needs to be further developed in order to support conservation actions. In the following of this introduction, I will discuss in sections 1.2) the river ecological concepts and their suitability for understanding ecohydrological floodplain functioning, 1.3) the influences of climate on river-floodplain ecological functions, 1.4) the nutrient cycling in river floodplains. Finally, in section 1.5) the structure of this thesis will be presented, including the objectives and the research questions of each chapter, and in section 1.6) the study areas will be presented.

1.2 The conceptualization of riverine ecosystems

The development of ecological concepts relevant to river and floodplain ecosystems can be traced back to the late 1970s to the early 1980s. One of the most well-known concepts developed in the early ’80s is the River Continuum Concept (RCC), proposed by Vannote et al. (1980). The concept emphasizes ecological processes along longitudinal gradients of streams and rivers. The RCC assumes that physical gradients in the river from upstream to downstream are responsible for a continuum of changes in ecological processes along the river. The input of nutrients to the river is mainly via organic material, which originates from 1) local inputs from terrestrial vegetation (allochthonous inputs), 2) primary production within the stream (autochthonous production), and 3) transport from upstream. The share of each source is expected to vary from upstream to downstream along a river. Because varied sources and forms of input, shading and turbidity affect the penetration of solar radiation into the water column, the functional groups of the biotic community adapt in response to that: with shredders and collectors dominating in the upstream aquatic community, grazers and collectors in the middle reach and collectors in the downstream river (Fig. 1.1). The RCC has been very useful in explaining ecological functions and processes in

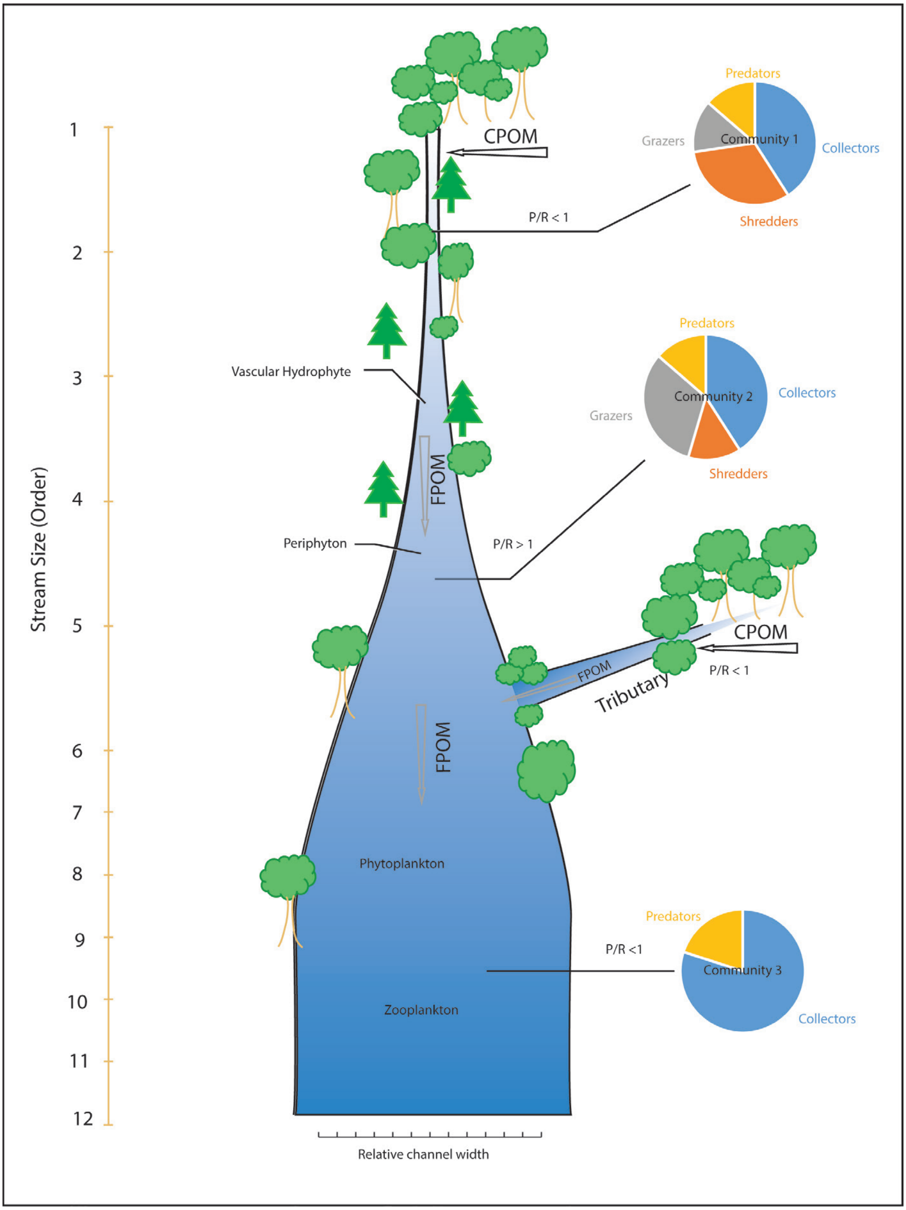

Fig. 1.1 Illustration of the River Continuum Concept (from Vannote et al., 1980) that assumes a change of biotic communities in response to the physical gradient of the river from upstream (top of the figure) to downstream. Relative channel width and the stream size increase downstream in relation to the stream order. Because of varied sources and forms of input material (fine and coarse particulate organic matter (FPOM and CPOM)) shading, and turbidity, the functional groups of the biotic community adapt in response to that, with shredders and collectors dominating in the upstream aquatic community, grazers, and collectors in the middle reach and collectors in the downstream trajectory of the river. P/R is the ratio of aquatic production and respiration in the river channel.

the main river channel but did not pay very much attention to rivers with extended floodplains, especially those in the tropics, such as the Amazon, where the floodplain is immense and serves many ecological functions that cannot be seen apart from the river (Sedell et al., 1989; Johnson et al., 1995). In addition, a river network may not always exhibit continuous gradients of physical and biotic conditions, as the concept assumes. Instead, as demonstrated by Statzner and Higler (1986, 1985), conditions in rivers may change abruptly in space depending on the geomorphology and landscape setting of the catchment. Furthermore, Townsend (1989) questioned if the RCC downstream continuous pattern can be generalized worldwide.

A second influential ecological concept for large river floodplains in tropical and temperate areas called the 'Flood Pulse Concept' was later presented by Junk et al. (1989). The Flood Pulse Concept (FPC) emphasizes the ecological processes that occur in rivers and floodplains. It states that a predictable (annual) flood pulse is an essential hydrological feature of a large river extending onto the floodplain. The floodplain receives fresh sediment from the river during floods, and nutrients and organic matter produced in the floodplain are exported and returned to the river during flood recession (Fig. 1.2.). In this view, organic matter from upstream has negligible effects on production compared to the locally produced organic matter on the floodplain. Predictable flood pulses of moderate duration allow aquatic and terrestrial organisms to adapt to the pulse. A regular flooding regime and associated sediment deposition help maintain high biotic diversity in floodplain forests. In the original concept, the FPC focused on nutrient cycling processes that were assumed to occur homogeneously over the floodplain and transversal exchange processes between the floodplain and river. Later, the FPC extension (Junk and Wantzen, 2004) included the longitudinal transport of organic matter in the river from upstream to downstream and from the river to the floodplain. Although the RCC and the FPC have served well as major ecological concepts for river and floodplain ecosystems, they have their limitations. Neither the RCC nor the FPC concepts fully explain river and floodplain processes (Johnson et al., 1995; Tockner et al., 2000; Thorp et al., 2006; Keizer et al., 2014). Especially when climatically different rivers are taken into consideration.

A third ecological concept also stresses that rivers and floodplains are closely interacting but acknowledges the impact of climate on how rivers and their floodplains might interact. During the flood, floodplains receive material transported by water from their parent river, and in return, floodplain-produced material is exported to the river. As floodplains and rivers are closely related spatially, Wiens (2002) suggested the Riverine Landscape Concept. This concept views the river from a landscape ecological angle that considers; 1) rivers as elements of a landscape mosaic, 2) rivers linked with their surroundings by boundary dynamics, and 3) rivers as internally heterogeneous landscapes. Wiens (2002) added: "Rivers exhibit longitudinal characteristics in the landscape and can be viewed as a landscape in itself." Later in 2006, Thorp et al. developed the Riverine Ecosystem Synthesis model (RES), which integrates longitudinal processes and patch-scale dynamics (Townsend, 1989). Although it acknowledges the longitudinal pattern of the river network, the concept does not view the river network as a simple continuous longitudinal gradient, neither physically nor as a biotic community (sensu Vannote et al., 1980). Instead, the RES views the river network as downstream arrays of large hydrogeomorphic patches formed by catchment geomorphology and flow characteristics. River and floodplain are complex in a multitude of spatial dimensions and are therefore composed of various subsystems, e.g., main channel, slack water habitat, sub-bank full area, supra-bank full area, and floodplain area. Hydrogeomorphology causes habitats to differ in physical and chemical conditions and bio-complexity. This creates a "Functional Process Zone" (FPZ), a habitat for various biotic communities. Different FPZs are present from

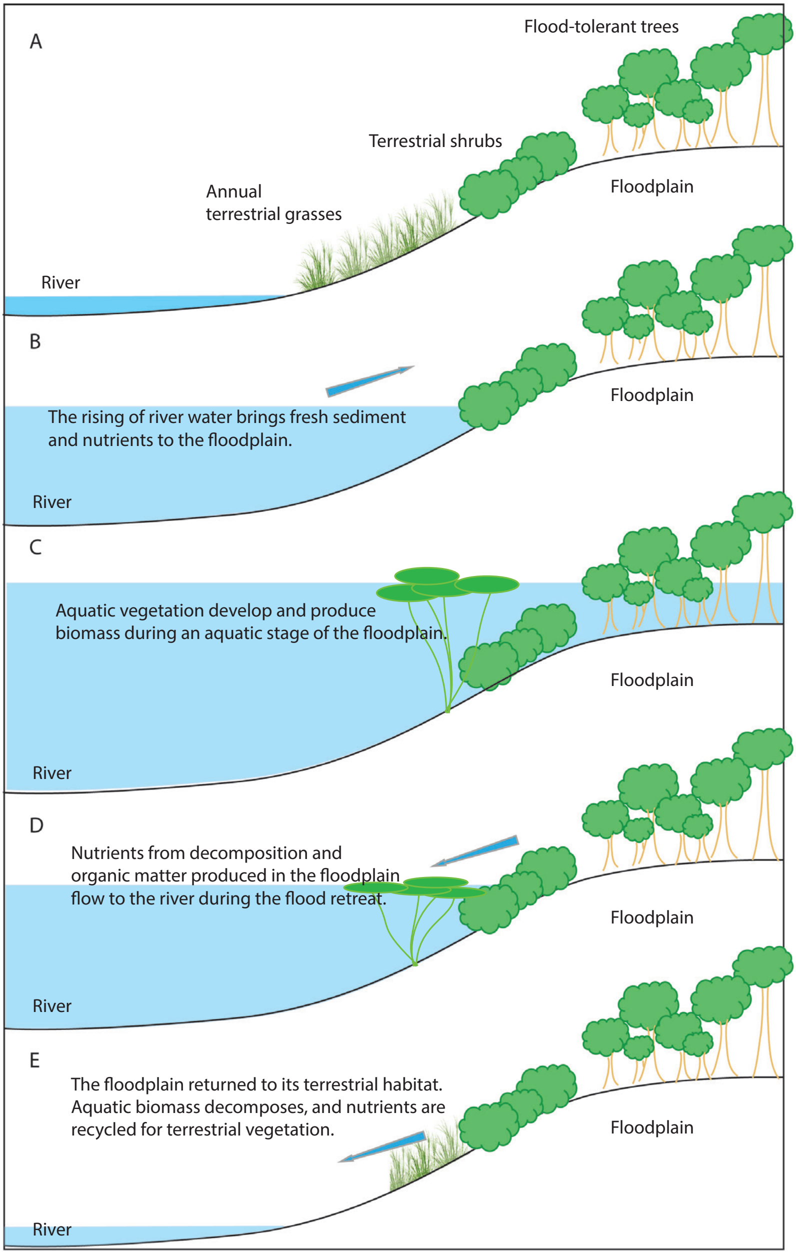

Fig. 1.2 Illustration of the Flood Pulse Concept shows the aquatic/terrestrial transition zone for river floodplains (adapted from Junk et al., 1989). A) During the terrestrial stage, floodplains are suitable for annual terrestrial grasses, terrestrial shrubs, and flood-tolerant trees. B) Floodplains receive fresh sediment and nutrients from the river during the rising stage of the flood. C) When terrestrial habitat turns to aquatic, biomass in floodplains decomposes. Aquatic vegetation develops and produces biomass. Organic matter is produced in the floodplain during the flood. D) Nutrients from decomposition and organic matter produced in the floodplain flow to the river during the flood retreat. And E) The floodplain returned to its terrestrial habitat. Aquatic biomass decomposes, and nutrients are recycled for terrestrial vegetation.

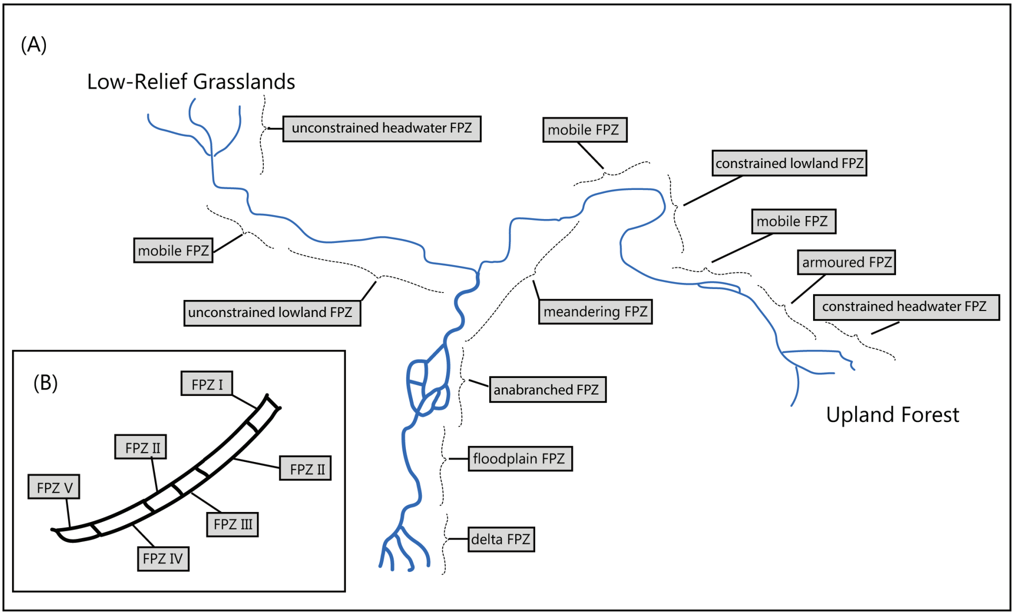

Fig. 1.3 Schematic view of a river by the Riverine Ecosystem Synthesis model (from Thorp et al., 2006). (A) shows different ecological Functional Process Zones (FPZ) from upstream to downstream. Hydrogeomorphology causes differences in habitats. Differing in physical and chemical conditions and bio-complexity creates a FPZ, a habitat for various biotic communities. (B) shows similar types of FPZ can be present at one or more river sections, and their occurrence cannot always be predictable in their arrangement.

upstream to downstream, and the same type of FPZ may be found more than once and arranged in a way that is not always predictable (Fig. 1.3). The same type of FPZ should exhibit a more similar biotic community than belonging to a different FPZ. Furthermore, climatic conditions are an important factor influencing these patches by steering runoff (of water, sediment, organic matter, and nutrients), riparian/floodplain vegetation, and aquatic vegetation. From this third conceptual view on rivers and floodplains (RES and FPZs), we may expect riverine functional process zones situated in different climate zones to exhibit different ecological processes and patterns.

1.3 Effects of climate on flood patterns and vegetation growth in floodplains

Temperature is a fundamental environmental factor that regulates plant growth and the length of the growing season. River floodplains in different climatic zones may experience different temperature and precipitation patterns that impact ecological processes. Tockner et al. (2000) showed that due to the high and relatively constant temperature in a tropical river (e.g., the Jong River in Sierra Leone), the flood pulse is a dominant ecological process in the floodplain. In contrast, as river water temperatures in the temperate zone show higher annual variability than the relatively stable temperature in tropical systems, the flood pulse can be asynchronous to the growing season in the floodplain. For instance, Fig. 1.4 shows clear differences in synchrony of temperature, discharge, flood period, and growing season of a temperate and a tropical river. In the temperate Polish river, the flood peak is at the end of winter/beginning of spring when temperatures are low. This while vegetation grows in summer when temperatures are high and the flood has receded. In

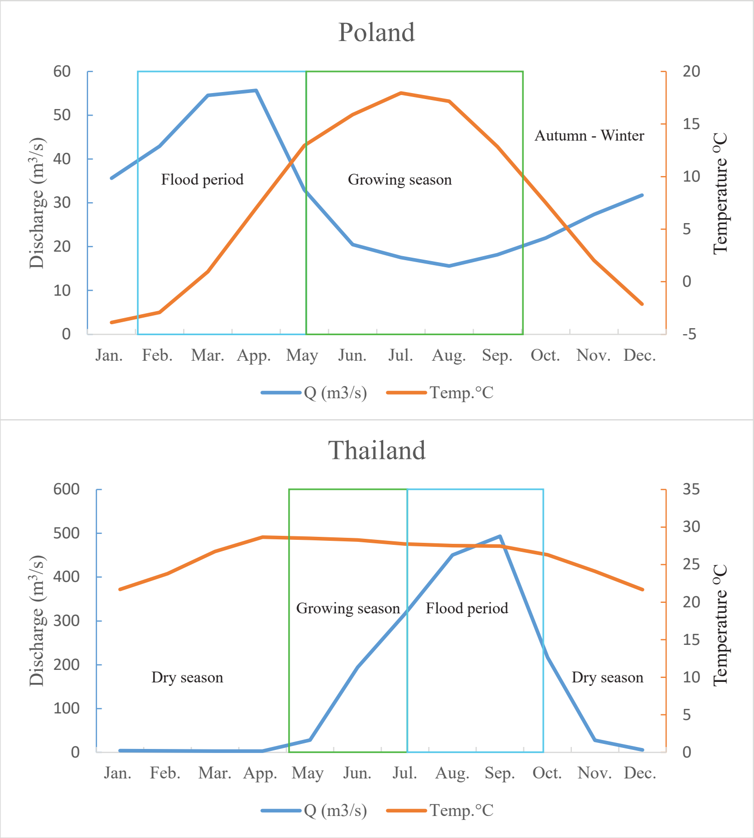

Fig. 1.4 Synchrony between the temperature and discharge pattern of the Polish temperate river (the Narew River) and the tropical monsoon river in Thailand (the Songkhram River). The peak discharge in Poland follows snowmelt in late winter and rainfall in early spring, whereas, in Thailand, the peak coincides with the monsoon season. The growing season is limited to summer in Poland, whereas in Thailand, the main growing season starts at the beginning of the monsoon season (around May.) and continues until the flood begins. Although the temperature in the tropics is optimal for growing all year round, lack of water during the dry season inhibits vegetation growth. So interesting is that for Poland, the growing season starts after the flood period, while for Thailand, the growing season is followed by a flood period.

the tropical Thailand monsoon river, temperatures are relatively stable and high throughout the year, and the growing season is longer. From here, it is clear that the flood regime for a tropical floodplain is a very important process in determining habitat patterns and explaining biological diversity (Junk and Piedade, 1993; Junk and Wantzen, 2004). For temperate floodplains, Tockner et al. (2000) suggest that nutrients and temperature are important factors that determine the floodplain ecology.

Vegetation in floodplains adapts to and benefits from flooding. River floodplain ecosystems receive water and material from floods that may be beneficial but may also pose stress for organisms. Different environmental factors together determine the spatial pattern of ecosystems across the floodplain. These factors are flooding depth, water velocity, oxygen and light stress during long-term inundations, and nutrient and sediment inputs. Floodplain vegetation responds to these environmental factors resulting in spatial differentiation in productivity and species, as shown for temperate river floodplains (Keizer et al., 2014; Wassen et al., 2003; Wassen and Joosten 1996; Wu and Blodau 2015). Similarly, clear vegetation zonation along flooding gradients are observed for large tropical floodplains, i.e., the Amazon basin, the Okavango Delta, the Mekong Tonle Sap, and the tropical Northern Australia wet-dry system (Parolin and Wittmann 2010; Parolin et al., 2016). Spatial patterns of vegetation in these tropical floodplains are the result of their adaptation and response to seasonal flooding characteristics, especially inundation depth and duration (Arias et al., 2016; Parolin et al., 2016). In addition, nutrient availability in floodplains is an important factor as it determines the productivity of the floodplains. Spatial patterns of nutrient availability can directly cause vegetation zonation but can also influence seedling establishment strategies which also result in spatial patterns of vegetation in floodplains (Parolin, 2002).

1.4 Nutrient retention and recycling functions of river floodplains

River floodplains are highly productive compared to many terrestrial or aquatic ecosystems (Junk et al., 1989). The most important factor that promotes the high productivity of river floodplains is the regular re-wetting process that takes place (Baldwin and Mitchell 2000), which causes a high rate of nutrient cycling. Second, additional dissolved and particulate materials transported by the river into the floodplains potentially deliver nutrient input and increase nutrient recycling.

Nutrient retention and recycling will vary during the three hydrological stages; 1) base flow stage, 2) rising stage, and 3) falling stage, as described in the River Wave Concept (Humphries et al., 2014) and the Flood Pulse Concept (Junk et al., 1989; Junk and Wantzen 2004). In the stage of rising, water from the river inundates the floodplain. The material transported by the inundation water locally adds sediments. The productivity of the floodplain system during the inundated aquatic phase is represented by the biomass of aquatic vegetation and phytoplankton in the water column. This aquatic vegetation's biomass and phytoplankton are a function of nutrient availability, temperature, oxygen, and turbidity in the water column. The latter may result from suspended sediment brought in but also from algal growth and may act as a limiting factor hampering the photosynthesis of submerged leaves(Basu and Pick 1996; Zohary et al., 2010; Bhat et al., 2015). During the flooded stage of the floodplain, one of the well-recognized ecological functions of the river floodplain is its nutrient removal capability (e.g., Gordon et al., 2020; Mcjannet et al., 2012). However, this process varies depending on the nutrient types (e.g., nitrogen and phosphorus) and forms (dissolved and particulate). For example, floodplains in a temperate climate (North America and Europe) demonstrated their capability to remove dissolved inorganic nitrogen (NO3-) and total or particulate phosphorus from floodwater (Gordon et al., 2020). In the tropical Zambezi River, Zuijdgeest et al. (2015) reported that the floodplain retains and breaks down particulate organic carbon and nitrogen, then exports dissolved organic and inorganic carbon and nitrogen to the downstream river. Since the ecological function of each floodplain can be different, studying individual floodplains is crucial to better understanding the ecological processes of floodplains.

1.5 Objectives and outline of this thesis

This thesis aims to further develop the knowledge body regarding rivers and floodplain ecosystems in a tropical region and compare it to those in a temperate climate, which will support management strategies and conservation actions. The two main objectives of this thesis are 1) to understand the ecological functioning of a river floodplain in a tropical climate and 2) to compare this with a temperate river floodplain to understand their similarities and differences in ecological functioning. As the ecological functioning of river floodplains in different climate zones could be similar or different, effective management and conservation strategies must understand the biogeochemical processes of the floodplain as an integral part of the whole river system. Fig. 1.5 demonstrates the links between the research chapters to the thesis's main objectives and aims.

Following the first objective, a pioneer study of the hydrochemical functioning of the tropical monsoon River Songkhram's floodplain is presented in Chapter 2. Next, in Chapter 3, the ecological functioning of the Songkhram River floodplain was analyzed in detail using data on nutrient status in soil, water, and vegetation. Chapter 2 and Chapter 3 together provide an understanding of the eco-hydrological function of the tropical river floodplain based on an example from Thailand's tropical monsoon river floodplain. For the second objective, Chapter 4 presents an ecohydrological analysis of the Narew River floodplain as an example of the ecological functioning of a relatively pristine river floodplain in temperate European. This is to be able to compare it with the tropical monsoon river. Then, in Chapter 5, the ecological functioning of the Narew River and the Songkhram River floodplains are compared in terms of hydrology, hydrochemistry, nutrient budget, and nutrient balance of floodplain vegetation. In Chapter 6, a synthesis is given with respect to research questions, research objectives, and implications for management strategies and conservation actions.

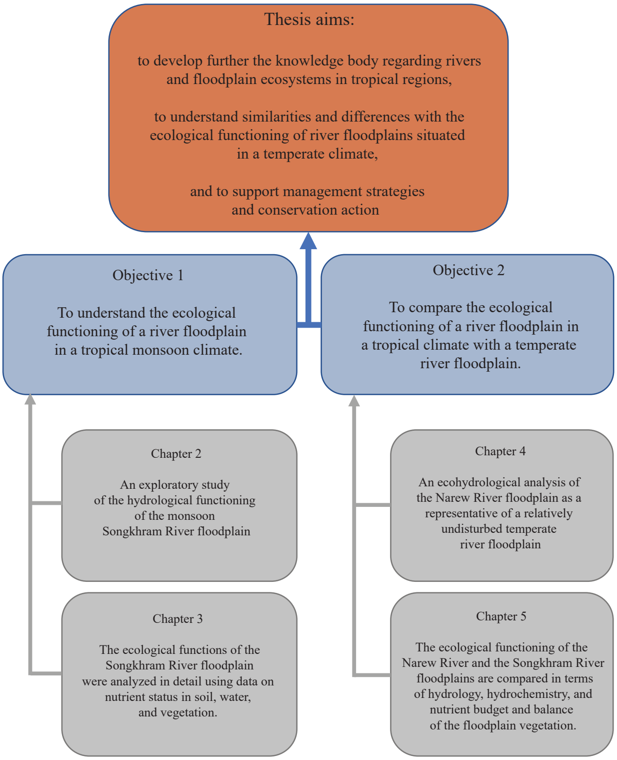

Fig. 1.5 Structure of this thesis shows the aims, the main objectives, and their links to each research chapter.

In chapter 2, following the first objective of the thesis, this chapter aims to explore the floodplain functioning of a tropical monsoon river system by studying the longitudinal and transverse floodwater hydrochemical characteristics in the Songkhram river (Thailand) and its floodplains. Also, the relationship between the hydrochemical status and the land use in the floodplain is analyzed. Hydrochemical characteristics are monitored during a flood event in the Songkhram River. The research questions of this study are 1) What are the longitudinal (upstream-downstream) and transverse (river–floodplain) trends in hydrochemistry and nutrient availability during the flood period in the monsoon river system? 2) Do nutrient availability and water chemistry differ significantly between the main river channel and the floodplain during the flood period? 3) Are these differences related to land cover on the floodplain?

In chapter 3, again, following the first objective of the thesis, we further investigate the ecological functioning of the Songkhram River floodplain and its floodplain vegetation. Two distinct vegetation zones in the floodplain (bamboo and grass) are studied in detail to explore spatial differences in the nutrient distribution in water, soil, and vegetation. Interaction between the flood characteristics and the vegetation with respect to nutrient fluxes and storage are analyzed for the two different vegetation zones. During the fieldwork, we observed that the highly productive flooded bamboo was found near the river, while the flooded grass vegetation was found next to the bamboo and extended upwards to the floodplain edge. The bamboo leaves and the grass biomass were harvested, estimated for annual production, and analyzed for nutrient concentration. We also investigated nutrients in the floodplain soil before and after the flood and analyzed the floodwater chemistry. The research questions of this study are 1) Are there spatial differences in the nutrient distribution in water, soil, and vegetation for two distinct vegetation zones (bamboo and grass) in the floodplain? And 2) What are the interactions between the flood characteristics and the vegetation concerning nutrient fluxes and storage?

Chapter 4, following the second objective of this thesis, presents the ecohydrological analysis of the Narew River floodplain in Poland. This study aims to understand the ecological characteristics of a relatively undisturbed river floodplain in a temperate climate. The understanding of the ecological character of a temperate floodplain in this study is a crucial part of a comparison with a tropical monsoon floodplain's ecological functioning. We analyze field observation data, including vegetation communities, soil, nutrient availability, and the chemistry of surface water and groundwater. We investigate three floodplain sites situated upstream, mid-lower, and downstream of the river. The research questions of this study are 1) Do the vegetation types that are laterally and longitudinally distributed over different locations along the floodplain differ in community structure? And 2) What environmental factors could explain the differences in the community structure of the vegetation?

In Chapter 5, to achieve the second main objective of this thesis, a comparison study of ecological functions between the floodplains in a temperate and a tropical monsoon system is conducted. The study aims to provide an understanding of similarities and differences in the ecological functioning of river floodplains in the two climate zones, which will provide basic knowledge to further effective management plans and conservation strategies for the river floodplains. This chapter presents a comparison of the hydrology, hydrochemistry, and nutrient status of the vegetation of the two river floodplains. Furthermore, a simple model for the nutrient (N and P) budget and balance of the floodplain vegetation of the two floodplains is developed and compared. We also evaluate the importance of nutrient input by floodwater and how this contributes to the nutrient budget and balance. The research questions of this chapter are 1) How do the seasonal patterns of river discharge influence nutrient concentration and nutrient loads of the rivers situated in temperate and tropical climates? 2) Is the eco-hydrological functioning (N and P budgets and balance) of the floodplains in the temperate and tropical monsoon climate systems comparable? 3)Are the Narew and the Songkhram floodplains a sink or a source of nutrients?

In Chapter 6, the main findings of this thesis are synthesized and discussed in light of the main objectives and aims and the research questions of the studies. The relevance of the acquired knowledge for river floodplain management is discussed, which aims at maintaining the studied rivers' relatively pristine ecological functioning in terms of nutrient transport, storage, and recycling as an integral part of the whole river system. Some suggestions for future research will be given.

1.6 The Study sites

The floodplain of the temperate Narew River, Poland (22°12' to 24°27' E and 52°36' to 54°16' N), and the floodplain of the tropical monsoon Songkhram River, Thailand (103°12' to 104°35' E and 16°55' to 18°23' N) were studied (Fig. 1.6).

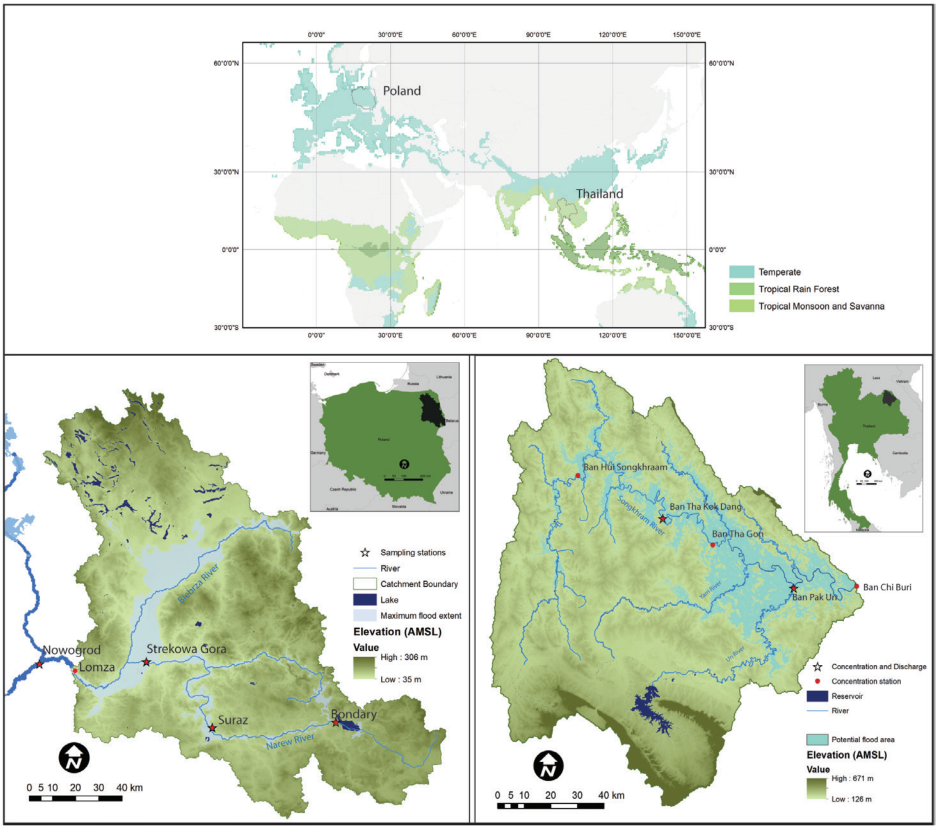

Fig. 1.6 Maps show the study area of the Narew River basin of Poland, situated in eastern Europe, and the Songkhram River basin of Thailand, situated in southeast Asia. Spatial scales are equal, showing comparable areas of the two basins. Note that elevation scales are different between the two basins. The distribution of the Temperate, Tropical Rain Forest, and Tropical Monsoon and Savanna areas in the upper map adapted from Beck et al. (2018).

The Narew River is a tributary of Poland's Vistula River. It originates in Belarus and flows through northeast Poland. The river's total length is ca. 484 km, and the total drainage area is ca. 28,000 km2 before the confluence with the Bug River (Gielczewski et al., 2011). The study area in this thesis focuses on the upper part of the Narew River upstream from the gauge station located at Lomza (Fig. 1.6). At this station, the drainage area of the basin is ca. 15,300 km2, and the upstream length of the river course is ca. 310 km. The basin is in a temperate climate zone with a yearly average temperature of 7.2 °C and gross precipitation of 617 mm (Gielczewski 2003). The upper part of the river runs through the middle Pleistocene plateaus before entering the Vistulian Glaciation area with loamy moraine plateaus or sandy glaciofluvial plains in the lower area (Górniak 2018). The width of the flood terrace of Narew is up to 10 km. Most land cover in the basin is agriculture and forest, which account for 55% and 32 %, respectively; around 10% of the catchment is a nature protection area (Gielczewski 2003). Regular and predictable flooding is a characteristic of the Narew River floodplains. The river is defined as a temperate snowmelt-fed river system characterized by increasing discharges and water levels after snowmelt that reaches a maximum level during spring in March and April. Water level and discharge decrease in summer and autumn until the mostly frosty winter period start.

The Songkhram River is a tributary of the Mekong River, located in north-eastern Thailand. The river is approximately 495 km long, and the drained area of this river basin is around 13,000 km2. This river is a tropical monsoon rain-fed river. The monsoon season lasts from May to September and is followed by a cool, dry season from October to February that is succeeded by a hot, dry season from March to April. During the monsoon season, the average precipitation is 1690 mm (range 906 – 2420 mm); this compares with an average precipitation of 270 mm (range 80 – 490 mm) during the dry season. Flooding in the Songkhram River floodplain occurs following the monsoon season, begins in May, and ends in October. The peak flood generally occurs in late August, and the water level gradually decreases to the base flow level in the dry season in November. This area's mean annual temperature is 26 °C and the warmest month is April (35 °C). The minimum temperature is around 15 °C from December to January. The river's discharge behavior is quite natural, as no large dams regulate water flow in the main channel. Extensive floodplains are found in the lower part of the basin. These inundate yearly due to high river discharges during the monsoon season (Blake et al., 2011). The average area flooded annually in the lower basin, estimated using Landsat images from 2000 to 2006, is 760 km2 (Thiha et al., 2012). The land uses in the Songkhram river catchment are agriculture (65% of the area), forest (20%), settlement (5%), surface water (5%), and other (5%) (Land Development Department 2014).

Floodplains of these two rivers share the characteristic of a relatively natural flood pulse. Natural patterns of floodplains' vegetation communities and productivity are found in both floodplains, although the Narew River floodplain soil is dominated by organic peat soil, while the Songkhram River floodplain soil is dominated by mineral soil.

Chapter 2

Flood water hydrochemistry patterns suggest sink function of the Songkhram River monsoon floodplains (Thailand)

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Abstract: Although important for the eco-hydrological functioning of the floodplain, the interactions between river and floodplain are not well understood, especially for rivers in the tropical monsoon region. To explore the floodplain functioning of a tropical monsoon river system the longitudinal and transverse floodwater hydrochemical characteristics were studied in the Songkhram river (Thailand) and its floodplains. Water samples were taken during the monsoon period from 61 locations in the river and on its floodplain. Analysis of floodwater hydrochemistry revealed a significant decreasing longitudinal trend for most dissolved solids, attributable to geological differences. We also observed a significant decreasing transverse trend from the river to the floodplain. Nutrient concentrations revealed lower dissolved nitrogen, phosphate, and potassium concentrations on the floodplain than in the river channel, which suggests the floodplain functions as a sink for nutrients and chemical species in the river floodwater. This sink function may be related to the presence of a belt of bamboo separating the river from the floodplain, which seems to act as a sediment trap and nutrient filter, but this needs to be verified by additional dedicated research.

Keywords: ecological function, bamboo, spatial pattern, South-east Asia, flood pulse concept, river continuum concept

2.1 Introduction

River floodplains are key elements in the landscape. Their numerous and diverse natural functions and ecosystem services include providing a refuge for many species (Ward et al., 1999; Ward et al., 2002; Tockner and Stanford 2002) river water purification (Costanza et al., 1998; Keddy et al., 2009), and flood storage and control (Banerjee et al., 2013; Grygoruk et al., 2013). The hydrology and ecosystem function of floodplains are highly dynamic (Junk et al., 1989; Bayley, 1995; Ward et al., 1999; Ward & Tockner, 2001). The extent, depth, and duration of inundation depend on the hydrology and local topography (Steiger and Gurnell 2003; Southwell and Thoms 2011; Langhans et al., 2013), while the chemistry of floodplain water is a function of exchange processes between groundwater and surface water and the influence of precipitation (Boulton et al., 1998; Doering et al., 2013; Keizer et al., 2014). Nutrient transport in the river–floodplain system is important for the productivity and species richness of floodplain vegetation.

The interactions and exchanges between the river and the floodplain during the inundation, when water, sediment, and nutrients move across the floodplain, can be described by the flood pulse concept (FPC), which was originally proposed by Junk et al. (1989) and Junk & Wantzen (2004). The re-wetting of dry sediment mobilizes nutrients and (in)organic matter from locally mineralized and decomposed organic matter (Baldwin and Mitchell 2000; McClain et al., 2003). In accordance with the FPC, it is assumed that river water covers the entire floodplain during the inundation, producing a homogeneous hydrochemistry over the inundated floodplain. However, it has been shown for several floodplains that the water quality is not homogeneous across the floodplain. Distinct spatial patterns in inundation water quality have been observed for temperate river floodplains in Poland (Chormanski et al., 2011; Keizer et al., 2014) and Austria (Tockner et al., 1999). Large river floodplains located from the Arctic to the Amazon also demonstrate a zone of mixing between the sediment-rich river water and the local water (groundwater and/or precipitation), defined as the "perirheic zone" (Mertes 1997). The spatial heterogeneity in the floodplains is thought to result from the presence of different water sources and the impact of antecedent moisture conditions; in turn, these may cause various processes over time, such as decomposition of organic matter, solute transport, and absorption/desorption to/from soil (Wassen and Joosten 1996; Lewis et al., 2000; Beumer et al., 2008).

The transverse transport of material across floodplains is not the only process relevant for river–floodplain ecosystems: also important is longitudinal transport. The water quality can be altered downstream along the river channel by spatial differences in geological substrates that result in varying dissolved material input to the river channel. In turn, the concentrations of dissolved material, such as nutrients, may be increased or decreased when river water spreads over the floodplain, affecting the floodplain ecosystems (Lewis et al., 2000). The longitudinal patterns can be explained by using the river continuum concept (RCC)(Vannote et al., 1980), which assumes that physical gradients in the river from upstream to downstream are responsible for a continuum of change in ecological processes along the river. According to the RCC, nutrient input is mainly from organic material and is expected to vary downstream along the river because sources and forms of input vary, shading and turbidity affect the penetration of solar radiation into the water column, and the biotic community adapts in response. The physico-chemical variables that most influence the longitudinal patterns in the river channel are watershed area, phosphate concentration, total dissolved solids, solar radiation, annual precipitation, the ratio of stream length to the watershed area, and terrestrial litter input (Cushing et al., 1983). However, the RCC does not describe ecological processes for rivers and floodplains combined but mainly predicts ecological processes in river channels. Also, the hydrochemistry can vary along the river due to discontinued geomorphological characteristics (Sedell et al., 1989; Tockner et al., 2003).

Recently, Humphries et al. (2014) proposed a new concept to merge the longitudinal and the transverse processes in rivers and their floodplains, called the "river wave concept". This concept sees river flow characteristics as waveforms and characterizes them according to positions on the ascending or descending discharge limb, trough, and crest. These positions correspond to stages of water level in the river and floodplain. Longitudinal and transverse processes of the river and the floodplain ecosystems are a function of these positions, temporally and spatially.

To the best of our knowledge, unifying concepts that describe the hydrochemistry and ecological functioning of floodplains have not been tested for tropical monsoon rivers. Such rivers provide important environmental, economic, and social benefits to local communities, including biodiversity hotspots, agricultural land, and freshwater. However, existing knowledge of tropical monsoon river–floodplain systems is insufficient for their efficient conservation and management (Bayley 1995; Arthington et al., 2010). To improve our understanding of the river–floodplain function in a tropical monsoon region, we examined the longitudinal and transverse spatial patterns of hydrochemistry, nutrient availability, and land cover along the Songkhram river, its tributaries, and floodplain in north-eastern Thailand. The Songkhram monsoon river is characterized by a relatively natural flow and can thus serve as a reference for tropical monsoon systems. In this research, the following three questions were central: 1) What are the longitudinal (upstream-downstream) and transverse (river–floodplain) trends in hydrochemistry and nutrient availability during the flood period in the monsoon river system? 2) Do nutrient availability and water chemistry differ significantly between the main river channel and the floodplain during the flood period? 3) Are these differences related to land cover on the floodplain?

2.2 Study area

The Songkhram river, a tributary of the Mekong River, is located in north-eastern Thailand (Fig.2.1). It is approximately 495 km long, drains an area of 13,000 km^2, and its average discharge is 226 m^3 s^{-1} during the monsoon season and 2.3 m^3 s^{-1} during the dry season. Precipitation records from 1980 to 2010 at Ban Tha Kok Deang, centrally located in the catchment, show that annual precipitation averages 1960 mm and ranges from 1090 to 2880 mm. The monsoon season lasts from

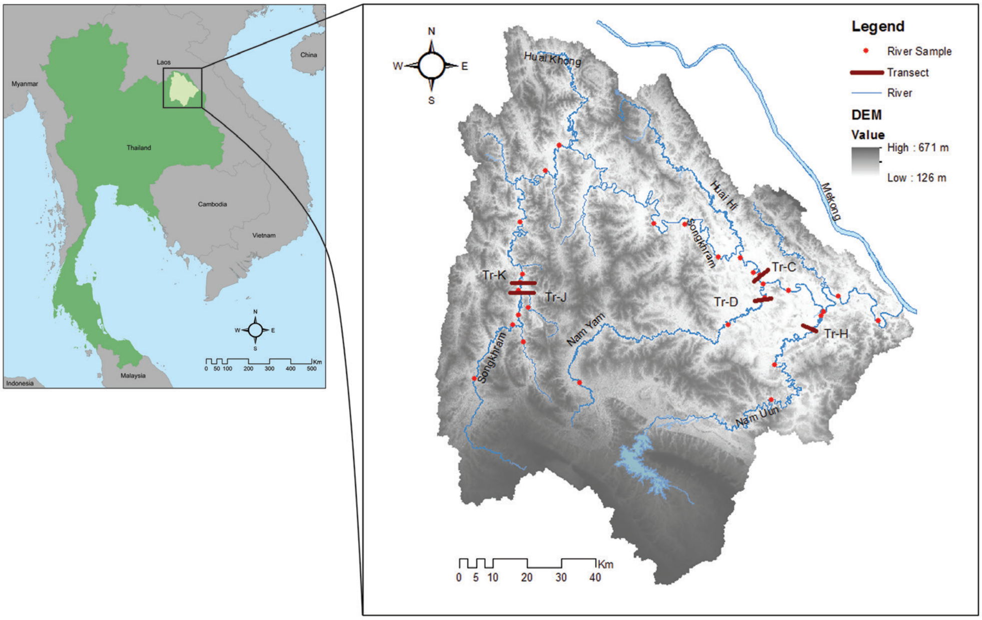


Fig.2.1 Location of the Songkhram river catchment in north-eastern Thailand (left) and surface water network and elevation (right). Sample locations in the main river channel and the locations of each transect across the floodplains are shown in red dots. Transects J and K are located in the upper course of the Songkhram river. Transects C, D, and H are located in the lower courses of the Songkhram, Nam-Yam, and Nam-Uun rivers, respectively. The elevation is in meters relative to mean sea level, based on a Digital Elevation Model (USGS, 2006).

May to September and is followed by a cool-dry season from October to February that is succeeded by a hot-dry season from March to April. During the monsoon season, the average precipitation is 1690 mm (range 906 – 2420 mm); this compares with an average precipitation of 270 mm (range 80 – 490 mm) during the dry season (figures compiled from daily data from the Department of Water Resources, Thailand). Mean annual temperature is 26 °C and the warmest month is April (35 °C). The minimum temperature is around 15 °C from December to January.

Extensive floodplains are found in the lower part of the basin as well as along the upper part of the river. These inundate yearly due to high river discharges during the monsoon season and water backing up from the Mekong River (Blake et al., 2011). There are two major tributaries: the Nam-Yam and Nam-Uun. These join the main river in the lower basin. The river's discharge behavior is quite natural, as there are no large dams that regulate water flow in the main channel. The average area flooded annually in the lower basin, estimated using Landsat images from the period 2000 to 2006, is 760 km^2 (Thiha et al., 2012).

The land uses in the Songkhram river catchment are agriculture (65% of the area), forest (20%), settlement (5%), surface water (5%), and other (5%) (Land development Department, 2014). The floodplain vegetation community is known as "Pa Bung Pa Taam" and is dominated by a dense thorny bamboo: *Bambusa flexuosa* (Blake et al., 2011; Khammongkol et al., 2013).

The geology of the catchment is characterized by sedimentary rocks, dominated by sandstone, siltstone, mudstone, and claystone of the Phu Thok formation (KTpt) of the Cretaceous and Tertiary age. In the upstream area of the catchment, the Maha Sarakham formation (KTms) from the mid-Cretaceous is found, containing a layer of readily soluble rock salt, gypsum, anhydrite, and potash. Alluvial deposits and terrace deposits are found on the floodplain, along the river channel: see Fig.2.2 (Department of mineral resources, 2012).

2.3 Methods

2.3.1 Floodwater sampling

During the monsoon season from 10 to 26 September 2013, we conducted a field campaign in the Songkhram river catchment to sample floodwater from the main river channel and along transects across the inundated floodplain. Samples were taken during the falling limb of the yearly flood curve: in September 2013, the average discharge of the Songkhram river was 1220 m^3 s^{-1}, whereas, in August, the average discharge was 1660 m^3 s^{-1} (Royal Irrigation Department, 2016).

We visited a total of 107 locations distributed along the entire length of the river. Accessibility was important, and therefore, most were at or near a bridge. Some locations in the Nam-Yam tributary were chosen because they could easily be reached by boat. The locations of the transects across the river floodplain were selected based on the classification of floodwater zones from a Landsat 8 image acquired on 13 August 2013, one month before the field campaign. Five transects were visited during the field campaign, three of which were in the lower basin: one across the Songkhram river (TR-C), one across the Nam-Yam river (TR-D), and one across the Nam-Uun river (TR-H). Two transects (TR-J and TR-K) were positioned across the Songkhram river in the upper basin (Fig. 2.1).

To select locations for water sampling, we measured electrical conductivity (EC), total dissolved solids (TDS), temperature, dissolved oxygen, and pH in situ using a YSI 556MPS Multi-parameter Instrument (YSI Environmental, 2009) that had undergone maintenance service just prior to use. Everyday pH and oxygen were calibrated before being measured. Along each transect, water

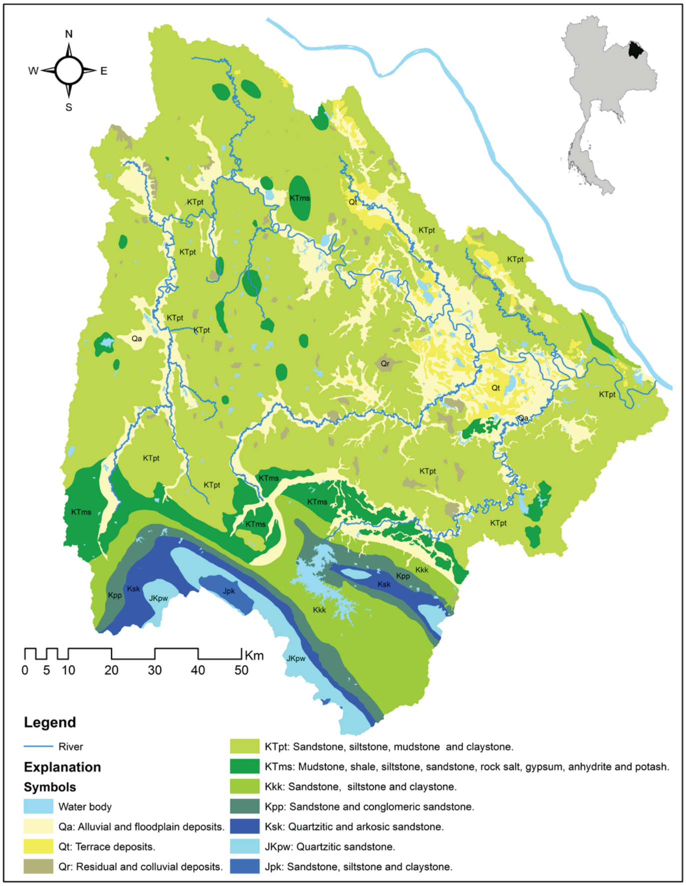


Fig.2.2 The geology of the Songkhram River catchment is dominated by sedimentary rock (Geological map of Thailand scale 1:250,000, Department of Mineral Resources, Thailand, 2012).

samples were taken in the river and at several locations across the inundated floodplain. In the floodplain zone, sampling locations were chosen in light of the EC measurements and the observed vegetation communities so that the sampling sites captured the variation in the EC and vegetation communities.

In total, 73 water samples were taken from 61 of the 107 locations in the rivers and floodplains. Not all 107 locations were sampled because some locations were close to each other, and the on-site EC measurement did not show notable differences. We used a Kemmerer-type water sampler 10 cm in diameter and 30 cm long, with a rope attached to open the lid for underwater sample collection, and a stainless steel rod 20 cm long extending from the base of the bottle. At each sampling location, 2000 ml of water was collected at ca. 30 cm below the water surface to avoid floating debris. Samples were taken from 33 locations in the river and 28 locations on the floodplain. In addition, to obtain insight into possible stratification in the water column, a second sample was collected at ca. 20 cm from the bottom at 12 locations (4 in the river; 8 on the floodplain). The vegetation and land use types around each sampling location were described.

The water samples were collected in a high-density polyethylene water container and stored immediately under dark conditions in a cooler on ice. The container was pre-washed on site, with the water to be sampled before being filled with the sample. Within the same day of collection, the samples were transported to the laboratory of the Aquaculture Research Institute, Department of Fisheries, Ministry of Agriculture and Cooperatives in Sakon Nakhon, for filtration and treatment.

In the laboratory, within 24 hours of the sampling, alkalinity was measured on a 5 ml aliquot using a chemical test kit (Merck KGaA, 2013). A 250 ml unfiltered water sample had been stored in a wide-mouthed Nalgene PE bottle (250 ml) and treated with 2 ml 0.05 M sulfuric acid. These samples were analyzed for total phosphorus (TP) using persulfate oxidation digestion and spectrophotometry (Spectronic Genesys 20, Laboratory of Environmental Studies, Faculty of Environmental and Resource Studies, Maha Sarakham University, Thailand).

From each water sample, 500 – 1000 ml (depending on filtration speed) was filtered through a 1.2 micron Whatman GF/C glass fiber filter. The filtrate was refiltered through a 0.45 micron Whatman cellulose acetate membrane filter, and an aliquot comprising the first 125 ml of filtrate was then stored in a wide-mouth PE bottle (125 ml), and 1 ml of 65% nitric acid was added. An aliquot comprising the second 125 ml of the filtrate was also stored in a wide-mouth PE bottle but was not acidified. Most samples were filtered on the day they were sampled; all samples were filtered within 48 hours of collection in the field. The first and second aliquots of the filtrate were kept under dark and cool conditions (approximately 4 °C) for approximately 2 days until they were transported to the GEO lab of Utrecht University, the Netherlands. The samples were in transit for 8 days. Using inductively coupled plasma optical emission spectrometry (ICP-OES), the first aliquots were analyzed for the following major cations, trace elements, and metals: aluminum (Al^{3+}), barium Ba^{2+}, calcium (Ca^{2+}), iron ($Fe^{2+/3+}$), potassium (K^{+}), magnesium (Mg^{2+}), manganese (Mn^{2+}), sodium (Na^{+}), silica (Si^{+}), strontium (Sr^{2+}), and zinc (Zn^{2+}). The second aliquots were analyzed for chloride (Cl^{-}), nitrate (NO^{3-}), nitrite (NO^{2-}), and sulfate (SO_4^{2-}) using ion chromatography. Ammonium (NH_4^{+}) and phosphate (PO_4^{3-}) were analyzed by a continuous segment flow analyzer (Seal Analytical, 2000).

2.3.2 Statistical characterization of floodwater hydrochemistry

To ascertain the variance of the hydrochemical parameters analyzed, a statistical overview was created showing the number, mean, minimum, maximum, range, standard deviation, and coefficient of variation of each parameter. To understand which combination of parameters accounted for the largest portion of the variance, we used principal component analysis (PCA) with the varimax rotation method performed on the standardized data. Next, the factor scores of each sample were determined by means of regression analysis. This reduced the chemical variables to three main factors, which were determined by a parallel analysis method (Franklin et al., 1995; Peres-Neto et al., 2005). Total dissolved nitrogen (TDN) was calculated by the summation of nitrogen in NH_4^{+}, NO^{2-}, and NO^{3-} . There were some missing values in the NO^{3-} dataset because concentrations were below the detection limit for some samples and some errors occurred when preparing samples. As PCA does not allow missing values, we first assumed that there were no NO^{2-} and NO^{3-} for the samples in question. Then we tested this assumption by only using NH_4^{+} as nitrogen and using the half values of the lowest detection limits for NO^{3-} and NO^{2-}. The subsequent PCA analysis did not reveal any significant differences. We did not include total dissolved solids (TDS) in the PCA since TDS is directly proportional to the measured EC.

2.3.3 Determining longitudinal and transverse trends

Longitudinal (upstream–downstream) trends in hydrochemistry were analyzed by plotting the scores of the three principal components against the distance to the river catchment outlet for samples taken in the river channel. The scores of the first principal component were also plotted on a map of the catchment to analyze their spatial distribution in the Songkhram river and its tributaries. Transverse hydrochemical trends in the river–floodplain system were analyzed by plotting the scores of the three principal components against the distance of the floodplain sampling location from the main river channel. This was done for all transects together and also for each individual transect.

Differences between river channel and floodplain concentrations of the nutrients phosphorus, potassium, and nitrogen in floodwater were analyzed by comparing box plots for all river channel samples with box plots for all floodplain samples.

2.3. 4 Relationship between floodplain land cover and hydrochemistry

To ascertain the relationship between floodwater hydrochemistry and land cover, the land cover under the flooded areas was analyzed by first estimating flood extent and then determining the land cover for that area.

To estimate the inundated area of the floodplain, we used satellite images of Landsat 7 ETM+ from 17 August 2000. Interpretation of the image of the upper part of the basin was hampered by cloud cover. Therefore the floodplain area we report on in this study refers to the lower part of the catchment only. The image, which has a spatial resolution of 30 m, was visually interpreted, and the flooded area was delineated using the ENVI 5.0 software package (Exelis Visual Information Solutions, 2014). The date on which it was acquired, 17 August 2000, is in the third quartile of the highest precipitation records in the period 1980-2010. Thus we consider this image to be representative of average to high floods.

The land cover classification for the lower river basin was produced using a Landsat 8 OLI scene acquired on 3 January 2014 during the dry season. This image also has a spatial resolution of 30 m. It was radiometrically corrected to the top-of-atmosphere reflectance image following the USGS guidelines (USGS, 2013). Land cover was determined using a supervised classification approach with the maximum likelihood classifier (Lillesand et al., 2008). This approach utilizes representative samples of particular land cover classes of interest as training regions. The training region is an area of known land cover from ground truth data assigned to the corresponding pixel(s) in the image, which the software uses as a guideline when assigning land cover classes to similar image pixels. When selecting training regions, we relied on information and experience acquired on the ground during fieldwork in February 2013.

The classification accuracy was estimated by randomly taking 330 locations in the classified image and comparing them with the land cover derived by visually interpreting a high-resolution satellite image available in Google Earth acquired on 10 January 2014. To estimate the accuracy of the supervised classification, a confusion matrix was computed; the matrix compares the classification result class with the actual class of land cover as determined by visual interpretation from Google Earth.

To determine the land cover characteristics of the lower basin floodplain area, we superimposed the map of the inundated area on the land cover class map.

2.4 Results

2.4.1 Statistical characterization of flood water hydrochemistry

Hydrochemical statistics of the sampled surface waters are summarized in table 2.1. The chemistry of the water is dominated by alkalinity, Cl^-, Na^+, Ca^{2+}, and Si^+. On average, the coefficient of variance (CV) is 67% over the area, indicating general great variability between the samples. The most variability was found for NH_4^+ and Mn^{2+}, although concentrations were low. Low variability (CV less than 40%) was found for temperature, pH, dissolved oxygen, and some ions (Ba^{2+}, $Fe^{2+/3+}$, Si^+, Zn^{2+}).

Table 2.1. Statistical summary of flood water hydrochemical variables measured in the field (above line) and from flood water sample laboratory analyses. SD is standard deviation, CV is coefficient of variation.

Variables	Units	(n)	Mean	Min	Max	Range	SD	CV
EC	μS/cm	118	73.19	12	309	297	51.11	0.7
TEMP	°C	116	31.09	24.16	40.86	16.7	2.05	0.07
pH	pH units	118	5.97	3.2	7.13	3.93	0.48	0.08
DO	mg/L	112	4.87	0.01	9.97	9.96	1.62	0.33
TDS	mg/L	116	46.97	8	201	193	32.96	0.7
Alkalinity	mg/L	72	21.02	4.25	131.75	127.5	15.38	0.73
TP	mg/L	73	0.05	0.01	0.16	0.15	0.03	0.63
PO_4^{3-}	mg/L	73	0.02	0.004	0.15	0.15	0.02	0.93
Cl^-	mg/L	73	15.32	0.56	74.09	73.53	12.63	0.82
NH_4^+	mg/L	73	0.06	0.01	0.61	0.6	0.07	1.13
NO_2^-	mg/L	2	0.17	0.07	0.28	0.22	0.15	0.87
NO_3^-	mg/L	10	0.58	0.11	1.43	1.32	0.46	0.79
SO_4^{2-}	mg/L	73	1.93	0.37	15.91	15.54	2.09	1.09
Al^{3+}	mg/L	73	0.6	0.17	2.66	2.49	0.66	1.11
Ba^{2+}	mg/L	73	0.05	0.02	0.16	0.14	0.02	0.38
Ca^{2+}	mg/L	73	4.31	0.52	27.88	27.36	3.29	0.76
$Fe^{2+,3+}$	mg/L	73	0.7	0.31	1.97	1.66	0.23	0.33
K^+	mg/L	73	1.74	0.27	10.9	10.63	1.23	0.7
Mg^{2+}	mg/L	73	1.27	0.15	4.51	4.36	0.6	0.47
Mn^{2+}	mg/L	73	0.07	0	0.44	0.44	0.09	1.33
Na^+	mg/L	73	9.91	1.17	42.8	41.63	7.33	0.74
Si^+	mg/L	73	2.24	0.44	6.63	6.19	0.88	0.39
Sr^{2+}	mg/L	73	0.02	0	0.12	0.12	0.02	0.78
Zn^{2+}	mg/L	73	0.02	0.01	0.05	0.04	0.01	0.27

PCA revealed that the three main principal components explain 62% of the overall variance in water chemistry (Table 2.2). The first PCA component (accounting for 44% variance) contains most of the chemical variables, with factor scores above 0.7 for EC, Ca^{2+}, Mg^{2+}, HCO_3-, Na^+, Cl^-, K^+, SO_4^{2-}, Si^+, and Sr^{2+}. We interpret this principal component as the enrichment of water with major ions resulting from weathering and dissolution of minerals.

The second PCA component (accounting for 10% variance) contains the variables Zn^{2+}, TP, and PO_4^{3-}, which correlate negatively with dissolved oxygen levels. The presence of high TP and PO_4^{3-} concentrations when dissolved oxygen is low indicates anaerobic and/or chemical reduction

Table 2.2 Principal component scores of flood water hydrochemical variables on the three main principal component axes (n=73). Scores higher than |0.5| are in bold.

Variables	PC 1	PC 2	PC 3
EC	**0.933**	-0.064	0.023
pH	0.442	-0.365	-0.065
DO	0.013	**-0.546**	-0.177
Alkalinity	**0.753**	-0.047	-0.304
Al^{3+}	-0.103	-0.1	**0.853**
Ba^{2+}	**0.608**	0.201	0.197
Ca^{2+}	**0.945**	0.061	-0.146
$Fe^{2+,3+}$	0.335	0.267	**0.593**
K^{+}	**0.824**	0.119	-0.151
Mg^{2+}	**0.908**	0.026	-0.089
Mn^{2+}	**0.589**	0.336	-0.205
Na^{+}	**0.88**	-0.099	0.088
Si^{+}	**0.758**	0.03	0.193
Sr^{2+}	**0.858**	0.125	0.008
Zn^{2+}	-0.23	**0.701**	0.067
TP	0.306	**0.637**	-0.243
PO_4^{3-}	0.357	**0.546**	-0.328
Cl^{-}	**0.84**	-0.156	0.089
SO_4^{2-}	**0.716**	0.196	-0.308
TDN	0.493	0.033	0.081
% of Variance	43.5	9.9	8.3

conditions during which PO_4^{3-} is released to the water. Thus, we interpret this principal component as low redox conditions enhancing the dissolution of phosphorus. It is notable that this condition was observed deeper in the water column, where dissolved oxygen is lower than at the surface.

The third PCA component (accounting for 8% variance) is associated with Al^{3+} and $Fe^{2+/3+}$, which we interpret as the dissolution of aluminum and iron compounds from the soil.

2.4.2 Longitudinal and transverse hydrochemical trends

Longitudinal trends in hydrochemistry were analyzed by plotting the scores of river samples on each principal component arranged from upstream to downstream (Fig.2.3). Only the first component correlated significantly with the relative distance to the river outlet ($r = -0.59$, $p < 0.05$), indicating that the dissolved solids decreased in the downstream direction. The spatial distribution also shows higher scores in the upstream part of the Songkhram river and its tributaries, with lower scores in the downstream part (Fig.2.4). This longitudinal trend is related to the geological substrate of the catchment (see Fig.2.2). In the upstream area the river channel is cut into bedrock: the KTms formation that consists of rock salt, gypsum, anhydrite, and potash, while the main geological substrate of the floodplain is alluvium. The correlation between the smallest distances of the sample location to the KTms formation and the PC1 score was significant, with $r = -0.43$ ($p < 0.05$). This implies that the concentration of dissolved material in the water is related to the distance from its geological origin.

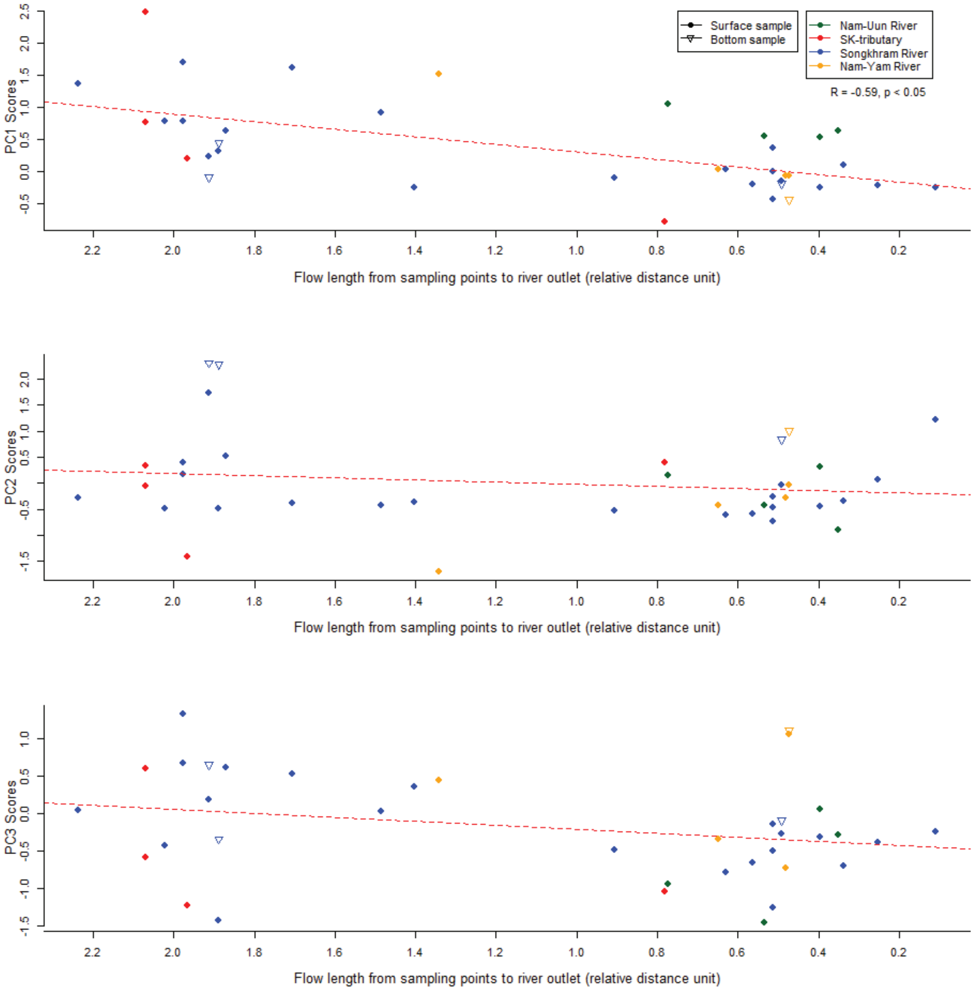


Fig.2.3. Longitudinal (upstream-downstream) trends in PCA scores of river channel sampling locations. Only the first PCA component scores are significantly correlated with the distance between the sampling location and the Songkhram catchment outlet (r = -0.59, p < 0.05). Surface samples were taken at 30 cm below the water surface, bottom samples at 20 cm above the bottom.

For the transverse trends across the floodplains using all transects (Fig.2.5), a significantly decreasing trend was observed for the first component. The scores of this component correlated significantly with the distance of each sampling location to the main river channel, with r = -0.32 ($p < 0.05$). This means the concentration of major dissolved solids in the floodplain inundation water is inversely related to the distance from the main river channel. In contrast, we found no significant longitudinal or transverse trends in principal components 2 and 3, nor did we find a correlation with the distance from the geological substrate.

The nutrient concentrations, expressed by the variables TP and PO_4^{3-}, total dissolved nitrogen (TDN), and potassium (K^+), of samples from the main river channel were compared with those

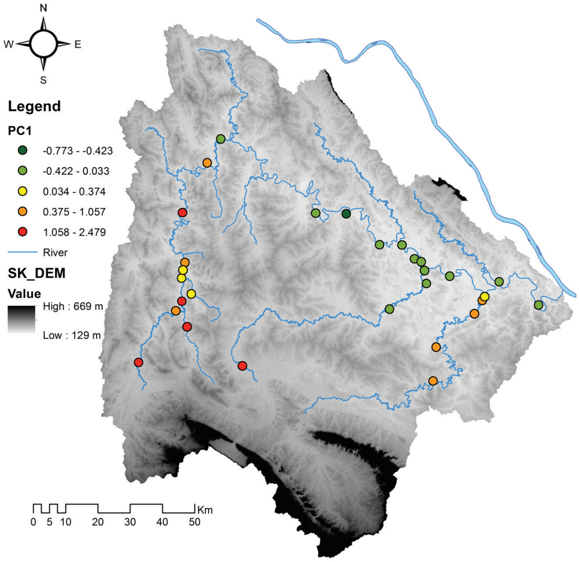


Fig.2.4. Spatial distribution of river water scores on the first principal component shows higher scores in the upstream part of the Songkhram river and its tributaries, with lower scores in the downstream part

from the floodplain to better understand the spatial patterns of these ecologically important elements. The concentrations of PO_4^{3-}, TDN, and K^+ were significantly higher in the main river channel than in the floodplains (t-test, $p < 0.05$), but the concentrations of TP did not have significantly higher values in the river channel (see box plots in Figure 2.6). This indicates that the floodplain generally functions as a sink for nutrients.

2.4.3 Relationship between hydrochemistry and floodplain land cover

The inundated area estimated from the Landsat 7 ETM+ image (17 August 2000) was ca. 855 km^2. Its shape is influenced by the topography: in low-lying areas, it extends further inland (see Figs 2.1 and 2.7), and flooded areas link up with permanent water bodies in depressions (see Fig.2.8).

Ten land cover types were distinguished in the lower floodplain of the Songkhram river catchment (derived from Landsat 8 OLI data, Fig.2.8). The major land cover type in the floodplain is agriculture, which is reflected in the classes rice paddy culture (both rain-fed and irrigated), plantations, and bare soil. Bare soil is usually the result of rice paddy field preparation or land that has recently been cleared for a new plantation of rubber (Hevea brasiliensis). These agricultural land cover types are highly dynamic during the year due to anthropogenic activities. The overall map accuracy was 72%, as validated by randomly generating locations for each mapping class (330 locations in total) and comparing them with ground cover assigned by eye on the basis of the high-resolution Google Earth images (see Table 2.3). The classification with the greatest uncertainty concerns rice paddy (45 %), which is mostly confused with the grass and herbaceous and shrub class or with the class "water". The settlement class also shows low accuracy (50%) as it can be confused with a similarly reflecting surface of the "bare soil" class and the "grass and herbaceous and shrubs" class. The bamboo vegetation class had high classification accuracy (90 %).

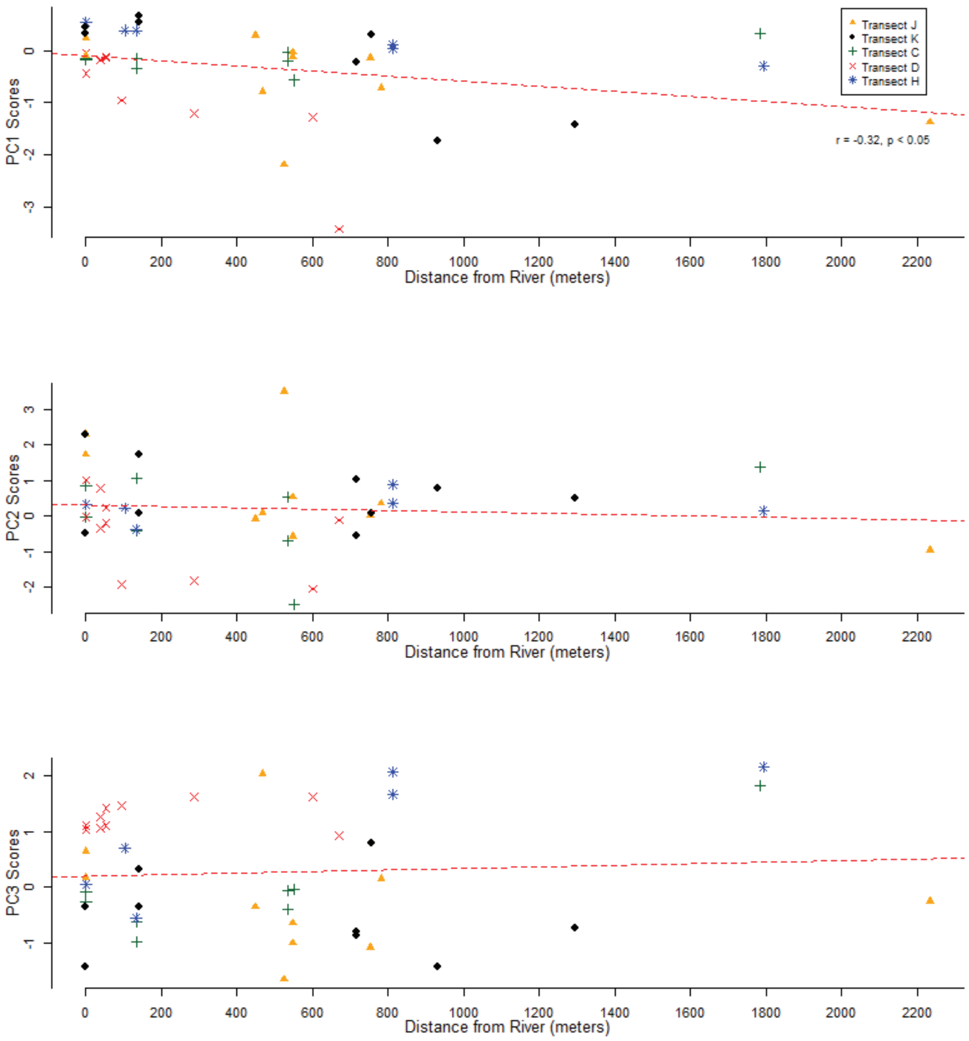


Fig.2.5. Transverse trends in PCA scores of floodplain samples taken in the transects, arranged from the main river channel out into the floodplain. Only the first principal component scores (PC1) are significantly correlated with the distance of the sampling location from the main river channel (r = -0.32, p < 0.05).

Superimposing the vegetation and land cover classes on the map of inundated areas (Fig.2.8) revealed that the land cover accounting for the largest proportion of flooded land was agricultural: 52% of the flooded area was comprised of bare soil, irrigated and rain-fed rice paddies, and plantations. The class containing grass, herbaceous vegetation, and shrubs together occupied 20 % of the flooded area. The remaining categories were open water (9%), marsh (8%), deciduous forest (6%), bamboo vegetation (4%), and settlements (1%).

It is clear from Fig.2.8 that bamboo vegetation is found along the river channels and, in most places, consists of a belt of a few hundred meters wide, with a maximum width of 1,200 m. Behind the bamboo belt, the class of grass, herbaceous, and shrubs is generally present. In the field, a narrow strip of a native thorny shrub was often observed growing next to the bamboo belt, with a gradual transition to grass and herbaceous vegetation. The irrigated rice paddy class was observed nearby water bodies that do not dry up in the dry season, such as lakes, oxbow lakes, and the main river channel. Rain-fed rice paddies were generally found further away from the river channel.

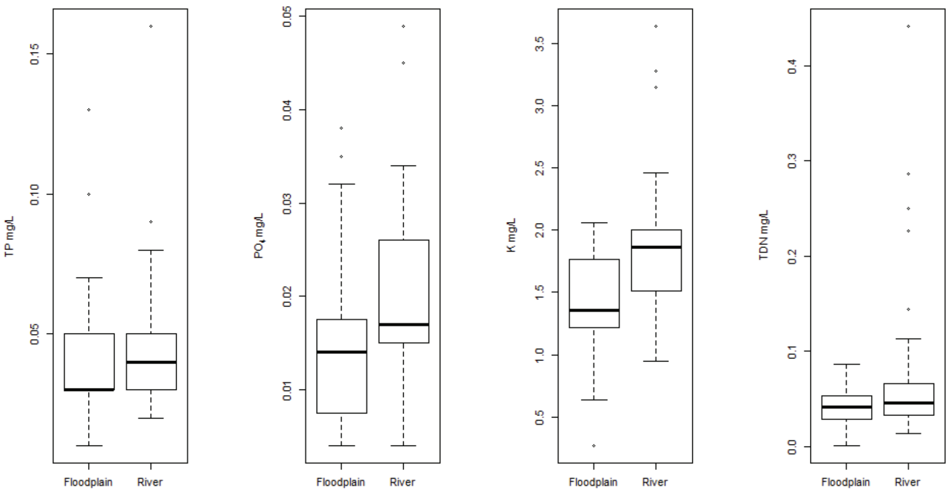
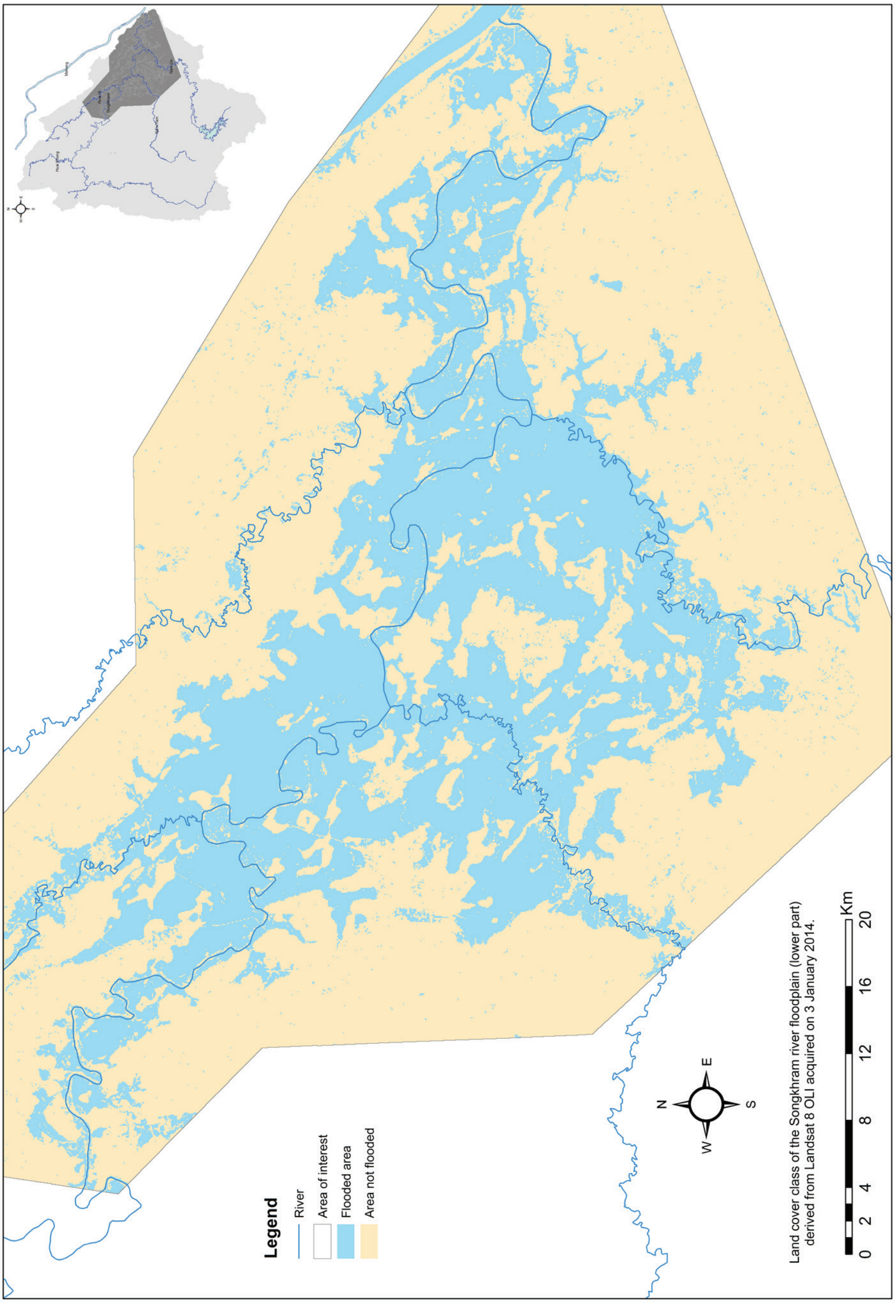


Fig.2.6. Box plots of major nutrients (TP, PO_4^{3-}, K^+, TDN) compare floodplains and the main river channel. PO_4^{3-}, TDN, and K^+ are significantly higher in the main river channel than in the floodplains (t-test, $p < 0.05$). Each box plot represents the minimum, first quartile, median (thick horizontal line), third quartile, and maximum. Dots depict outliers.

Table 2.3. Confusion matrix for the vegetation and land cover map accuracy assessment.

verified class	Map class											
	Bamboo	Bare soil	Urban	Irrigated rice paddy	Rain fed rice paddy	Forest	Grass, shrubs	Marsh	Plantation	water	Total	N. correct
Bamboo	27	0	0	7	0	0	0	0	0	0	34	27
Bare soil	0	26	4	0	0	0	2	0	0	0	32	26
Urban	0	0	15	0	0	0	1	0	0	0	16	15
Irrigated rice paddy	0	0	2	27	0	0	1	6	0	0	28	18
Rain fed rice paddy	0	1	2	1	27	0	1	0	0	0	32	27
Forest	1	0	1	1	0	24	2	1	1	0	31	24
Grass, shrub	2	3	4	9	3	5	21	0	6	0	53	21
Marsh	0	0	0	2	0	0	0	19	0	0	21	19
Plantation	0	0	0	1	0	1	0	1	23	0	26	23
Water	0	0	0	7	0	0	0	1	0	30	38	30
mixed	0	0	2	5	0	0	2	2	0	0	11	0
Grand Total	30	30	30	30	30	30	30	30	30	30	330	238
Accuracy	90%	87%	50%	45%	90%	80%	70%	63%	77%	100%		**72%**



Land cover class of the Songkhram river floodplain (lower part) derived from Landsat 8 OLI acquired on 3 January 2014.

Fig.2.7. The extent of the flooded area in the lower basin of the Songkhram River was derived from a Landsat 7 ETM+ image of 17 August 2000.

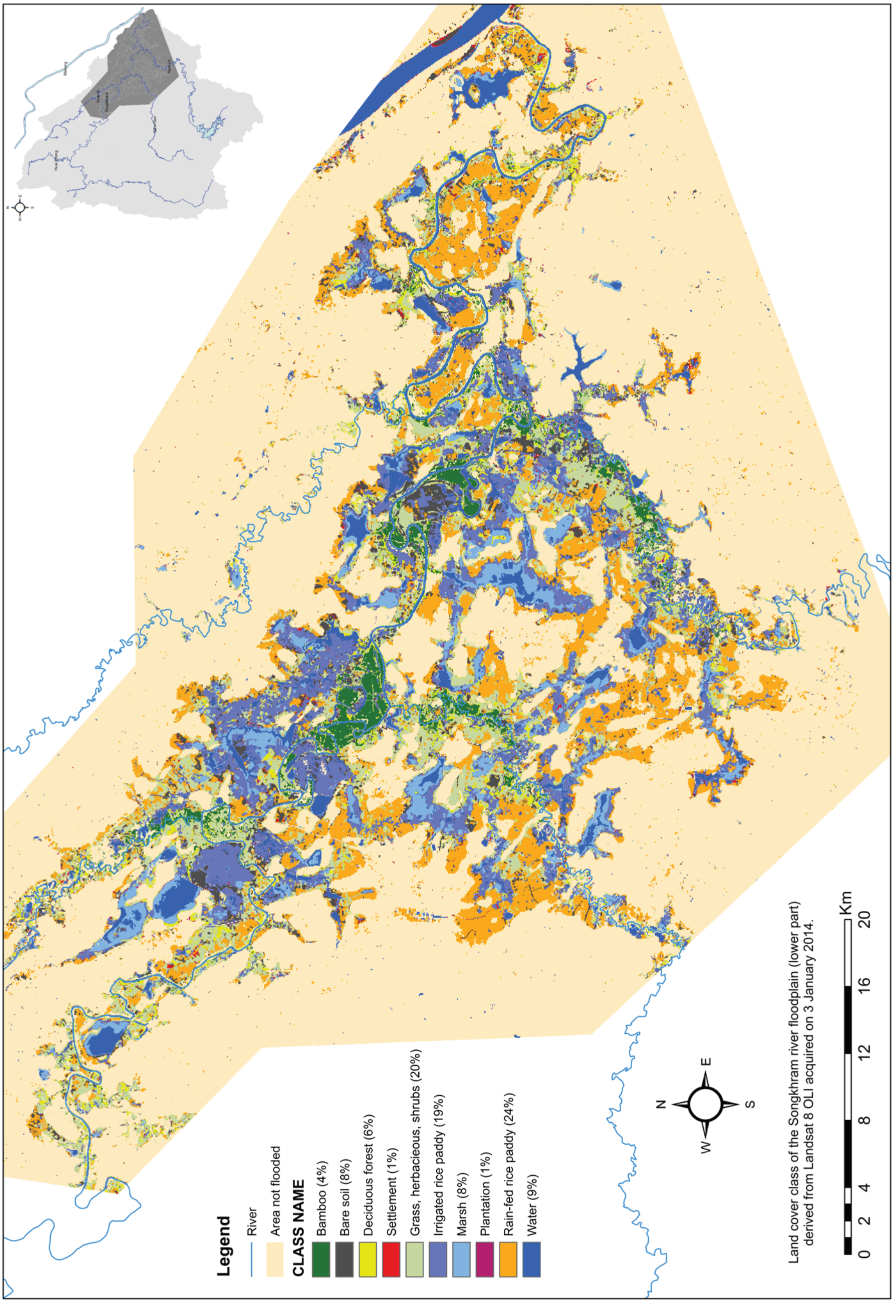


Fig.2.8. Land cover classes for the flooded area in the lower basin of the Songkran River (see Fig. 7). The results were obtained by a supervised classification with the maximum likelihood method of the Landsat 8 OLI image for the dry season in January 2014.

2.5 Discussion

2.5.1 Longitudinal and transverse hydrochemical trends

Our sampling strategy was designed to capture the maximum spatial variability of floodwater chemistry in the river channel and floodplain. We sampled along the main river channel as well as its tributaries. The transect locations were selected to represent variability in the floodplains in the upper and lower parts of the river basin. Water chemistry is influenced by the origin of the water and by certain natural and anthropogenic factors. The following factors are relevant: the occurrence of highly soluble or easily weathered minerals; the distance from the marine environment, which controls the exponential decrease of ocean aerosols that are input to the bordering land; the aridity (precipitation/runoff ratio), which determines the concentration of dissolved substances; terrestrial primary productivity (which controls the release of nutrients); and ambient temperature. Our hydrochemical data on the Songkhram monsoon river revealed that concentrations in the river and floodplain inundation water were low. The water was poor in dissolved solids and nutrients and slightly acid. The dominant ion concentrations were Na^+, Cl^-, Ca^{2+}, and alkalinity (HCO_3-), which are related to the weathering products of the Songkhram river catchment geology, especially the KTms formation which is the likely source of river water sodium and chloride from rock salt, calcium and sulfate from gypsum and anhydrite, and potassium from potash. The relatively soft sandstone is a source of silica.

The EC, which is a good indicator of dissolved materials in the water, was on average 73 µS/cm. This is much lower than the EC of the 3 groundwater samples we took during the fieldwork (EC average 414 µS/cm). This difference can be attributed to the river water being greatly diluted during the monsoon season by the large amounts of rainfall, which has a low EC (Meybeck & Helmer, 1989). Decreased solute concentrations during the monsoon have indeed been reported in a previous study of the Songkhram river (Satrawaha et al., 2009) as well as for monsoon rivers in India (Mehto & Chakrapani, 2013; Kumarasamy et al., 2014; Thomas et al., 2014).

The relatively high average coefficient of variation indicates that the hydrochemistry of the floodwater of the Songkhram monsoon river and its floodplain is very variable. The longitudinal variability of hydrochemical concentrations in the Songkran River showed a decreasing trend from upstream to downstream. We relate this trend to the upstream occurrence of the geological KTMms formation with highly soluble minerals, as substantiated by the significant correlation between the PC1 score and the smallest distances of the sample location from the KTms formation.

The transverse hydrochemical trend revealed solute concentrations decreasing from the Songkhram river channel to its floodplain. This was evident both from the PC1 scores, which reflected the concentrations of most elements, and from the box plots, which showed significantly higher concentrations in the river channel than on the floodplain for PO_4^{3-}, TDN, and K^+. We, therefore, conclude our hydrochemical floodwater pattern suggests a sink function of the monsoon floodplains for dissolved solids from the Songkhram river in Thailand.

2.5.2 Bamboo as a sediment and nutrient filter

The water column on inundated floodplains is shallower than it is in the main river channel. This allows more light to penetrate the floodplain water column, leading to higher temperatures. These conditions favor the growth of green algae and of aquatic vascular plants in the floodplain, leading to higher productivity than in the river channel. Thus the decrease in nutrients in floodwater on the floodplain might be attributed to uptake by aquatic vegetation growing in the floodwater (Lewis et al., 2000). However, this might partly be only a temporary sink since nutrients taken up by algae will

Fig.2.9. Clump of bamboo with sediment accumulated around it (left: red arrow) as observed in the dry season, and occurrence of algae around bamboo as observed in wet season floodwater

be largely released when algae die, and only the portion of the nutrients taken up by bamboo and other vascular plants may be stored in a sink for a longer time.

During the classification of land cover in the flooded areas, it was noted that bamboo vegetation is found in a zone immediately adjacent to the river channels. The bamboo vegetation is generally very dense, and during fieldwork, sedimentation and algae growths were observed around the bamboo stems (see Fig.2.9). The clumps of bamboo along the Songkhram river reduce the velocity of floodwater, which may enable sediments in the water to settle. The bamboo is also highly productive, as evidenced by its large standing biomass. This suggests it is efficient in taking up nutrients, either directly from the floodwater or, in the dry season, from the sediment remaining after the flood. We did not find any clear data on these processes in the literature or in the field. Nonetheless, we would argue that the floodplain functions as a net sink of nutrients, mediated by highly productive bamboo. And this indicates that the river is a source of nutrients and sediment for the floodplain.

Although our results show how the river and its floodplain interact in terms of hydrochemistry, we still lack a clear pattern of transport of sediment, nutrients, and organic material. Candidate topics for future research could therefore be the pathways and transformation of particulate material in the river and floodplain, as well as the temporal variation in processes affecting transport and transformation. In addition, dedicated research should test our hypothesis that the sink function of the Songkhram monsoon floodplain is primarily related to the presence of a bamboo strip in the floodplain, which seems to act as a sediment trap and solute filter. We suggest future analyses on sediment characteristics in the river and floodplain, as this may also be important for nutrient cycling in the aquatic system, and such analyses may explain the source of $Fe^{2+, 3+}$ and Al^{3+} and the processes steering their dissolution.

2.5.3 Ecological and hydrological concepts for monsoon river systems

The decreasing longitudinal trend of hydrochemical concentrations in the river during flooding, as observed in our study, corresponds to the physical gradient from upstream to downstream as described in the river continuum concept (Vannote et al., 1980). The limited information we gathered indicates this concept may be applied to explain the ecological functioning of our river system. The observed decreasing trend of EC from upstream to downstream may indicate a shift in the biotic community along the river, as suggested by Jiang et al. (2011). However, in order to draw conclusions about the longitudinal ecological functioning of the monsoon river system, research needs to be done on the response of the biotic community to the hydrochemistry gradient.

The river/floodplain system we studied is also subject to transverse processes affecting the chemistry of the floodwater on the floodplain. The flood pulse concept (Junk et al., 1989), explains the ecological functioning of large river floodplain systems in terms of the lateral exchange of water, sediment, and nutrients between the river and the floodplain. In our study, the river functions as a transportation route and source of dissolved material for the floodplain, including nutrients PO_4^{3-}, TDN, and K^+ as postulated by the flood pulse concept. It is, therefore, likely that both concepts are applicable to explain the ecological functioning of our river system during the flood period. This is in line with the suggestion of Humphries et al. (2014), who propose the river wave concept that merges the RCC and FPC and combines it with the riverine productivity model (RPM) proposed by Thorp & Delong, 1994. The RPM postulates that the river bank vegetation is highly productive due to nutrient input from the river, which may be applicable to the bamboo zone we described.

Although some general observations can be made based on our data for one monsoon river, there is a need for further data collection in monsoonal river systems to verify to what extent different river concepts also hold for river systems of this type.

2.6 Acknowledgments

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Chapter 3

Unraveling the ecological functioning of the monsoonal Songkhram River floodplain in Thailand by integrating data on soil, water, and vegetation

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Abstract: Although the functioning of river floodplains as sinka or sources of nutrients has been studied extensively for temperate regions, similar studies in tropical regions are less abundant, and studies integrating data about floodplain soil, vegetation, and water are scarce. We examined and compared nutrient contents in soil, water, and vegetation tissue in two different vegetation zones (bamboo and grass) on the monsoon Songkhram river floodplain (Thailand). Significant differences were found between the bamboo and grass zones. The soil in the bamboo zone is more fertile than the soil in the grass zone, as indicated by the lower C/N ratio, and has significantly higher organic matter and higher total N and K. Bamboo leaf tissue had significantly higher concentrations of nutrients than grass biomass. The growth of the bamboo is P-limited, but the grass is N-limited. In both zones, the soil-available P and organic carbons after flooding were significantly lower than before flooding. Floodwater in both zones had low dissolved solid concentrations. After the flood peak, most concentrations tended to increase, especially organic carbon and dissolved nitrogen but phosphorus decreased. The results suggest a significant loss of organic carbon from the soil after flooding, indicating that the floodplain acts as a source of carbon that is exported downstream. Nonetheless it is also evident that the floodwater brings in sediment and nutrients. Based on rough estimations of nutrient budgets, we conclude that the highly productive bamboo zone adjacent to the river filters out the nutrients before they reach the grass zone.

Keywords: floodplain functioning; vegetation zonation; nutrient limitation; ephemeral wetlands; Mekong River

3.1 Introduction

River floodplains have been studied by wetland scientists for decades since they represent ecosystems with valuable services to mankind. Understanding their hydrological and ecological functioning adds insight into their key processes and how to preserve and protect them. The relevance of preservation of floodplains goes beyond the actual floodplain itself since floodplains are typical connecting elements in the landscape between the hinterland and the river and also connect upstream areas with downstream areas. Due to this landscape connectivity, river floodplains harbor longitudinal and lateral gradients (Humphries et al., 2014; Junk and Wantzen, 2004; Vannote et al., 1980), and both vegetation productivity in floodplains and nutrient processes are related to the size of the parent river and its water quality (Spink et al., 1998; Thorp and Delong, 1994). It is therefore important to study floodplain processes further to understand how these processes are linked to spatial zonation in the floodplain, upstream areas, and their distance from the river.

The hydrology and topography of floodplains largely determine their water flow, the development of gradients, and the existence of zones with different biological communities. Two other important factors that determine nutrient cycling in these communities are temperature and hydrochemistry. Floodplain hydrochemistry depends on the sources of inundation water: the principal sources are river water, groundwater, and precipitation, or mixtures of these. River floodwater is generally a source of nutrients (suspended and dissolved) (Mertes, 1997; Olde Venterink et al., 2006; Wassen et al., 2003). Gradients in flood stress (e.g., depth, current velocity and oxygen stress during long-term inundations) and different magnitudes of nutrient and sediment inputs bring about spatial differentiation in productivity which, together with nutrient cycling processes, result in distinct vegetation patterns in temperate floodplains (Keizer et al., 2014; Wassen et al., 2003; Wassen and Joosten, 1996; Wu and Blodau, 2015). Similar to the temperate floodplains, clear vegetation zonation along flooding gradients is observed in large tropical floodplains around the world i.e., the Amazon basin, the Okavango delta, the Mekong Tonle Sap, and the tropical Northern Australia wet-dry system (Parolin et al., 2016; Parolin and Wittmann, 2010). Spatial patterns of vegetation in these tropical floodplains are the result of their adaptation and response to seasonally flooding characteristics, especially depth and duration (Arias et al., 2016; Parolin et al., 2016). Although each individual floodplain can have additional factors that influence the development of zonation, such as interactions between soil, surface water, and groundwater affecting the salinity in the Okavango floodplain (Ellery et al., 1993; Ellery and Tacheba,2013), the effect on soil moisture due to disturbances from humans and fire in the Mekong Tonle Sap (Arias et al., 2013) and changing stream velocities during a flood in the Northern Australia wet-dry tropics (Finlayson, 2005; Finlayson et al., 1990). In addition, nutrient availability in floodplains is an important factor as it determines the productivity of the floodplains. Spatial patterns of nutrient availability can directly cause vegetation zonation but can also influence seedling establishment strategies which result in spatial patterns of vegetation in floodplains (Parolin, 2002)

Crucial factors that determine nutrient dynamics and floodplain productivities are the hydrological regimes and geochemical characteristics of the catchment (Spink et al., 1998). The hydrological regime may be characterized by three main river discharge stages; 1) a base flow stage , 2) a rising stage, and 3) the falling stage, as described in the river wave concept (Humphries et al., 2014) and flood pulse concept (Junk and Wantzen, 2004). During the base flow stage, the river and the floodplain are in a stage of low connectivity. During intense rainfall, the resulting terrestrial runoff not only causes water levels in the river channel to rise (the rising stage), but also transports dissolved and particulate nutrients. When the river overtops its banks, water from the river channel will inundate the floodplain, importing nutrients. At that moment, an aquatic system establishes on the floodplain, and the floodwater transports suspended matter, dissolved solids, and propagules. The transport distance and the sedimentation rate are both a function of water velocity and floodplain topography, and they lead to the spatial redistribution of matter and organisms (Ward et al., 2002; Wiens, 2002; Zuijdgeest et al., 2015). Floodplain productivity is determined by the biomass production of phytoplankton, macroalgae, aquatic plants, and helophytes. The major source of nutrients for aquatic production during the inundation phase is thought to be floodwater, with the floodplain soil playing a minor role; thus when water stops overtopping the river banks, the supply of nutrients diminishes, as do nutrient concentrations in the floodwater (Lewis et al., 2000). In turn, floodplains can be an important source of organic carbon exported downstream via the river after the floods retreat (Junk and Wantzen, 2004; Zuijdgeest et al., 2015).

To date, most of the studies on the nutrient cycling processes occurring in floodplains have been on temperate systems (e.g., Baldwin and Mitchell, 2000; Olde Venterink et al., 2003, 2002; Wassen et al., 2003). They have shown that river floodplains can function as a sink for nutrients such as N and P, and for sediment. Since both biomass production and organic matter decomposition depend greatly on temperature (Baldwin and Mitchell, 2000), it can be expected that there will be a clear difference in these processes between temperate catchments and tropical catchments. River floodplains in tropical regions may therefore be very different from temperate regions. McJannet et al. (2012) showed that a tropical floodplain was a sink for phosphorus but found no evidence for a nitrogen sink. Most studies in tropical river floodplains have analyzed the relationship between soil characteristics, hydrology, and vegetation structure and composition (e.g., Arias et al., 2013; Finlayson, 2005; Murray-Hudson et al., 2011; Wittmann et al., 2008), and to some extent the hydrochemistry, e.g., Ellery et al. (1993). Vegetation community patterns in tropical floodplains show clear correlations with flood characteristics such as flood duration and flood depth. Arias et al. (2016) demonstrated in their recent hydrogeological concept for vegetation distribution in tropical floodplains that lower species diversity was found with longer flood duration and larger flood depth. Beside the relationship between flooding and vegetation types, flood characteristics also influence soil properties and nutrient contents (e.g., Arias et al., 2013).

However, little is known about the rate of nutrient cycling in tropical floodplains and how this relates to seasonal dynamics. Tropical monsoon rivers, in particular, exhibit a strong seasonal dynamic hydrologic pattern. The large amounts of rain characteristic of the monsoon period lead to low concentrations of dissolved matter and nutrients in river water during floodplain inundation (Walalite et al., 2016). However, similar to temperate floodplains, monsoon floodplains may show a distinct zonation of more productive and less productive vegetation (Arias et al., 2016; Walalite et al., 2016; Zuijdgeest et al., 2015). In the present study, we contribute to the sparse knowledge on tropical monsoon floodplain ecological functioning by presenting data on the Songkhram river in Thailand. Our two aims are: to explore spatial differences in the nutrient distribution in water, soil, and vegetation for two distinct vegetation zones in the floodplain (bamboo and grass) and to understand the interaction between the flood characteristics and the vegetation with respect to nutrient fluxes and stores. In a previous study (Walalite et al., 2016), we identified two major vegetation communities that dominate in the floodplain: a bamboo zone that is widespread throughout the floodplain in a belt close to the river and a grassland type behind the bamboo zone and thus further away from the river. In our earlier paper, we hypothesized that the high annual biomass production of the bamboo zone is driven by the floods importing nutrients and sediment We urged further research to analyze nutrient input and uptake in the grass and the bamboo zone. The present paper aims to verify this hypothesis and test if the less productive grassland zone behind the bamboo does indeed receive less input of nutrients from the river.

3.2 Study area

The Songkhram river catchment is situated in the monsoon climate region of north-eastern Thailand (Fig.3.1). It is approximately 495 km long, drains an area of 13,000 km^2, and its average discharge is 226 m^3 s^{-1} during the monsoon season and 2.3 m^3 s^{-1} during the dry season. Annual precipitation averages 1960 mm and ranges from 1090 to 2880 mm. The monsoon season lasts from May to September and is followed by a cool-dry season from October to February that is succeeded by a hot-dry season from March to April. During the monsoon season, the average precipitation is 1690 mm (range 906 – 2420 mm); this compares with an average precipitation of 270 mm (range 80 – 490 mm) during the dry season (figures compiled from daily data from the Department of Water Resources, Thailand). Mean annual daily temperature is 26 °C and the warmest month is April (monthly mean of 35 °C). From December to January, the minimum night temperature is around 15 °C.

The floodplain we studied lies in the lower catchment of the Songkharam river (Fig.3.1) and is inundated yearly due to the high river discharges during the monsoon season. The average flooded area of this floodplain is estimated to be 760-855 km^2 (Thiha et al., 2012; Walalite et al., 2016). The land uses of the flood-prone area in the non-flood season are agriculture (52 %), grassland, herbaceous vegetation and shrubs (together 20 %), open water (9%), marsh (8%), deciduous forest (6%), native riparian bamboo (4%) and buildings (1%).

The native floodplain vegetation community, which is known as "Pa Bung Pa Taam" (Fig.3.2), comprises a distinct strip of dense thorny bamboo (*Bambusa flexuosa*) next to the river channel, behind which is a zone of grassland communities dominated by *Miscanthus fuscus* (Walalite et al., 2016; Blake et al., 2011). Figure 3.3 presents a conceptual cross-section from the river across the floodplain to the higher non-flooded land on the side of the river valley, showing the zonation of bamboo and grass communities.

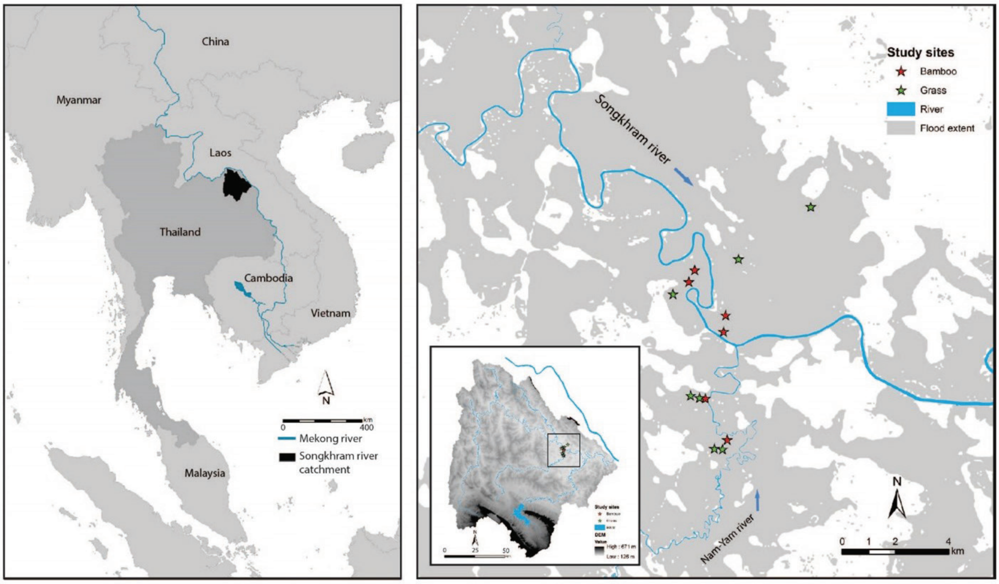

Fig.3.1 Location of the study area in the lower basin of the Songkhram river where the Nam-Yam tributary joins the main river.

Fig.3.2 Dense bamboo thicket close to the river (left) appears adjacent to the river channel and the grass zone next to the bamboo (right).

3.3 Methods

3.3.1 Sampling locations and time line of fieldwork campaign

We established four transects in the monsoon floodplain of the Songkhram river (Fig.3.1). Each transect started on the river bank and extended over the vegetation gradient of the bamboo thicket on the river bank and the grass communities behind (both of which are inundated during the monsoon), as far as the higher-lying non-flooded forest zone (See Fig.3.2 and 3.3). Vegetation, soil, and floodwater were sampled during different periods in 2015: Figure 3.4 depicts them in relation to rainfall and river water levels.

3.3.2 Vegetation sampling and analysis

The bamboo fresh mature leaves were sampled in February 2015 in order to determine nutrient concentrations (see below): we took samples from 15 different locations distributed over the seasonally flooded bamboo zone. Aboveground standing crop was harvested as a proxy for annual plant production. As the bamboo produces fresh shoots and leaves all year round, we counted the newly formed shoots per m^2 and ignored the shoots from previous years. Shoots were dried and weighed in order to estimate the annual aboveground production (g dry wt/m^2).

For the grass zone, we harvested aboveground living biomass from 9 locations in August 2015, which was when grass growt peaked following monsoon rainwater input. At each location, three 50 x 50 cm plots were harvested. The bamboo leaves and the grass biomass were dried at 105 °C for 4 hr., and the standing crop was expressed as g dry wt/m^2. The three replicates were averaged.

The dry plant material was ground and analyzed for nitrogen (N) and carbon (C) using a C/N analyzer. Part of the ground sample was digested by nitric acid (65% HNO_3) and analyzed for phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), aluminum (Al), silica (Si), iron (Fe), sulfur (S), and manganese (Mn) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

3.3.3 Soil sampling and analysis

Soil samples were collected during two field campaigns – before the flood (June-July 2015) and after the flood (November 2015) – at the same locations. Seven of the sites were in the bamboo zone, and 6 were in the grassland zone. The soil samples were taken using a stainless steel soil corer (5.2 cm long, 5 cm diameter). Three cores were collected at each site (in an area of ca.10 m^2).

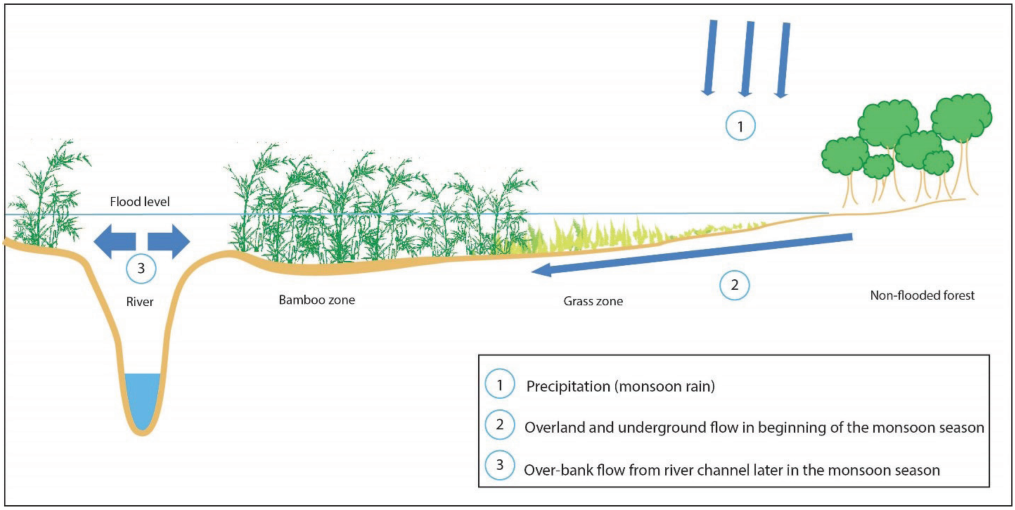

Fig.3.3 Conceptual cross-section of the Songkhram monsoon river floodplain, showing characteristic vegetation zonation and hydrological system. At the start of the monsoon season: (1) rainfall is intense, and (2) overland and underground flow of water and transport of dissolved solids from the floodplain increase. During this period, bamboo and grass grow rapidly until the river overflows (3), and the floodplain enters the aquatic phase.

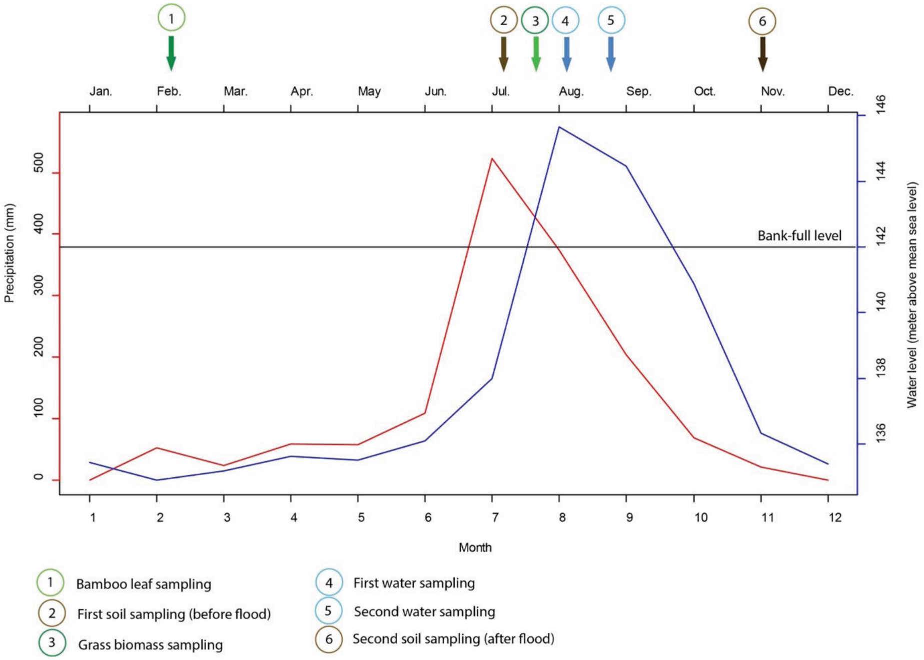

Fig. 3.4 Rainfall (red line) and water level (blue line) of the Songkhram river in 2015, with indication of sampling moments of soil, water, and vegetation.

Soil samples were air dried at room temperature for 2 weeks. After drying, the soil was ground and sieved through a 0.5 mm sieve for further chemical analysis. Soil pH was measured from a solution of 10 g soil sample with 10 ml of demineralized water. The available phosphorus (P) in the soil sample was determined from 5 g of soil, using Bray 2 solution as extractant. The concentration of the extractable phosphorus was determined by colorimetric and spectrophotometric methods. Ammonium exchangeable potassium (K) in the soil sample was also determined from 5 g of soil, using 1 M ammonium acetate as extractant. The K concentration in the extracted solution was determined using a flame photometer. Total organic carbon (TOC) and total nitrogen (TN) were determined by the Walkley-Black and macro Kjeldahl digestion methods, respectively.

3.3.4 Floodwater sampling and analysis

In total, 33 samples of floodwater were collected at two stages of the flood. The first (17 samples) were obtained during the peak flood (10-15 August 2015), and the second (16 samples) were obtained while the flood was subsiding (27-28 August 2015). Along each transect, the sampling sites were in the main river channel, bamboo zone, and grass zone.

At each site, four liters of water were collected from approximately 30 cm below the level of the floodwater using a polyethylene (PE) bottle, which was pre-washed by the water to be sampled on-site. To collect a sample, the bottle was dipped into the floodwater. As soon as a sample had been taken, its EC, temperature, dissolved oxygen, and pH were determined. The sample was then stored in a cooler at approximately 4 °C. The depth of floodwater at each site was measured using a measuring tape weighted at one end.

The water samples were delivered to a laboratory for preparation and treatment within 24 hr. of collection. Each sample was mixed thoroughly and then divided into three subsamples. The first subsample was filtered through 0.45 micron cellulose acetate membrane filter and divided into two aliquots of 50 ml. To the first, 1 ml of nitric acid (65% concentration) was added and analyzed for ions by means of ICP-OES. The second was not acidified and prepared to analyze dissolved organic carbon (DOC) and total dissolved nitrogen (TDN).

The second subsample was prepared for unfiltered water analysis. Aliquots of 250 and 125 ml from this unfiltered subsample were stored in wide-mouth PE bottles. The first 250 ml was acidified by adding 2 ml of 65% concentrated nitric acid for total phosphorus (TP) analysis. The 125 ml was not acidified prior to analyses for TOC and total nitrogen (TN). Prior to analysis, all samples were kept in cool (ca. 4 °C) and dark conditions. Additionally, within 24 hr. of collection, a 5 ml aliquot was taken, and its alkalinity was measured using a HI-3811-100 chemical test kit (Hanna instruments, 2016).

The third subsample was prepared to determine total suspended solid (TSS) and organic matter (OM). Between 500 and 1000 ml (depending on filtration speed) was filtered through 0.7 micron Whatman GF/F glass fiber filter of known weight. The filter with its residual suspended solid was then dried at 105°C for 24 hr., cooled in a desiccator, and weighed. Subsequently, the filter was combusted at 400 °C for 16 hr., and the weight after combustion was used to determine the amount of OM lost during combustion.

3.3.5 Determination of nutrient limitation in vegetation

To determine the type of nutrient limitation, we followed Olde Venterink et al. (2003), who used a method based on critical values of N: P, N: K, and K: P ratios in aboveground plant material. N-limited sites were those with N: P ratio < 14.5 and N: K ratio < 2.1, whereas P-limited sites and sites limited in both P and N were those with N: P ratio > 14.5 and K: P ratio> 3.4. Sites limited in K or in K+N were those with N: K ratio > 2.1 and K: P ratio < 3.4.

3.3.6 Estimation of nutrient storage in soil and vegetation and input from floodwater and atmosphere

The total N and available P and K in the soil were determined by analyzing the top 5 cm of each soil core. Concentrations of total N, available P, and K in mg per gram soil were multiplied by the soil bulk density (g soil per m^3 volume) and the volume of the top 5 cm soil in 1 m^2.

To obtain an indication of the annual aboveground nutrient storage (g nutrient/m^2) in the bamboo zone, we multiplied the dry weight/m^2 by the nutrient (N, P, and K) concentrations measured in the fresh leaves (mg nutrient/g dry wt), assuming this to be a reasonable estimate for the whole shoot. For the grass zone, we used the sampled aboveground biomass of grass (g/m^2) and multiplied it by the nutrient concentrations (mg nutrient/g dry wt) in the grass biomass sample of each site.

To estimate the potential amount of nutrients imported by floodwater to a certain area, we averaged the concentrations of nutrients and the depth of floodwater for the 2 flood stages from each site. The volume of standing water (l/m^2) was calculated from the average depth of each site. Then the average nutrient concentration was multiplied by the volume of the standing water (l/m^2). By using the above method, we assumed that the system works with a peak discharge in the floodplains, after which no new water enters the floodplain anymore, and only water outflow takes place after the peak. If this is the case, it is justified to use our calculation. An alternative would be to consider every time step a new inflow and probably also outflow, but we did not observe any indication of this in the field.

Total N and K from atmospheric deposition in Thailand were extracted from World Data Centre for Precipitation Chemistry (Vet et al., 2014).

3.4 Results

We found significant differences between the bamboo and grass zones (Table 3.1). Both before and after the flood, the soil in the bamboo zone had significantly higher OM contents, higher total N and K contents, and lower bulk density. Before the flood, the soil in the bamboo zone had higher organic carbon (TOC) and available phosphorus (P) and a lower C/N ratio than the grass zone. These results indicate that the bamboo soil is more fertile than the grass soil. However, the high C/N ratios in both zones (bamboo ≥ 52, grass ≥ 48; Table 3.1) indicate that both soils have poor N fertility. After the floods, a significant decrease in organic carbon from the soil in both zones is found, and further, the drop in the C/N ratio shows that the floods export organic carbon from the floodplain and fertilize both zones.

A comparison of the water samples taken at the peak of the flood and during its recession reveals that, after the peak, sedimentation of suspended matter occured and the concentration of dissolved solid increased, possibly due to high evapotranspiration caused by the high tropical temperatures (30+ °C) (Table 3.2). This is reflected in decreases in TSS and increases in EC, Cl, and other major ions. During the subsidence of the flood, dissolved oxygen (DO), TP, and PO_4^{3-} also decreased significantly in the floodwater, and alkalinity increased (Table 3.2), probably because of the algal blooms we observed during the second sampling.

Table3.1. Soil characteristics and soil nutrient concentrations before and after flooding for the bamboo and grass zones: comparison of means (± standard error of the mean). Values with different letters (a, b, and c) indicate significant differences ($p<0.05$; Paired t-test for within zone and independent t-test for between zone). * indicates variable changed significantly after flooding ($p<0.05$; Paired t-test).

Variable (Soil)	Bamboo (n samples = 21)			Grass (n samples = 18)		
	Before flood	After flood	% change	Before flood	After flood	% change
pH	4.41 ± 0.04 a	4.73 ± 0.03 b	7	4.46 ± 0.03 a	4.86 ± 0.04 c	9*
Bulk density (g/cm3)	0.27 ± 0.01 a	0.26 ± 0.01 a	-4	0.33 ± 0.01 b	0.34 ± 0.01 b	3
Organic matter (g/kg)	56.6 ± 3.7 a	54.9 ± 3.5 a	-3	27.0 ± 2.3 b	25.7 ± 2.5 b	-5
Organic carbon (g/kg)	118.7 ± 10.7 a	88.0 ± 18.1 bc	-26*	86.2 ± 8.1 b	48.5 ± 8.2 c	-44*
Total N (g/kg)	1.67 ± 0.11 a	1.75 ± 0.11 a	4	0.91 ± 0.08 b	0.95 ± 0.09 b	3
Available P (mg/kg)	11.9 ± 1.1 a	8.8 ± 1.8 bc	-26*	8.6 ± 0.8 b	4.9 ± 0.8 c	-44*
K (mg/kg)	127.0 ± 12.8 a	114.3 ± 10.0 a	-10	70.8 ± 7.5 b	48.0 ± 5.8 c	-32*
C/N ratio	74 ± 6 a	52 ± 9 b	-30*	95 ± 19 c	48 ± 5 b	-49*

Table 3.2. Floodwater chemistry from Songkhram river floodplain: comparison of the mean (± standard error of the mean (SE)) nutrient concentration from the first sampling during flood peak periods and the second sampling sample during subsidence of the flood (two weeks after the first sampling). Asterisked values indicate a variable with a significant difference (* $p<0.05$, ** $p<0.01$, paired t-test). NA indicates values below the method's detection threshold.

Variables (Water)	Units	Mean ± SE		% change
		First sampling (n samples =17)	Second sampling (n samples =16)	
Temperature	°C	32.2 ± 0.3	33.3± 0.3	3*
Depth	meter	4.1 ± 0.1	1.6 ± 0.3	-61**
EC	µS/cm	41.3 ± 2.3	88.4 ± 9.4	114*
DO	mg/l	4.8 ± 0.4	1.9 ± 0.2	-60**
pH	-	6.8 ± 0.04	6.5 ± 0.02	-4**
Alkalinity	mg/l	17 ± 0.7	20 ± 0.7	18**
TSS	mg/l	4.72 ± 0.26	2.60 ± 0.29	-45**
OM	mg/l	1.30 ± 0.06	1.34 ± 0.08	3
TOC	mg/l	4.35 ± 0.12	5.00 ± 0.17	15**
DOC	mg/l	3.62 ± 0.10	4.80 ± 0.08	33**
TN	mg/l	0.68 ± 0.03	0.64 ± 0.03	-6
TDN	mg/l	0.50 ± 0.02	0.53 ± 0.01	6*
TP	mg/l	0.05 ± 0.01	0.04 ± 0	-20*
PO_4^{3-}	mg/l	0.04 ± 0	NA	NA
K^+	mg/l	1.64 ± 0.02	2.38 ± 0.15	45**
Mg^{2+}	mg/l	0.73 ± 0.03	1.24 ± 0.05	70**
Mn^{2+}	mg/l	0.02 ± 0	0.06 ± 0.01	200**
Ca^{2+}	mg/l	2.12 ± 0.1	3.63 ± 0.17	71**
Cl^-	mg/l	13.59 ± 1.64	24.67 ± 3.46	82**
$Fe^{2+/3+}$	mg/l	0.29 ± 0.02	0.53 ± 0.03	83**
Na^+	mg/l	6.67 ± 0.52	15.07 ± 1.74	126**
S^-	mg/l	0.59 ±0.08	0.61 ± 0.03	3
Si^+	mg/l	1.50 ± 0.04	1.89 ± 0.07	26**

Table 3.3. Comparison of mean and standard error (SE) of the vegetation tissue nutrient constituents of bamboo leaves and grass aboveground biomass (units in mg element per g of biomass dry weight). * Indicates a variable that is significantly higher (independent t-test, p<0.05).

Variables (Plant)	Unit	Mean ± SE Bamboo (n samples = 15)	Mean ± SE Grass (n samples = 27)
C	mg/g-dry wt	408.7 ± 4.5	425.2 ± 2.6
N	mg/g-dry wt	18.7 ± 0.8*	6.31 ± 0.30
P	mg/g-dry wt	1.26 ± 0.08*	0.68 ± 0.05
K	mg/g-dry wt	10.5 ± 0.5*	7.45 ± 0.30
Al	mg/g-dry wt	0.64 ± 0.04*	0.37 ±0.04
Ca	mg/g-dry wt	4.32 ± 0.25*	1.60 ± 0.09
Fe	mg/g-dry wt	0.41 ± 0.02*	0.25 ± 0.03
Mg	mg/g-dry wt	1.11 ± 0.07	0.97 ± 0.05
Mn	mg/g-dry wt	0.42 ± 0.04*	0.25 ± 0.02
S	mg/g-dry wt	2.03 ± 0.09*	1.06 ± 0.04
Si	mg/g-dry wt	1.25 ± 0.04*	0.97 ± 0.04
C/N	-	22.2 ± 0.9	70.4 ± 2.6*
C/P	-	340 ± 19	726 ± 61*
N/P	-	15.4 ± 0.7*	10.7 ± 1.0
K/P	-	8.5 ± 0.4	12.6 ± 1.1*
N/K	-	1. 83 ± 0.09*	0.91 ± 0.08
C/K	-	40.4 ± 2.3	60.1 ± 3.2*
Above-ground production	g/m^2	521 ± ? (n = 1)	386 ± 58 (n = 6)

The productivity of the bamboo vegetation is high: estimated to be ca. 5 tons dry wt/ha/yr of aboveground biomass. The grass zone is also productive, though less so: it averaged >3.5 tons dry wt/ha/yr (Table 3.3). Analysis of aboveground plant tissue indicates that concentrations of all three major nutrients (N, P, and K) are significantly higher in the bamboo vegetation zone than in the grass zone. Nutrient ratios indicate that bamboo growth is limited by P, whereas the vegetation of the grass zone is limited by N. We did not find any indications of K co-limitation (Table 3.3).

3.5 Discussion

3.5.1 Similarities and differences in ecological functioning between temperate and tropical floodplains

Integration of our data on soil, water, and vegetation led to the emergence of a coherent pattern of flood-related nutrient and carbon fluxes that are spatially and temporarily differentiated. First, the significant loss of organic carbon from the soil after the flood indicates that the floodplain is a source of carbon, and this carbon is probably exported downstream. This is also illustrated by the DOC and TOC in the floodwater, which increases significantly after the floodplain becomes an aquatic system while inundated. This implies that organic carbon produced in the floodplain is exported via the retreating floodwater. This was also reported by Zuijdgeest et al. (2015) for the floodplain along the Zambezi in Southern Africa, where OM that had been produced upstream was transported downstream and exported. This illustrates how large floodplain systems act as large biogeochemical reactors that behave distinctly different from the rest of the catchment (Zuijdgeest et al., 2015). In our case, the part of the floodplain we sampled seems to be a source of carbon for the river and downstream areas.

Second, we clearly observed the role of the vegetation zonation in floodplain functioning. In the Songkhram floodplain, clear zonations of bamboo and grass are present. It was found earlier that for tropical floodplains vegetation patterns in structure and community are determined by the duration and the depth of the flood (Arias et al., 2016; Parolin et al., 2016). In addition to these main factors, the hydrochemistry of inundated water, the soil, and topography can cause stress in vegetation functioning and therefore cause patterns in vegetation. In the tropics, where vegetation production is optimal around the year, adaptation to flood stress seems to be the key mechanism of spatial heterogeneity in species communities (Parolin and Wittmann, 2010). Further Arias et al. (2013) showed that the mean annual flood duration and soil properties determined canopy height, canopy cover, and aboveground biomass of the Tonle Sap floodplain forest in Cambodia.In our Songkhram river floodplain, the zones of bamboo and grass experience different stresses, i) a higher flood stress, higher nutrient input, and higher productivity in the bamboo zone and ii) a lower flood stress, lower nutrient input, and lower productivity in the grassland.

The bamboo experiences higher flood depth and duration, forcing bamboo to take up available nutrients quickly and have fast shoot growth to escape the flooding. The higher productivity is supported by additional nutrient uptake from the flood water. As a result, OM production is much higher in the bamboo zone than in the grassland, leading to higher OM content in the soil of the bamboo zone. This difference is attributable not only to the vigorous growth of the bamboo but also, at least partly, to the prominent algal blooms in this zone. After the floods have receded, these algae remain on the ground and start to decompose rapidly in warm and still moist conditions. A comparison of the temperatures in our tropical catchment with the temperature ranges of seven large floodplains in North America and Europe reported in Spink et al. (1998) shows that the temperatures in Songkhram are very different: they are consistently very high.

The grassland zone is usually found next to the bamboo zone. Although the flood depth and duration in this zone are lower than the bamboo zone due to its topography, vegetation in this zone is fully submerged. Limited nutrients in this zone lead to lower productivity. Therefore the combination of flood stress and nutrient limitation determines the vegetation in this zone.

Interestingly, we found the Songkhram is very similar to the river Shannon in Ireland in terms of catchment size, discharge, and soil and vegetation nutrient contents (data on the Shannon reported by Spink et al., 1998). The Shannon is a typical example of a predominantly rainwater-fed river poor in solutes, as is the case for the Songkhram river and also for the Siberian river Ob, which is fed mainly by snow melt (Schipper et al., 2007). In the floodplains of these three rivers with very different climates, vegetation production is driven more by sedimentation and mineralization of OM than by dissolved nutrients brought in by floodwater.

Although the Songkhram floodwater exports OM from the floodplain, it is also evident that the floods import sediment and nutrients. The water samples taken and flooding depths measured at the peak and at the end of the flood period illustrate this. At the peak of the flood, the floodwater is very deep: on average 4 m; after the monsoon rains had ceased, the concentration of TSS in the sampled water was only half of the peak flood's TSS concentration (Table 3.2). Visual observations also revealed that the water at the second sampling was much more transparent.

3.5.2 Nutrient budgets

We roughly estimated the nutrient budgets for the bamboo and the grass zone (see Methods: Estimation of nutrient storage in soil and vegetation and input from floodwater and atmosphere) and were able to further differentiate between N, P, and K fluxes and reserves (Fig.3.5), although it must be noted that our estimates are only rough, approximating indicators.

Nitrogen: Although atmospheric deposition of N in the Songkhram catchment is significant (6.5 kg N/ha/yr) it is moderate compared to the deposition in other areas in S.E Asia (Vet et al., 2014), and the floods bring in twice as much N into the grass zone and three times as much into the bamboo zone than is deposited from the atmosphere (Fig. 3.5a). Most of the N stored annually in the aboveground biomass must thus be obtained from the soil. This is especially evident for the bamboo zone since the N from atmospheric N deposition plus the estimated N input via the flood adds up to far less than the N in biomass. Additional N input to the system can also relate to large particulate organic matter (POM) from flood water. N from the floodwater is rather not (only) originating from dissolved organic matter but also relates to POM. This POM in flood water would also be an important source of N input to the floodplains. This is also demonstrated by our data, showing that water OM did not change, but TOC and DOC increased in the second sampling. This indicates that organic matter is also a source of nutrients during the flood. N from the POM is then filtered by the bamboo, deposited on the soil, and becomes quickly part of the soil through bioturbation (Mermillod-Blondin, 2011).

Our schematic cross-section in Fig.3.5 also reveals that the bamboo zone may function as a filter, trapping most of the N from the floodwater before the water reaches the grass zone further away from the river.

Phosphorus: Atmospheric deposition of P is probably negligible unless dust storms occur, which to our knowledge, has not been the case. It appears that compared with the amount of P that could hypothetically be imported from the atmosphere and the floods, the amount of P stored annually in aboveground biomass is four times higher in the bamboo zone and two to three times higher in the grass zone. So, as was the case for N, the soil must also be an important source of P. Remarkably, the soil in both zones contains only minor amounts of P, which implies that most of the available P is taken up rapidly, as is also observed in tropical forests, where almost all nutrients are sequestered in standing vegetation (Vitousek and Sanford, 1986). The bamboo zone may – as was the case for N – also filter out P, taking up P from the floodwater before it reaches the grass zone further away from the river.

Potassium: It is very clear that the flood is the major source. Compared to the amount of K available in the soil and the amount of K deposited from the atmosphere, the potential input of K from the floods is important. Again, we speculate that the bamboo zone may function as a filter, taking up K from the floodwater before it reaches the grass zone more distant from the river. As illustrated in figure 3, which shows (i) some depression within the bamboo zone and (ii) the bamboo zone is wider than the grass zone in the higher 'flooding littoral', it should not be surprising that the bamboo is the dominant filtering vegetation unit, especially regarding the height above the mean and the bank full water levels.

A comparison of our very roughly estimated nutrient flows with the flows reported by other studies in river floodplains reveals some general patterns. Our findings are similar to those of Olde Venterink et al. (2002) for temperate European river systems. These authors also found most of the

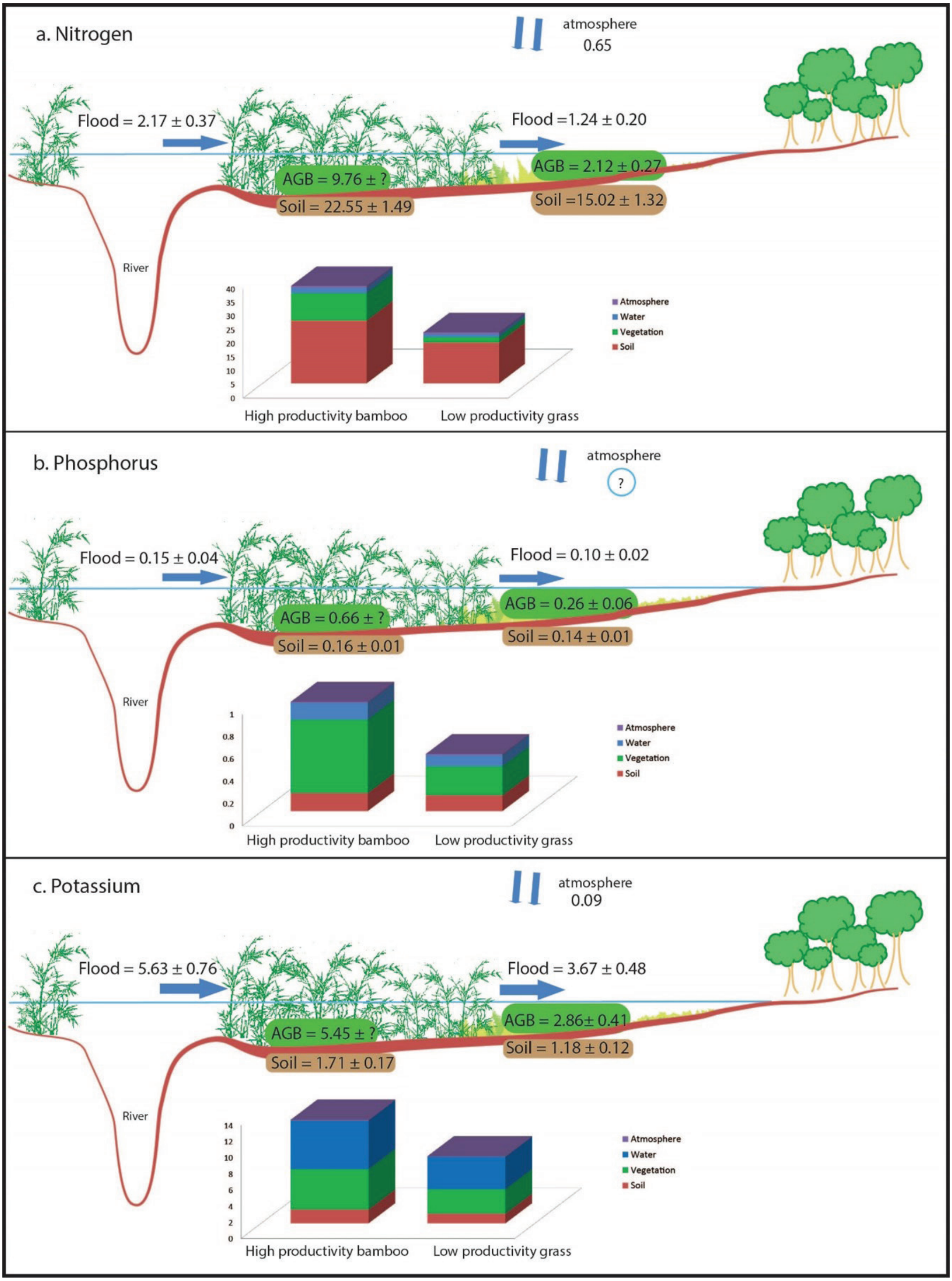

Fig. 3.5 Estimated N, P, and K storage in soil and above-ground biomass (AGB) of vegetation and the contribution of floodwater and atmospheric deposition. The numbers represent Mean ± SE (g/m2).

N in aboveground vegetation was obtained from turnover in the soil, but they also concluded that the input of P and K from the river must have been substantial. In another study performed in the floodplain of the European river Rhine, Olde Venterink et al. (2006) reported similar findings to ours: sediment deposition was an important mechanism of retention of nutrients, especially of P, and nutrient retention was much greater in reed-beds – comparable to our bamboo zone – than in grasslands. The authors postulated that the high sediment deposition rate in their floodplain reed-bed was the result of the roughness of the vegetation structure, which reduced the water velocity, facilitating sedimentation and trapping nutrients. In contrast to this, McJannet et al. (2012) argue that in tropical riverine wetlands where there is strong seasonality in flows and short residence time during the periods of maximum sediment and nutrient loads, there is likely to be limited overall filtering potential. This aspect certainly needs further study, although our results support the hypothesis we put forward in our previous study (Walalite et al., 2016), that the high annual biomass production of the bamboo zone is driven by the floods, which import nutrients and sediments filtered out by this zone. The less productive grassland zone located behind the bamboo receives less input of nutrients from the river.

If we focus on the type of nutrient limitation, we notice that, in contrast to what we found for Songkhram, Olde Venterink et al. (2006) found low N:P ratios in their reed vegetation along the river Rhine, indicating N limitation; our bamboo zone is clearly P-limited, as can be inferred from the N:P ratios we found. A comparison of our data with the data from the floodplain of the river Biebrza in Poland (Olde Venterink et al., 2009) reveals that in the Biebrza floodplain vegetation, both N and P are lower, whereas K is slightly higher. Nevertheless, there are also indications for the Biebrza floodplain to be P-limited, as is our bamboo zone. When Spink et al. (1998) experimentally tested nutrient limitation by conducting fertilization experiments in seven floodplains, they found that only in one floodplain – the Irish river Shannon – plant growth was nutrient-limited (in their case, N and P co-limitation). In the other six floodplains, climatic factors (temperature, latitude) seemed to be the dominant drivers of productivity. Thus it seems that most river floodplains do not face nutrient limitations. In cases where nutrient limitation has been found, both the monsoon river Songkhram and the temperate rivers Biebrza and Shannon differ from the river Rhine in that their vegetation is limited or co-limited by P. The absence of P limitation in the Rhine floodplain is probably attributable to the large input of P by the river Rhine, the water of which contains wastewater discharge and runoff from farmland in the human-dominated catchment of the Rhine (Billen G., 2011). This has also been observed in other human-impacted rivers in Europe and North America (Caraco and Cole, 1999; Sjodin et al., 1997). Perakis and Hedin (2002) sampled rivers from 100 unpolluted primary forests in temperate South America and compared them to streams in polluted regions in temperate North America, concluding that in unpolluted regions, the stream water nitrate concentrations were low and dissolved organic nitrogen was responsible for most of the nitrogen losses from these forests. It is, however, unclear if this also holds for tropical rivers in unpolluted areas. Putting the scarce information about N and P cycling and fluxes in tropical rivers and the role floodplains play into perspective, it is clear that we are only beginning to understand how N and P cycling is driven by climate, river characteristics, and human interference, and how important floodplain processes are in nutrient cycling and retention.

3.6 Acknowledgments

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Chapter 4

Ecohydrological analysis of the relatively pristine floodplain of the Narew River, Poland

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Abstract: The floodplain of the Narew River is a relatively pristine wetland area in Central Europe. The hydrology of the river is relatively undisturbed compared to other European river systems. Fundamental knowledge about how European river floodplains ecologically function under pristine conditions is of importance for the restoration of degraded systems. We analyzed floodplain vegetation communities, soil, nutrient availability, and the chemistry of surface water and groundwater. Vegetation was found to be grouped into 3 types: 1) a distinct forest understory community with *Urtica dioica* and *Ribes nigrum* dominance, 2) a relatively species-rich tussock sedge community dominated by *Carex elata,* and 3) a tall sedge community with *Carex acuta* and/or *Glyceria maxima* dominance. The distribution of these plant communities on the floodplain was related to the local flood characteristics and site physical characteristics. In all communities, plant productivity was limited by nitrogen. Chemical characteristics differed in water from different sources. River water had significantly higher concentrations of NO_3^-, Cl^- and K^+ than groundwater and floodplain water from puddles and an oxbow lake, whereas floodplain water stood out by high organic carbon. The occurrence of water quality and vegetation gradients in the floodplain suggest a relatively undisturbed floodplain compared to many other European rivers where polluted river water dominates floodplain water chemistry and overrules natural vegetation gradients. This study contributes to our understanding of how relatively undisturbed European rivers and river floodplains may ecologically function. Such rivers and floodplains are valuable for their intrinsic value and as a source of scientific information.

Keywords: Ecological gradient, ecohydrology, hydrochemistry, nutrients, plant communities, soil.

4.1 Introduction

River floodplains are among the most complex and dynamic ecosystems. Ecological gradients of river floodplains exhibit longitudinal and lateral gradients. The former is driven by upstream-downstream connections and the latter between landscape connectivity between the river and the adjacent hinterland (Vannote et al.,1980; Ward et al., 1999; Junk and Wantzen, 2004; Batzer et al., 2018). Plant species and vegetation types are distributed along such environmental gradients primarily because of underlying ecologically steering factors such as soil characteristics and water and nutrient availability (Wassen et al., 1990, Olde Venterink et al., 2002), but also because of differences in tolerance to flooding stress (Parolin, 2002; Beumer et al., 2008; Junk et al., 2012). In floodplains, in particular, flood regime and water chemistry play an important role as determining factors for plant distribution and vegetation zonation (Beumer et al., 2008). However, most studies on European rivers have been carried out in floodplains of regulated rivers in which the discharge regime of the river is heavily influenced by dam construction and embankment enforcement (Tockner and Stanford 2002). Moreover, most European rivers are polluted. During the last decade, river rehabilitation programs have remediated point pollution sources and created more room for the river during high discharges, for instance, in the Rhine and its tributaries (Admiraal et al., 1993), the Oder (Marszelewski and Piasecki, 2020), the Elbe (Meyerhoff and Dehnhardt, 2007), the Loire (Bergerot et al., 2008), the Meuse (Admiraal et al., 1993) and the Danube (Tockner et al., 1998; ICPDR, 2009).

Since these rivers went through a deterioration and rehabilitation process, and monitoring programs were usually only installed after the deterioration started, there is a fundamental gap in knowledge of how rivers and river floodplains ecologically function under more pristine conditions (Brierley and Fryirs, 2008). It is important to investigate ecological processes in relatively undisturbed European rivers and floodplains in order to have a reference for the restoration of deteriorated systems. Here we present an ecohydrological analysis of such a river: The Narew river in Poland.

Several studies regarding the environmental and ecological characteristics of the Narew river and its floodplain have been conducted from various disciplinary angles. These include hydro-ecological characteristics of the river and floodplains (e.g., Gielczewski, 2003; Miroslaw-Swiatek et al., 2007), chemical characteristics of the river water, and ecological functioning of the river (Zielinski et al., 2003; Górniak, 2018), the role of vegetation in the development of the anastomosing system (Gradziński et al., 2003), changes in riparian plant communities in response to changing flood regime (Szewczyk et al., 2003) and the relation between aquatic vegetation in the river channel and environmental variables (Barendregt and Gielczewski, 1998). These studies provide insight into the ecological functioning, and the hydrological and hydrochemical aspects, notably the river itself. However, the vegetation and ecological functioning of the river floodplain has not been studied so far. A study of aquatic vegetation by Barendregt and Gielczewski (1998) demonstrated that a longitudinal gradient of in-stream plant communities was related to physical gradients in the river (discharge, flow velocity, width, and depth) and to water chemistry. Additionally, a detailed study of the upper Narew riparian vegetation communities by Szewczyk et al. (2003) demonstrated transversal vegetation patterns related to groundwater and flood regime. However, no analysis of floodplain plant communities in relation to environmental conditions and nutrients and their spatial location has been undertaken for the Narew floodplain.

We aim to describe vegetation communities of the Narew river floodplain, link them to environmental conditions, and discuss if the floodplain can still be interpreted as a pristine system that can be used as a reference site for European floodplains. We present vegetation community data and nutrients in vegetation, as well as soil nutrient and hydrochemical data of each community.

4.2 Study area

The Narew River originates in Belarus and flows through northeast Poland (Fig. 4.1). It is the largest lowland right-bank tributary of the Vistula River, with a total length of ca. 484 km and a total drainage area of ca. 75,000 km^2 (Gielczewski et al., 2011). The basin is situated in a temperate climate zone with a yearly average temperature of 7.2 °C and gross precipitation of 617 mm

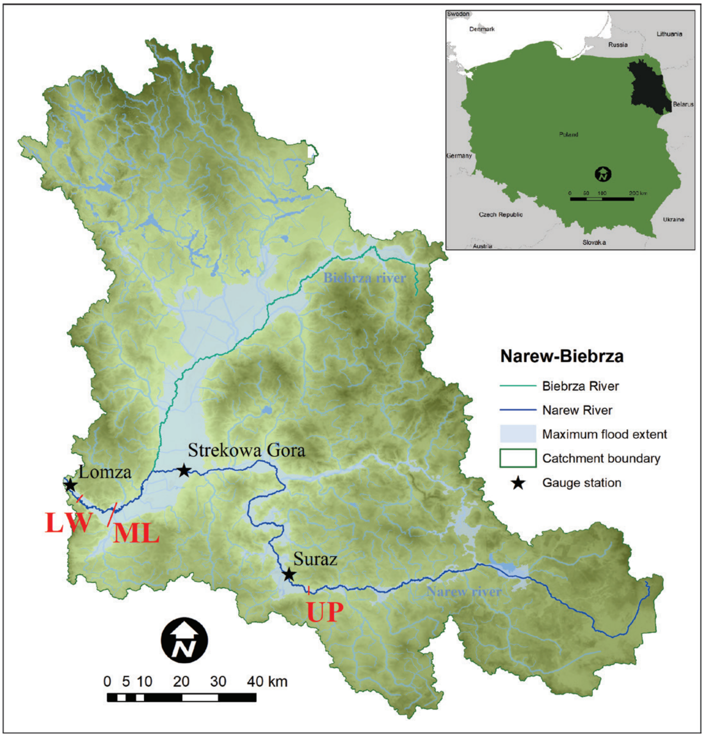

Fig.4.1. Location of the Narew River basin in north-east Poland (inset) and topographic features of the study area. Grey color indicates river valleys, and green colors indicate elevation in the catchment (darker = higher). Red strips indicate transects where soil and vegetation were examined. The river water was sampled at the gauge stations.

(Gielczewski 2003). The upper part of the river runs through the middle Pleistocene plateaus before entering the Vistulian Glaciation area with loamy moraine plateaus or sandy glaciofluvial plains in the lower area (Górniak 2018). The width of the flood terrace of Narew is up to 10 km. Inter-channel areas and floodplains are mostly covered by a thick layer of peat. Most land cover in the basin is agriculture and forest, which account for 55% and 32%, respectively; around 10% of the catchment is a nature protection area (Gielczewski 2003). Regular and predictable flooding is a characteristic of the Narew River floodplains. The river is defined as a temperate snowmelt-fed river system that is characterized by increasing discharges and water levels after snowmelt reaches a maximum during spring in March and April. Water level and discharge then decrease in summer and autumn until the mostly frosty winter period starts (Fig. 4.2).

The floodplains of the Narew River (N.E. Poland) form a relatively pristine wetland area in Central Europe. Due to their importance as a natural and biodiversity reservoir for many species, parts of the Narew floodplains are under national and European protection. In the absence of heavy industry, big cities, and intensive irrigation, the hydrological system of the river basin is relatively undisturbed compared to many other European river systems.

The anastomosing multi-channel reach in the Narew National Park downstream from Suraz is globally well known. The meandering reaches of the river between Tykocin and Nowogrod where the Narew joins the Bug River, are nice examples of relatively undisturbed lowland European river stretches. However, since the economic boom in Poland started, agricultural practices are becoming more intense and of a larger scale with a concomitant increase in fertilizer utilization. Ecosystem

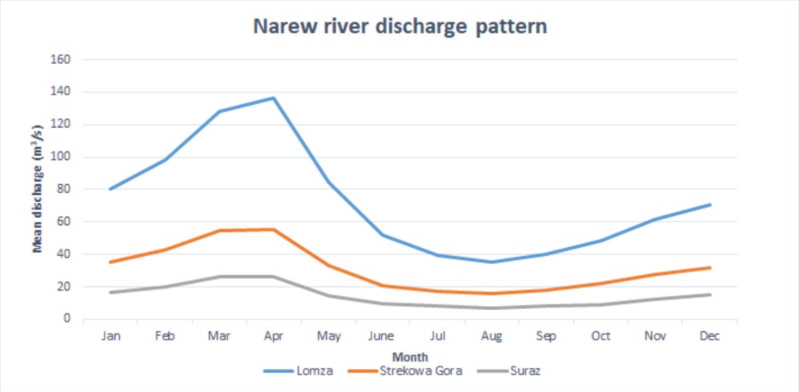

Fig. 4.2. The average monthly discharge of the selected gauge stations of the Narew River was calculated for the period 1986 to 2015 on the basis of daily measurements (Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB), Poland).

functions and services of the Narew floodplain may come under pressure, and with expected climate change, this may further increase in the future (Okruszko et al., 2011; Piniewski et al., 2014; Moomaw et al., 2018). Furthermore, the Siemianówka Reservoir, situated in the upper part of the river and constructed in 1992, has significant effects on the hydrological regime of downstream river sections (Marcinkowski and Grygoruk 2017).

This study focuses on the upper part of the Narew River upstream from the gauge station located at Lomza (Fig. 4.1). At this station, the drainage area of the basin is ca. 15,300 km^2, and the upstream length of the river course is ca. 310 km. Daily discharge measurements for the period of 1964 – 2019 showed that mean low discharge and mean high discharge at this gauge station are 16.7 m^3/s and 246.2 m^3/s, respectively (Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)).

4.3 Methods

4.3.1 Sampling locations

Since this paper aims to describe possible variations in floodplain habitats present in the upper Narew floodplains while considering accessibility, we carefully selected three sites. At these 3 sites (Fig.4.1) we installed 7 sampling plots encompassing various floodplain vegetation communities. The first site was located furthest upstream near Suraz and contained two sampling plots (UP1 and UP2). The plots were aligned perpendicular to the river channel at a distance to the river of approximately 700 and 430 m for UP1 and UP2, respectively (Fig.4.3A). At this site, the river channel was relatively narrow (ca.20 m), and the extent of the floodplain was ca. 1- 1.5 km wide.

The second site's location was at a so-called mid-downstream area near Strekowa Gora just after the tributary river Biebrza joins Narew. This site is lined between the villages named Krzewo and Gac. Here, the main channel has expanded to ca. 40 m width, and the lateral extent of the floodplain at this location is about 4 – 6 km. At this site, a floodplain forest appeared at the floodplain edge and expanded into the floodplain area before the vegetation changed to a floodplain fen-meadow type. Three sampling plots were established at this floodplain site. The first (ML1) and the second (ML2)

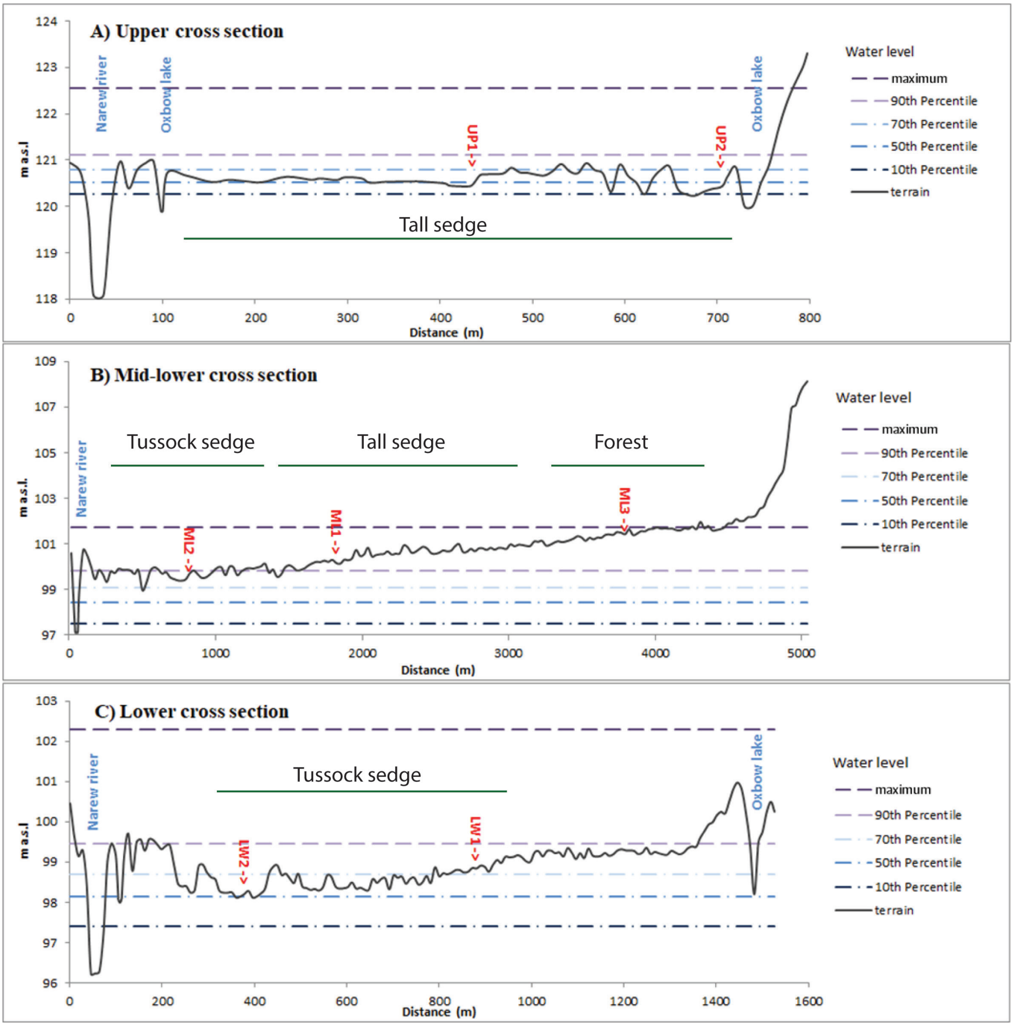

Fig. 4.3. Cross-sections across the valley at locations UP (A), ML (B), and LW (C) with the water level at the 10th, 50th, 70th, 90th percentile, and terrain elevation. The line of the 90th percentile indicates the water level that encompasses 90% of the observations, so 90% of the observations have a water level that is lower than this line, whereas the 10th percentile line indicates that only 10% of the observations have a lower level than this line

were in the fen-meadow vegetation near the forest edge and the rich fen vegetation near the main river channel, respectively, while the third plot (ML3) was in the forest (Fig.4.3B).

The third site was located further downstream near Lomza, where the floodplain was constrained by the post-glacial moraines surrounding the valley, and its width had decreased to ca.2 km. The width of the river channel was ca. 40 m. At this site, we established two sampling plots: LW1 at ca. 50 m from the floodplain edge close to the moraine and LW2 near the main river channel (Fig.4.3C).

4.3.2 Flood characteristics of each floodplain site

Water level statistics of each floodplain site were obtained from the Mike11 hydrological model developed within the framework of the Polish governmental project 'Review and analysis of flood risk' (IMGW-PIB and ARCADIS 2020). The model established relationships between river water levels at each of our floodplain sites and the nearest water gauge station. The relationships were verified by field measurements carried out with the GPS-RTK technique. Based on the relationships, we determined the daily water level at each particular floodplain site for the period 1964 – 2019. Water level statistics representing the 10th, 50th, 70th, and 90th percentile were related to the elevation along the cross-section of each floodplain site, as shown in Fig.3. Thus, the line of, e.g., the 70th percentile indicates the water level that encompasses 70% of the observations, so 70% of the observations have a water level that is lower than this line, whereas the 10th percentile line indicates that only 10% of the observations have a lower level than this line. The occurrence of inundation at each sampling plot was then calculated per day for the period 1964 to 2019 by subtracting the daily water level with the site's elevation. Each resulting inundation level at a particular sampling plot that was higher than zero was counted as a river inundated event. These were used to determine average inundation depths and the average number of inundated days per year in the period 1964 – 2019 (shown in Table 4.1). Statistics for seasons were based on the assumption that a flood counted as a flood event if it occurred more than 5 days per season (with a maximum of 1 flooding event per season and 4 per year).

4.3.3 Vegetation sampling and analysis

Vegetation sampling was conducted between 29 May and 3 June 2015. This period is considered representative of the recognition of fully grown and flowering plants and the harvesting of biomass as a proxy for above-ground productivity. A square plot of 10 m^2 (3.3 X 3.3 m) was established at each sampling plot. Plant species were recorded following the Braun-Blanquet approach, and cover-abundance values were later transferred into a semi-decimal scale following van der Maarel (1979). In the forested plot (ML3), we recorded trees and shrubs in two additional plots of 100 m^2 (10 X 10 m) to have a better description of the species composition of the shrub and tree canopy layer.

In each of the 7 sampling plots, above-ground biomass was harvested by clipping living herbaceous plant material down to the ground surface and collecting litter in a square of 50 X 50 cm (three replicates for each plot). Litter and dead standing biomass were separated from the living plant material. The dry weight of dead and living biomass was determined by weighing after drying for 48 hours at 70 °C.

Subsequently, the dried plant biomass was grounded and analyzed for nitrogen (N) and carbon (C) using a C/N analyzer. Part of the ground sample was digested by nitric acid (65% HNO_3) and analyzed for phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), aluminum (Al), silica (Si), iron (Fe), sulfur (S), and manganese (Mn) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Analyzes were performed at the chemical lab of the Faculty of Geosciences, Utrecht University, The Netherlands.

4.3.4 Soil sampling and analysis

Soil samples were collected at the same sites as where vegetation samples were taken. In April 2015, three soil cores (10 cm depth, 5 cm diameter) were taken using PVC tubes at each plot. The soil samples were analyzed for soil water content, bulk density, pH, and extractable nutrients (N, P, K) in the laboratory of SGGW, Warsaw University of Life Sciences, Poland.

First, the volume and wet weight of fresh soil of each core were determined. Next, the soil was mixed homogeneously, and three sub-samples of approximately 10 g. were taken from each sample and weighed. Next, these were oven-dried at 105 °C for 48 hours. Subsequently, the dry weight of each sub-sample was determined. The water content of the sub-sample was calculated from the difference between wet and dry weight and expressed as % of wet weight. The water content of the sample was then calculated by using the wet weight of the sample and the average percentage of water of the 3 sub-samples. Next, the water percentage of each sample was used to calculate the dry weight of each sample. Bulk density was determined for each sample by dividing the soil's dry weight by the core volume. Another three sub-samples of 10 grams of wet soil were taken from the homogenously mixed soil from each core to determine available nutrient concentrations.

Available nitrogen in the soil as present in the forms of nitrate (NO_3^-) and ammonium (NH_4^+) was determined. For this, we used 49 ml of 1 M of KCL solution to extract available nitrogen from 10 grams of wet soil. The sample was shaken for 15 minutes at room temperature (ca.25°C) and then centrifuged. The supernatant was used for analyzing concentrations of nitrate (NO_3^-) and ammonium (NH_4^+) by using a continuous segment flow analyzer (Seal Analytical, 2000). We also measured pH from this supernatant.

For P and K, we used a mixed solution of 0.1 mol/L ammonia (NH_3) + 0.4 mol/L acetic acids + 0.1 mol/L lactic acids (following Olde Venterink et al., 2002). We used 49 ml of this solution to extract 10 grams of wet soil. The samples were shaken for 15 minutes at room temperature (ca.25°C) and then centrifuged. The supernatant was analyzed by ICP-OES to determine the concentration of P and K in the extractant.

4.3.5 Water sampling and analysis

We took 17 river water samples, 3 samples of floodplain surface water, and 4 samples of groundwater. River water samples were collected from 3 locations, i.e., Suraz, Strekowa-Gora, and Piatnica-Lomza gauge stations (Fig.4.1). We sampled these stations in five periods: sampling periods were 19 – 24 December 2014, 14 – 18 January 2015, 25 February – 1 March 2015, 29 March – 3 April 2015, and 10-14 April 2015. We applied an integrated sampling approach for river water collection, which implies that three equal sub-samples were taken at each location, one in the middle of the river and one at the river edge ca. 2 m from each levee. The sub-samples were carefully put together, stirred gently, and divided into three parts. The first part was stored in a 12ml PP bottle and filtered directly in the field through a polytetrafluoroethylene (PTFE) membrane syringe filter with 0.45 µm pore size and frozen for nutrients and major ion concentrations. The second part was stored in 50 ml glass bottles and frozen until analyzed for total nitrogen and carbon. The third part was stored in a 2000 ml bottle, kept cool in the dark (basement conditions during winter in Poland), and later analyzed for total suspended solids.

In the Surface Water Monitoring Laboratory, Water Centre of the Warsaw University of Life Sciences, Poland, the first part of the river water sample was analyzed for major ions, i.e., chloride (Cl^-), nitrate (NO_3^-), nitrite (NO_2^-), sulfate (SO_4^{2-}), ammonium (NH_4^+), sodium (Na^+), potassium (K^+) and calcium (Ca^{2+}) using an ion chromatography method. The sample was also analyzed for orthophosphate (PO_4^{3-}) using a spectrophotometer method. Total phosphorus (TP) was determined using an acid-persulfate digestion method applied to an un-filtered part of the water sample. This method turns particulate phosphorus into PO_4^{3-} after which the concentration of PO_4^{3-} was determined by a spectrophotometer.

The second part of the water sample (50ml bottle) was used to determine total organic carbon (TOC) and total nitrogen (TN) in the unfiltered sample by high-temperature catalytic oxidation method at 850 °C using Skalar Formacs HT/TN device (compliance next methods respectively: ISO 8245, EPA 415.1 and ISO 11905-2, DIN ENV 12260, DIN 38409 H27). Similarly, the filtered sample was analyzed for dissolved organic carbon (DOC) and total dissolved nitrogen (TDN).

The third part of the water sample (2000 ml bottles) was used to determine total suspended solids (TSS) and organic matter (OM). From this, a known amount of the water (1000 – 1500 mL) was filtered through a GF/F filter (0.7 µm pore size). The filters were pre-dried and weighed to know the initial weight before use. The filters with the residual suspended solids were then dried at 105 °C for 4 hours and weighed to determine the TSS after allowing them to cool down in a desiccator. Subsequently, the filters were ignited at 400 °C for 16 hours. Weight loss in the ignition process is considered to be organic matter.

Floodplain surface water samples were collected in April 2015 from 3 plots: LW1, LW2, and UP2. Two of the floodplain water samples were collected from small puddles near LW1 and LW2, while one sample near UP2 was collected from an oxbow lake. Groundwater samples were collected from four piezometers with filter depths of ca.100 cm below the surface. One piezometer was installed in the upstream site near plot UP2. Three piezometers were installed in the mid-downstream locations: two were situated near plots ML3 and ML1, and one was close to the lower floodplain (LW) site.

Floodplain water samples were treated similarly to the river water samples and analyzed for hydrochemical variables the same way as river water. Groundwater samples were treated similarly to the river water and floodplain water samples and analyzed for hydrochemical variables except for TSS, TOC, TN, and OM.

4.3.6 Data Analysis

Cover-abundance values for plant species in the vegetation recordings were first transformed for each plot to a scale number ranging from 0 – 9, according to van der Maarel (1979). The species data were then ordered using hierarchical clustering to explore the degree of similarity in plant species composition. Plant species from each plot were then grouped based on the similarity between the community structure of the clustering. Furthermore, the species data were square root transformed to down-weigh potential influences of species-poor sites or rare species in the data set. Subsequently, detrended correspondence analysis (DCA) was applied to explore the variability of vegetation communities' structure in our data set.

Variability of biomass and nutrients in biomass among plots was analyzed using one-way ANOVA and HSD post-hoc. Variability of soil variables and extractable nutrients among sampling plots were analyzed using Kruskal-Wallis analysis of variance and Dunn's test. Differences in the mean of nutrient concentrations in living biomass as well as extractable soil nutrients of different plant communities were tested using an independent samples t-test.

The nutrient ratio of the living biomass was used as a proxy for nutrient limitation of vegetation in which nitrogen limitation is indicated by a value of N/P ratio lower than 14.5 and N/K ratio lower than 2.1. N-K co-limitation is indicated by a value of N/P ratio lower than 14.5 and N/K ratio higher than 2.1 (Olde Venterink et al., 2003).

A linear regression model was used to analyze trends of change in water chemical characteristics over the winter to spring period. The differences in variabilities of water chemistry from river water, groundwater, and floodplain water were analyzed using Kruskal-Wallis one-way analysis of variance. This analysis was also applied to variabilities of water chemistry from different gauge stations.

The differences among the samples were tested by Wilcoxon signed-rank test for water chemistry from river water, groundwater, and floodplain water. Wilcoxon pairwise post-hoc test was applied for river water chemistry from different gauge stations.

4.4 Results

4.4.1 Flood characteristics

Long-term water level probability statistics show that plot UP1 in the upper floodplain site was most frequently inundated (Table 4.1). The second most frequently flooded plot was LW2 in the lower floodplain site. The plots in the mid-lower site were the least frequently inundated. Especially, plot ML3 in the forest was an outlier that had only one single day of inundation by the river. Plots that were located closer to the river tend to be more frequently flooded and experience deeper floods than plots situated further away from the river.

The average (± standard deviation) inundation depth of the plots of the upper floodplain site were 0.37 ± 0.13 m and 0.27 ± 0.11 m for UP1 and UP2, respectively. In general, the inundation depths increase downstream. Remarkably, the average inundation depth of plot ML1 in the mid-lower site was lower than on the two upper site plots. The plots LW1 and LW2 of the lower floodplain site had the largest average inundation depths (Table 4.1).

4.4.2 Vegetation community

In total, 53 plant species were recorded in the 7 studied plots. The number of recorded species varied between 4 and 27 species per plot. The most common species were *Phalaris arundinacea* and *Galium palustre,* which were found in 6 and 5 plots, respectively (Table 4.2).

At the upstream plots UP1 and UP2, approximately 580 and 350m located from the main river channel, 17 species were recorded, of which 11 species at UP1 and 12 species at UP2. Dominant species common to both plots were *Carex elata, Galium palustre, Ranunculus repens,* and *Phalaris arundinacea.* Species like *Carex acuta, Caltha palustris,* and *Stellaria uliginosa* were found to be (sub)dominant in UP1 but absent in UP2.

Table 4.1. Summary of sampling site characteristics showing the distance to the river, elevation, average inundation depth (mean ± SD), and average flood events per season: averaged over a period of 56 years (1964-2019). *Flood event counted if it occurs more than 5 days per season (there can be a maximum of 1 flooding event per season and 4 per year).

Flood characteristic	Site name						
	UP1	UP2	ML1	ML2	LW1	LW2	ML3
Distance to Narew river (m)	430	700	1670	720	880	360	3730
Elevation (M S.A.L)	120.32	120.72	100.21	99.27	98.75	98.3	101.6
Number of flooded year	56	56	25	54	55	56	1
Average depth (m)	0.37 ± 0.13	0.27 ± 0.11	0.15 ± 0.14	0.45 ± 0.24	0.62 ± 0.43	0.85 ± 0.49	0.12
Average events per winter*	1	0.9	0.1	0.7	0.8	0.9	0
Average events per spring*	0.9	0.3	0	0.2	0.3	0.4	0
Average events per summer*	1	1	0.3	0.8	0.9	0.9	0
Average events per autumn*	0.9	0.3	0	0.2	0.2	0.4	0
Average events per year*	3.8	2.5	0.5	1.9	2.1	2.7	0
Average duration day/year	**292.4**	121.4	9.4	91.8	106.5	153.1	0

Table 4.2. Species diversity, above ground biomass, and cover-abundance values of plant communities of the Narew River floodplains, Poland. The first symbol given for species indicates cover (after Wassen et al. (1990): r covering less than 5% of the plot surface; + 5 - 10% cover; I 11 – 20 % cover; II 21 - 40 % cover; III 41 – 60% cover). The second symbol indicates a combined cover-abundance value calculated after Van der Maarel (1979). This scale is a 9-point scale with increasing numbers indicating increasing cover and abundance.

Site Name	UP1	UP2	ML1	ML2	LW1	LW2	ML3
Distance to the river (m)	430	700	1670	720	880	360	3730
Number of species	11	12	27	4	7	14	17
Litter Biomass (dw-g/m^2)	317 ± 133	304 ± 189	10 ± 5	504 ± 192	935 ± 131	99 ± 16	89 ± 38
Living Biomass (dw-g/m^2)	215 ± 67	269 ± 38	195 ± 35	292 ± 144	147 ± 75	353 ± 86	162 ± 27
Phalaris arundinacea	5	r 2	r 2	r 2	r 3	I 6	
Galium palustre	r 4	r 4	r 2		r 2	5	
Ranunculus repens	r 4	I 5	5			r 1	
Carex acuta	II 6			r 4	II 6	II 7	
Caltha palustris		r 4	r 2			r 1	r 4
Cardamine pratensis		r 2	r 2			r 2	r 2
Lychnis flos-cuculi	r 2	r 2	r 4				
Agrostis stolonifera	r 2	r 2				r 1	
Calamagrostis canescens		r 2			r 2		r 4
Carex elata	I 6	III 8	II 7				
Glyceria maxima	r 2			II 7		II 6	
Rorippa amphibia	r 2			r 4		5	
Glechoma hederacea			r 2				r 2
Taraxacum officinale			r 4			r 1	
Agrostis canina			r 4				r 4
Lathyrus palustris			r 2		r 2		
Myosotis palustris			r 2				r 2
Stellaria uliginosa		r 4	r 2				
Alnus glatinosa							II 6
Corylus avellana							r 1
Dryopteris carthusiana							r 3
Filipendula ulmaria							r 3
Fraxinus excelsior							r 1
Iris pseudacorus	r 4						
Prunus padus							r 2
Ribes nigrum							I 5
Scirpus sylvaticus							r 2
Scutellaria galericulata							r 2
Urtica dioica							II 7
Alopecurus geniculatus			r 4				
Alopecurus pratensis			r 2				
Anthoxanthum odoratum			r 4				
Calamagrostis stricta			I 6				
Carex appropinquata			r 4				
Carex disticha					r 3		
Carex nigara			r 4				
Carex vesicaria		r 1					
Galium uliginosum			r 2				
Glyceria fluitans						r 4	
Lysimachia nummularia			r 4				
Lysimachia thyrsiflora		r 1					
Mentha aquatica			r 2				
Plantago major			r 4				
Poa palustris						r 2	
Polygonum amphibium						r 1	
Potentilla anserina			r 2				
Stachys palustris							r 2
Stellaria palustris	r 2						
Succisa pratensis			r 2				
Symphytum officinale			r 2				
Thalictrum flavum					r 1		
Trifolium repens			r 4				
Valeriana officinalis						r 1	

The vegetation recordings in the mid-downstream site were very different from each other. Plot ML1 showed very species-rich vegetation (27 recorded plant species). This plot was located ca. 1720 m. from the main river channel at the edge of the open floodplain in a fen-meadow before the floodplain forest. The most dominant and sub-dominant species at this plot were *Carex elata, Calamagrostis stricta* and *Ranunculus repens.* Fourteen out of the 27 species found were not found in any other plot. Plot ML2 was closest to the river channel (c. 620 m) and had the lowest number of species, with only 4 species recorded. The vegetation at this plot was dominated by *Glyceria maxima,* and sub-dominant species were *Rorippa amphibia* and *Carex acuta.* Lastly, plot ML3 in the floodplain forest, situated at the valley edge at c. 3530 m. from the main river channel, was covered by black alder trees (*Alnus glutinosa*) and contained 13 herbaceous or shrub species. Seven of these species were not found in any of the non-forested plots (Table 4.2). The other 8 species were restricted to this forest floor plot and included blackcurrant (*Ribes nigrum*), a faithful species of black alder forests, as well as stinging nettle (*Urtica dioica*).

In the most downstream site, we recorded 18 species, of which 7 species were found in LW1 and 14 species in LW2. Plot LW1 at c. 600m from the river is dominated by *Carex acuta,* whereas LW2 at 120 m from the river is dominated and co-dominated by species such as *Carex acuta, Glyceria maxima, Phalaris arundinacea, Galium palustre,* and *Rorippa amphibia.*

The hierarchical clustering revealed that the 7 plots could be classified into 3 groups based on their species composition (Fig.4.4). Table 4.3 presents a summary of the dominant species of each plot. The three clusters were: 1) a distinct forest plot (ML3) with *Urtica dioica* and *Ribes nigrum*

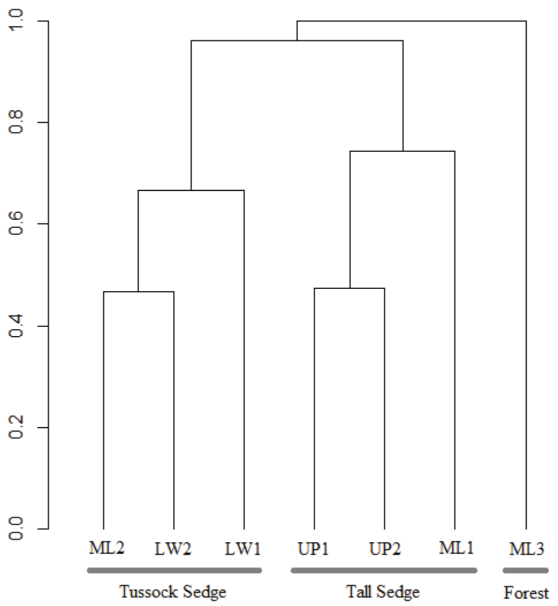

Fig. 4.4. Dendrogram of the hierarchical clustering showing two clusters of 3 plots each and plot ML3 separated from the other plots on a high dissimilarity level. The vertical axis indicates dissimilarity.

Table 4.3. Summary of characteristics of the vegetation clusters, nutrients in plant tissue, and in soil for each plot. Living biomass is of herbaceous layer only and does not include shrubs and trees. Living biomass and plant carbon concentration did not differ between the plots, whereas litter biomass, N, P, and K concentrations were different (one-way ANOVA, $p<0.05$). Values that share the same character after numbers indicate no difference between plots (HSD post-hoc). The nutrient limitation was inferred after Olde Venterink et al. (2003). Soil characteristics and extractable nutrients in the soil were tested for significant differences between plots (Kruskal-Wallis and Dunn's test, $p<0.05$). Values that share the same characters after numbers indicate no difference between plots. NA indicates a value lower than the detection limit. The number of samples for vegetation data and soil bulk density was 3 per plot, and the number of samples for other soil variables was 9. The table is organized from left to right from upper, middle to lower reach of the river, which coincides to a large extent with the tussock sedge community, tall sedge community and forest.

Site location	**Upper**		**Mid-Lower**		**Lower**		**Forest**
Plot name	UP1	UP2	ML1	ML2	LW1	LW2	ML3
Vegetation community	Tussock sedge			Tall sedge			Alder forest
Dominant species	*Carex acuta* (II) *Carex elata* (I) *Phalaris arundinacea* (+)	*Carex elata* (III) *Ranunculus repens* (I)	*Carex elata* (II) *Calamagrostis stricta* (I)	*Glyceria maxima* (II) *Carex acuta* (r) *Rorippa amphibia* (r)	*Carex acuta* (II) *Phalaris arundinacea* (r) *Carex disticha* (r)	*Carex acuta* (II) *Glyceria maxima* (II) *Phalaris arundinacea* (I)	*Alnus glutinosa* (II) *Urtica dioica* (II) *Ribes nigrum* (I)
Distance to the river (m)	430	700	1670	720	880	360	3730
Number of species	11	12	27	4	7	14	13
Living Biomass (dw-g/m2)	215 ± 67	269 ± 38	195 ± 35	292 ± 144	147 ± 75	353 ± 86	162 ± 27
Litter Biomass (dw-g/m2)	317 ± 133ab	304 ± 189ab	10 ± 5a	504 ± 192b	935 ± 131c	99 ± 16a	89 ± 38a
Plant N (mg/g-dw)	23.52 ± 2.10bc	22.09 ± 1.27abc	22.39 ± 1.61abc	16.26 ± 0.27a	22.65 ± 0.82abc	19.19 ± 3.04ab	27.33 ± 4.09c
Plant P (mg/g-dw)	2.82 ± 0.35a	2.58 ± 0.22a	2.50 ± 0.21a	2.36 ± 0.07a	2.34 ± 0.15a	2.02 ± 0.23a	4.81 ± 0.68b
Plant K (mg/g-dw)	14.05 ± 3.27ab	8.60 ± 1.74a	16.68 ± 1.65b	12.87 ± 1.40ab	19.57 ± 4.17b	13.83 ± 1.74ab	17.94 ± 3.02b
Plant C (mg/g-dw)	425.7 ± 5.6	430.2± 7.8	414.0 ± 4.71	424.0 ± 4.61	430.3 ± 5.0	433.9 ± 58.6	391.7 ± 13.8
C/N	18.21 ± 1.83	19.51 ± 0.83	18.56 ± 1.35	26.08 ± 0.58	19.01 ± 0.49	22.74 ± 1.11	14.62 ± 2.90
N/P	**8.35 ± 0.31**	**8.62 ± 1.13**	**8.98 ± 0.96**	**6.90 ± 0.30**	**9.72 ± 0.89**	**9.47 ± 0.77**	**5.71 ± 0.81**
C/P	152.38 ± 19.7	167.7 ± 16.3	166.2 ± 15.4	180.0 ± 7.3	184.5 ± 13.8	214.9 ± 11.4	82.7 ± 13.5
N/K	1.72 ± 0.46	**2.62 ± 0.36**	1.35 ± 0.14	1.27 ± 0.16	1.20 ± 0.27	1.39 ± 0.21	1.53 ± 0.18
C/K	31.59 ± 8.41	51.23 ± 8.89	25.01 ± 2.84	33.17 ± 3.36	22.66 ± 4.74	31.47 ± 3.53	22.33 ± 4.52
K/P	5.00 ± 1.20	3.37 ± 0.86	6.66 ± 0.23	5.46 ± 0.59	8.32 ± 1.25	6.90 ± 0.93	3.72 ± 0.18
P/K	0.21 ± 0.05	0.31 ± 0.08	0.15± 0.01	0.18 ± 0.02	0.12 ± 0.02	0.15 ± 0.02	0.27 ± 0.01
Soil moisture (%)	65 ± 4ab	66 ± 1ab	70 ± 2bc	76 ±1d	79 ± 3d	36 ± 5a	73 ± 2cd
Bulk density (g-dw/cm3)	0.33 ± 0.08ab	0.35 ± 0.01ab	0.29 ± 0.02ab	0.22 ± 0.02a	0.19 ± 0.02a	0.84 ± 0.14b	0.24 ± 0.01ab
Soil pH	5.2 ± 0.1ab	5.0 ± 0.1a	6.6 ± 0.5d	5.7 ± 0.1bc	5.3 ± 0.05ab	6.8 ± 0.5d	6.4 ± 0.5cd
Soil N-NO_3- (mg/kg)	12.9 ± 15.7ab	7.6 ± 6.7a	11.0 ± 11.8ab	NA	19.2 ± 11.6b	10.1 ± 4.6ab	48.0 ± 17.3c
Soil N-NH_4^+ (mg/kg)	44.5 ± 10.3d	30.0 ± 5.1bc	38.7 ± 9.8d	40.1 ± 4.5d	26.8 ± 13.8b	6.0 ± 4.5a	36.6 ± 11.1cd
Soil extractable N (mg/kg)	57.4 ± 23.2bc	37.6 ± 8.6b	49.7 ± 16.4bc	40.1 ± 4.5b	46.0 ± 15.8b	16.1 ± 5.3a	84.6 ± 27.7c
Soil extractable P (mg/kg)	15.0 ± 2.5bc	12.2 ± 2.5ab	20.3 ± 2.4cd	12.5 ± 2.3ab	12.7 ± 1.6ab	8.3 ± 1.5a	63.5 ± 15.1d
Soil extractable K (mg/kg)	92.8 ± 28.3d	51.2 ± 6.4ab	79.3 ± 26.9 cd	68.0 ± 7.3bcd	91.2 ± 22.6cd	23.1 ± 8.1a	61.7 ± 22.6bc

dominance in the understory, which, as expected, is separated from the other plots on a high dissimilarity level; 2) a relatively species-rich tussock sedge community dominated by *Carex elata* consisting of plots ML1 near the floodplain-forest edge and the two plots in the upper floodplain (UP1 and UP2) and 3) a tall sedge community with *Carex acuta* and/or *Glyceria maxima* dominance consisting of two lower floodplain plots (LW1 and LW2) and the mid-lower floodplain plot ML2.

To explore the variability of vegetation community structure, a detrended correspondence analysis (DCA) was applied to the plant species data. The DCA bi-plot of the first two axes (Fig. 4.5) revealed that the forest plot ML3 is indeed different since it is positioned far from the other plots. Species-rich plot ML1 is located quite centrally in the bi-plot, where many species are plotted. Fig. 5 also shows that the 3 plots of the tussock sedge community are aligned along the first axis and are positioned from the center to the negative side. Plot LW1 of the tall sedge community is located very close to UP1 of the tussock sedge community, illustrating the species composition of these two plots has similarities. The other two plots of the tall sedge community (ML2 and LW2) are located further down (negative) on axis 2, illustrating that in these plots, some species occur which are not found in any of the other communities. The species associated with plots situated relatively close (120m-620 m) to the main river channel (ML2, LW1, LW2, UP1, and UP2) are restricted to the negative side of the first axis of the bi-plot, while plots ML1 and ML3 plot on the positive side of the axis are located further from the river (resp. 1720 and 3530 m).

Fig. 4.5. Bi-plot of the first two axes of a detrended correspondence analysis showing species and plots.

4.4.3 Biomass and nutrients in biomass

Living biomass, as well as litter biomass, were highest in the tall sedge community (Table 4.3). Nutrient plant concentration (N, P, and K) in the living biomass varied among plots (Table 4.3). N concentration ranged from 16.26 ± 0.27 mg/g-dw in the lowest diversity ML2 plot to 27.33 ± 4.09 mg/g-dw in the forest plot. P concentration ranged from 2.02 ± 0.23 mg/g-dw to 4.81 ± 0.68 mg/g-dw. The concentration of P in plant tissue was significantly higher in the forest plot than those in the sedge communities. K concentration ranged from 8.60 ± 1.74 mg/g-dw in the tussock sedge plot UP2 in the upper part of the river valley to 19.57 ± 4.17 mg/g-dw in the tall sedge plot LW1 in the lower part.

We further compared nutrients in the living biomass between the communities. It appeared that N and P concentration in the herbaceous layer of the forest plot was significantly higher than in samples from both sedge communities (one-way ANOVA and HSD post-hoc; Fig.4.6). K concentration tended to be higher in the forest plot and in the tall sedge community than in the tussock sedge community.

We compared nutrient ratios with the ratios that indicate nutrient limitation. N:P ratio in all plots was well below 10, and N:K ratio was lower than 2.1 indicating that vegetation in our study area was limited in growth by N (Table 4.3). One site (UP2) showed co-limitation by N and K. There was no indication for P limitation in any plot.

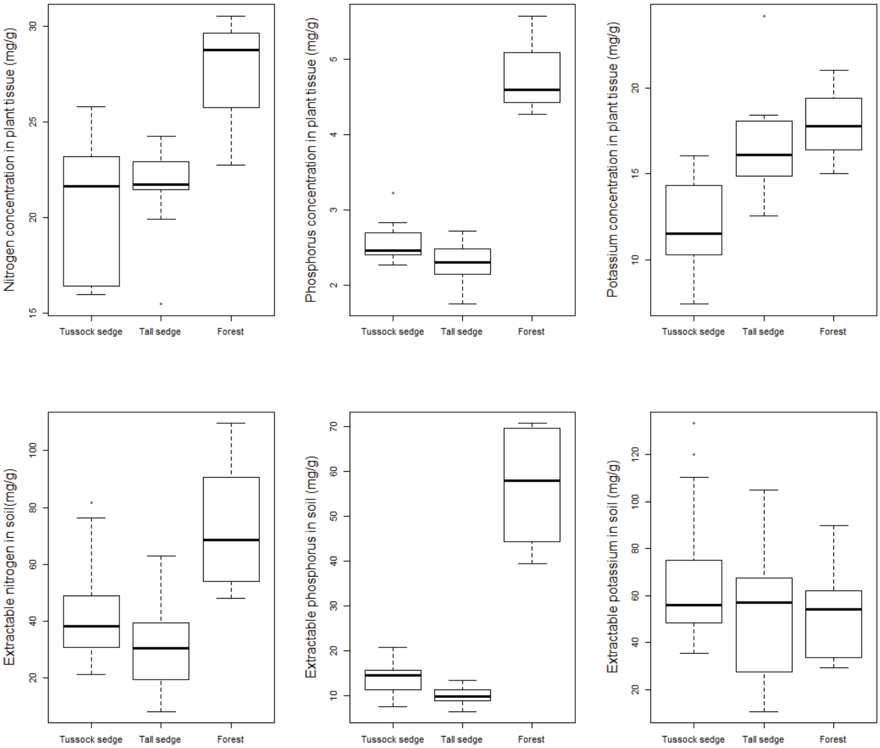

Fig.4. 6. Boxplot compares nutrient concentrations in living biomass and soil available nutrients of the three plant communities.

4.4.4 Soil nutrients

Soil extractable nutrients (N, P, K) varied among the studied plots, comparable to nutrients in biomass (Table 4.3). Soil extractable N (sum of N-NO_3^- and N-NH_4^+) was dominated by N-$NH_4^{+,}$ which has a much higher concentration than N-NO_3^-, except for one of the tall sedge plot (LW2) and the forest plot (ML3). The concentration of N-NH_4^+ ranged from 6.0 ± 4.5 mg/kg in one of the tall sedge plots (LW2, also having the highest bulk density) to 44.5 ± 10.3 mg/kg in the tussock sedge plot UP1.

Extractable P varied in a similar way ranging from 8.3 ± 1.5 mg/kg in plot LW2 to 63.5 ± 15.1 mg/kg in plot ML3. Extractable K showed the lowest concentration (23.1 ± 8.1 mg/kg) in plot LW2 and the highest concentration (92.8 ± 25.0) in plot UP1. The fact that soil extractable nutrients (N, P, K) were lowest in LW2 can be explained by the high bulk density: apparently, in this site, the mineral content of the soil is higher, and the organic matter content is lower, resulting in less extractable nutrients.

Analysis of differences in extractable soil nutrients between the vegetation communities (one-way ANOVA and HSD post-hoc; Fig.4.6) revealed that soil extractable N and P were significantly higher in the forest plot than in the sedge community plots. No significant differences were found for extractable K among the communities.

Table 4.4. Summary of water chemistry variables showing mean concentration and standard deviation of surface water from the Narew River and its floodplains and groundwater collected from piezometers installed next to the plots. Number of samples: floodplains = 3, groundwater = 4 except for TP = 1, river water = 17.

Water variables		River water	Floodplains	Groundwater
	units	mean	mean	mean
EC	µS/cm	**403 ± 40ab**	**272 ± 114a**	**596 ± 254b**
pH	pH unit	**7.9 ± 0.2b**	**6.9 ± 0.4a**	**6.9 ± 0.3a**
HCO3-	mg/L	230 ± 40	146 ± 85	418 ± 220
NO_3^-	mg/L	**4.22 ± 1.12b**	**0.12 ± 0.04a**	**0.17 ± 0.11a**
NH_4^+	mg/L	**0.40 ± 0.24b**	**0.05 ± 0.05a**	**0.72 ± 0.66 ab**
PO_4^{3-}	mg/L	0.08 ± 0.05	0.04 ± 0.03	0.40 ± 0.74
K^+	mg/L	**3.69 ± 0.71b**	**1.07 ± 1.29a**	**0.88 ± 0.97a**
Cl^-	mg/L	**11.10 ± 1.30b**	**2.83 ± 1.57a**	**7.67 ± 2.10a**
SO_4^{2-}	mg/L	23.14 ± 3.57	23.03 ± 8.23	44.95 ± 29.97
Na^+	mg/L	**13.50 ± 2.27b**	**8.59 ± 2.08a**	**14.57 ± 8.40ab**
F^-	mg/L	**0.12 ± 0.02a**	**0.13 ± 0.05ab**	**0.29 ± 0.19b**
Ca^{2+}	mg/L	95.31 ± 10.18	77.41 ± 37.29	163.64 ± 74.82
TDN	mg/L	**2.05 ± 0.38b**	**1.41 ± 0.09a**	**1.62 ± 0.20ab**
DOC	mg/L	**18.11 ± 1.85a**	**26.23 ± 2.80b**	**28.55 ± 4.32b**
TOC	mg/L	**19.85 ± 1.97a**	**28.17 ± 1.51b**	NA
TN	mg/L	**2.34 ± 0.42b**	**1.62 ± 0.14a**	NA
TSS	mg/L	9.56 ± 3.95	8.47 ± 2.15	NA
OM	mg/L	4.65 ± 2.24	6.38 ± 2.46	NA
OM (%)	%	48.27 ± 16.32	77.21 ± 27.67	NA
TP	mg/L	0.19 ± 0.11	0.08 ± 0.04	1.097

Variables in bold indicate a significant difference between the columns (Kruskal-Wallis, P<0.05). Numbers sharing the same letter indicate no statistical difference (Wilcoxon signed rank test, P<0.05). NA indicates variables with no measurements.

4.4.5 Hydrology and water chemistry of the Narew river

The Narew river is a lowland river in a temperate climate system. High discharge generally occurs during spring floods between March and May due to the melting of accumulated snow during the winter period. The long-term average annual discharges measured at Lomza, Strekowa Gora, and Suraz gauge stations are 2287 x 10^6 m^3, 974 x 10^6 m^3, and 454 x 10^6 m^3, respectively (Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)). The peak discharge occurs in mid-April, and the lowest flow is in mid-August (Fig. 4.2). However, there was no flood event in the period that we conducted the field campaign (autumn 2014 – summer 2015). Therefore, we sampled the main river channel, the surface water on the floodplain that we found in an oxbow and in shallow pools, and groundwater. River water and groundwater had the highest values of EC, reflecting high concentrations of inorganic substances dissolved in the water (Table 4.4). River water also had high concentrations of nitrate (NO_3^-), potassium (K^+), and chloride (Cl^-), whereas groundwater had the highest concentrations of phosphate (PO_4^{3-}), alkalinity (HCO_3^-), sulfate (SO_4^{2-}), and calcium (Ca^{2+}). The floodplain water showed the lowest ion concentrations in general but differed from river water and groundwater by high organic matter and carbon (DOC, TOC, and OM).

Table 4.5. Mean concentration (± standard deviation) of the water chemistry of the Narew river comparing three different gauge stations (see Fig. 1). The values were calculated from 5 or 6 samplings taken in the period December 2014 to April 2015 (see Methods).

Water variables	units	Suraz (upper, n = 6)	Strekowa Gora (middle, n = 6)	Lomza (lower, n = 5)
EC	**µS/cm**	**388 ± 16b**	**395 ± 58ab**	**433 ± 16a**
pH	pH unit	7.9 ± 0.2	8.0 ± 0.3	7.9 ± 0.2
HCO3-	mg/L	223 ± 25	230 ± 59	239 ± 32
NO_3^-	mg/L	4.07 ± 1.17	4.47 ± 1.32	4.12 ± 0.97
NH_4^+	mg/L	0.44 ± 0.25	0.37 ± 0.28	0.38 ± 0.22
PO_4^{3-}	mg/L	0.06 ± 0.04	0.09 ± 0.06	0.09 ± 0.07
K^+	**mg/L**	**2.98 ± 0.44b**	**3.88 ± 0.44a**	**4.3 ± 0.48a**
Cl^-	**mg/L**	**10.2 ± 1.3b**	**12.1 ± 1.0a**	**10.9 ± 0.9ab**
SO_4^{2-}	**mg/L**	**19.8 ± 2.8b**	**24.2 ± 1.6a**	**26.0 ± 3.1a**
Na^+	**mg/L**	**11.7 ± 2.0b**	**15.0 ± 1.9a**	**13.9 ± 1.6ab**
F^-	**mg/L**	**0.10 ± 0.01b**	**0.13 ± 0.02a**	**0.13 ± 0.02a**
Ca^{2+}	mg/L	93.3 ± 8.1	96.8 ± 11.7	95.9 ± 12.3
TDN	mg/L	2.11 ± 0.40	2.03 ± 0.47	2.01 ± 0.27
DOC	**mg/L**	**19.4 ± 1.8b**	**16.9 ± 1.8a**	**18.0 ± 1.1ab**
TOC	**mg/L**	**20.8 ± 1.3b**	**19.5 ± 2.8ab**	**19.1 ± 1.1a**
TN	mg/L	2.29 ± 0.36	2.43 ± 0.55	2.28 ± 0.39
TSS	mg/L	9.0 ± 2.5	10.3 ± 3.6	9.4 ± 6.1
OM	mg/L	4.63 ± 3.19	5.18 ± 1.60	4.04 ± 1.81
OM (%)	%	47 ± 27	51 ± 6	47 ± 8
TP	mg/L	0.15 ± 0.05	0.21 ± 0.14	0.19 ± 0.14

Variables in bold indicate differences between the columns (different letters indicate significant differences; Kruskal-Wallis one-way analysis of variance and Wilcoxon pairwise post-hoc; p-value < 0.05).

The spatial pattern of river water chemistry was analyzed by comparing the average concentrations in the river water between the gauge stations (Table 4.5). Increases in concentration in the downstream direction were observed for EC, K^+, SO_4^{2-}, and F^- Surprisingly, Cl^- and Na^+ were higher in the middle location.

Table 4.6. Correlation coefficient, adjusted R-squared, p-value and slope (a) and intercept (b) of general linear model (y = ax + b) calculated between the values of the water variables (y) measured at 5 different moments in time (x) between November 2014 and April 2015. A weak correlation indicates strong variation between values measured at different sampling moments and a negative or positive slope indicates a decrease (-) or an increase (+) over time. For values see Fig. 4.7 and Fig.4.8.

Water variables	units	Slope (a)	Intercept (b)	Correlation coefficient	Adjusted R-squared	p-value
EC	µS/cm	10	373	0.39	0.1	0.12
pH	**pH unit**	**0.07**	**7.7**	**0.48**	**0.18**	**<0.05**
HCO3-	**mg/L**	**19**	**174**	**0.72**	**0.48**	**<0.01**
NO_3^-	**mg/L**	**-0.4**	**5.4**	**-0.55**	**0.25**	**0.02**
NH_4^+	**mg/L**	**-0.15**	**0.84**	**-0.95**	**0.89**	**<0.01**
PO_4^{3-}	**mg/L**	**-0.02**	**0.15**	**-0.64**	**0.38**	**<0.01**
K^+	mg/L	-0.16	4.2	-0.34	0.06	0.18
Cl^-	mg/L	0.23	10	0.27	0.01	0.3
SO_4^{2-}	mg/L	-0.61	25	-0.26	0.01	0.31
Na^+	mg/L	0.3	13	0.21	-0.02	0.43
F^-	mg/L	0.006	0.1	0.44	0.14	0.08
Ca^{2+}	**mg/L**	**4**	**83**	**0.61**	**0.33**	**<0.01**
TDN	**mg/L**	**-0.12**	**2.4**	**-0.5**	**0.2**	**0.04**
DOC	mg/L	0.1	18	0.08	-0.06	0.75
TOC	mg/L	-0.07	20	-0.06	-0.06	0.83
TN	**mg/L**	**-0.16**	**2.8**	**-0.6**	**0.31**	**0.01**
TSS	mg/L	-0.69	12	-0.27	0.01	0.3
OM	mg/L	-0.38	5.8	-0.26	0.005	0.32
OM (%)	%	0.006	48	0.001	-0.07	1
TP	mg/L	-0.027	0.27	-0.36	0.07	0.15

Variables in bold indicate significant linear relationship between concentration and time (p-value < 0.05).

The temporal pattern of water chemistry over the sampling moments was analyzed by calculating a linear regression model (y = ax + b) between water variables (y) and time steps (x) (Table 4.6). The correlation coefficients showed a significant ($p<0.05$) increasing trend of concentrations of HCO_3^-, $Ca^{2+,}$ and pH values from winter to spring. In contrast, concentrations of NO_3^-, NH_4^+, PO_4^{3-}, TDN, and TN significantly decreased from winter to spring. From Fig. 4.7 it became clear that organic carbon (TOC and DOC) showed a pattern of decreasing concentrations from December 2014 to February 2015 and then increased in March and April 2015. Similarly, TSS and organic matter showed a pattern of a swift drop in January 2015 before gradually increasing over the next period. Dissolved nutrients, i.e., PO_4^{3-}, NO_3^-, $NH_4^{+,}$ and K^+ tend to decrease when water level and discharge increase over the spring period (Fig.4.8).

4.5 Discussion

To explain plant species occurrence in river floodplains, environmental factors such as floodwater chemistry and flood characteristics should be taken into account (e.g., Bufkova and Prach, 2006; Beumer et al., 2008). We analyzed these factors in order to understand the ecological functioning of the relatively undisturbed Narew river in Poland as a reference for the restoration of deteriorated European rivers and floodplains.

In our study, plant communities were categorized into 3 types, i.e., 1) a distinct forest understory community with shrubs, herbs, and grasses; 2) a relatively species-rich tussock sedge community

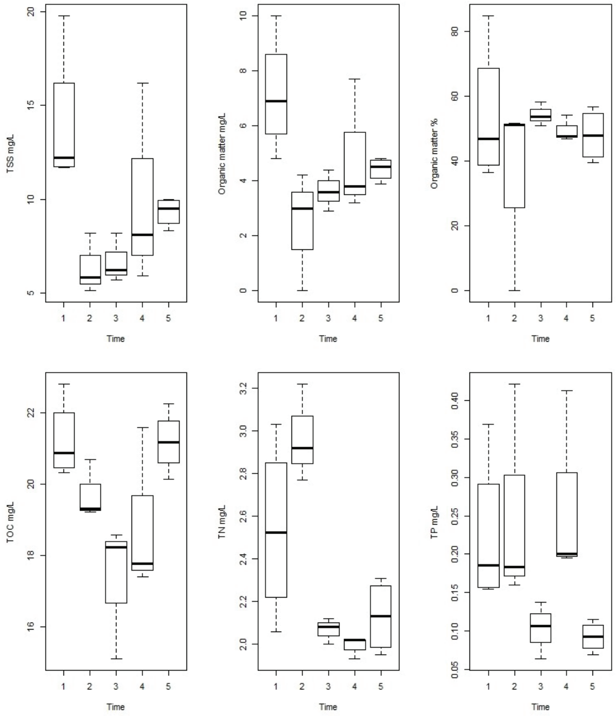

Fig.4.7. Boxplot of concentrations of particulate nutrients measured in the river water in five sampling campaigns between December 2014 to April 2015 (1 = 19 – 24 December 2014; 2 = 14 – 18 January 2015, 3 = 25 February – 1 March 2015, 4 = 29 March – 3 April 2015 and 5 = 10-14 April 2015).

dominated by *Carex elata* and 3) a tall sedge community dominated by *Carex acuta* and/or *Glyceria maxima*. The distribution of these communities was related to the position within the floodplain, flood frequency and depth, site physical characteristics, and soil available nutrients. The forest community that experienced no influence from the river was clearly different from the other two types. This was related to differences in physical factors (no inundation, upward groundwater flow, less light availability in the understory) and soil nutrient characteristics: soil available nutrients (both N and P) were higher in the forest. The other two communities were the tussock sedge and tall sedge communities that were influenced by floodwater. We found no significant differences in soil characteristics and nutrient availability between these two communities, but indeed the different position in the floodplain was prominent.

The communities' differentiation was linked to the longitudinal and transversal position of the plots over the river floodplain gradient and the inundation characteristic. For instance, the tussock sedge community that was found in plot ML1, which is located far away from the river channel near the floodplain-forest edge, was, as may be expected, inundated to a minor degree, whereas the two plots in the upper floodplain site (UP1 and UP2) were experiencing more inundation since located closer to the river although this may not be expected on their longitudinal position (upstream). The river influences the latter two plots more than plot ML1, which, although at a large distance from the river, experiences irregular floods in the wide valley in the mid-lower floodplain. The tall sedge community was found in two plots (LW1 and LW2) of the lower floodplain site and the plot ML2 of

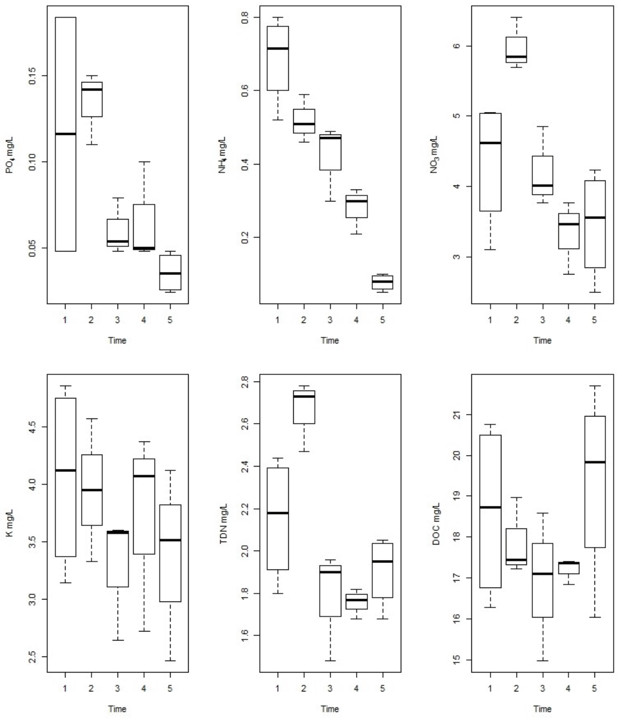

Fig.4.8. Boxplot of concentrations of dissolved nutrients measured in the river water in five sampling campaigns between December 2014 to April 2015 (1 = 19 – 24 December 2014; 2 = 14 – 18 January 2015, 3 = 25 February – 1 March 2015, 4 = 29 March – 3 April 2015 and 5 = 10-14 April 2015).

the mid-lower floodplain site. These plots experienced major river influences as discharges increased downstream, and the locations of the plots were near the main river channel. These floodplain sites had a deeper average flood depth than the tussock sedge community sites. It appeared that the tussock sedge was distributed in the upstream floodplain and further away from the main river channel in the mid-lower floodplain site. In contrast, the tall sedge community was found closer to the river in the mid-lower floodplain and in the lower floodplain. These distribution patterns demonstrate that both longitudinal and transversal gradients of vegetation communities exist on the floodplain.

The topography of a floodplain is an important feature that controls hydrological and hydrochemical processes, which relate to plant species distributions in the floodplain (e.g., Loeb et al., 2006; Antheunisse and Verhoeven, 2008). Although the number of our sampling plots was low, the plant communities were distributed non-randomly longitudinally and laterally over the river floodplain, demonstrating the distribution of vegetation communities over the Narew river floodplain related to the topographic position.

Interestingly, aquatic vegetation in the Narew river channel was also found to differ from upstream to downstream (Barendregt and Gielczewski, 1998). This was related to the physical gradient of the river characteristic (discharge, flow velocity, width, and depth) and water chemistry.

A comparison of extractable soil nutrients from our study with the adjacent pristine floodplain of the Biebrza river (Olde Venterink et al., 2009) showed that the Narew river floodplain had higher soil nitrogen and potassium concentrations but lower extractable P than the Biebrza river floodplain. Concentrations of extractable soil nitrogen, specifically N-NH_4^+ in the Narew tussock sedge community and the tall sedge community, were 37.74 ± 2.00 and 24.30 ± 3.19 mg/kg, respectively, which is 2 to 5 times higher than the N-NH_4^+ concentration found in the floodplain tall sedge community of Biebrza (6.8 ± 0.7 and 10.4 ± 1.8 mg/kg for unmown and mown floodplain tall sedge sites). High concentrations of soil N-NH_4^+ suggest high rates of N mineralization. N mineralization in floodplain systems can increase strongly with decreasing water tables that facilitate mineralization (Olde Venterink et al., 2009). This is also in line with our observation that no flood occurred during the year of our field campaign, which could have facilitated mineralization and may explain the high ammonium concentrations. Furthermore, the Narew river is experiencing a shortening of spring floods due to dam construction in the upstream section and decreasing summer flood durations, which are related to a changing climate (Marcinkowski and Grygoruk, 2017). Drying up peat in summer may boost mineralization resulting in high concentrations of N-NH_4^+ and a shift from a nitrogen-limited system to a non-limited floodplain system (Spink et al., 1998).

Concentrations of extractable soil P in our tussock sedge and tall sedge communities appeared lower than in the nearby floodplain fen and tall sedge communities of the Biebrza floodplain (Olde Venterink et al., 2009). Soil extractable P concentrations in both Narew (in this study) and Biebrza (Wassen and Olde Venterink, 2006; Olde Venterink et al., 2009) were lower than those observed in disturbed floodplains like e.g. Steenwaard (the Netherlands) and the Dommel (the Netherlands and Belgium) (Wassen and Olde Venterink, 2006; Antheunisse and Verhoeven, 2008).

Whether the Narew can be considered as a pristine floodplain is supported by two observations: (i) water with different water chemistry at different places in the floodplain and (ii) predominantly N limitation compared to anthropogenic disturbed European floodplains that are generally not limited by nutrients. Flooding is considered a natural disturbance factor that resets the system after every flood cycle (Beumer et al., 2008). The topography of the floodplain relative to the river water level determines flood frequency, length, and amplitude. It hereby also influences the input of nutrients to the soil, steering higher productivity and causing spatial patterns of plant communities (Wassen et al., 2003). The part of the floodplain near the river is supposed to have higher productivity caused by additional nutrient input from the river (Beltman et al., 2007; Chormanski et al., 2011; Keizer et al., 2014). However, our results show that extractable N and P in the soil of the floodplain where tussock sedge and tall sedge communities grew were lower compared to those in the forest soil. This suggests that the forest must receive additional nutrients from other sources. As the forest site was less influenced by flooding, more aeration and oxidation will lead to mineralization, as opposed to the waterlogged peat soil of the floodplain. This mineralization process potentially releases a significant amount of nutrients to the forest soil. Additionally, N-fixation by symbiotic fungal with Alder trees is a potential process that adds up nitrogen to the forest soil (Arnebrant et al., 1993; Walker et al., 2014).

Although topography and distance to the river, at first sight, served as an explanation for some patterns observed in our study, we think that the source of the flooded water is even more important. Clear distinctions in floodwater chemistry were found between different water sources, i.e., river water, groundwater, or rain/snowmelt (Chormanski et al., 2011; Keizer et al., 2014). This can also be observed in our results, which show that water from different sources, i.e., the river and groundwater had different water chemistry. The river water had high concentrations of nitrate (NO_3^-), potassium (K^+), and chloride (Cl^-), whereas groundwater had high concentrations of phosphate (PO_4^{3-}), a high alkalinity (HCO_3^-), and high sulfate (SO_4^{2-}), manganese (Mn^{2+}) and calcium (Ca^{2+})

concentrations. The water we sampled on the floodplain generally showed lower dissolved solids concentrations, as indicated by EC, than river and groundwater, indicating rainwater or snowmelt water influences. Also, high organic carbon (DOC, TOC) and organic matter (OM) were found in floodplain water, which suggests the floodplain itself is a source of carbon that probably gets mobilized from the floodplain by shear stress from flowing floodwaters. Floodplains being a source of organic carbon, have been demonstrated for tropical rivers (Junk and Wantzen, 2004; Walalite et al., 2018).

All plant communities in our study were N limited except one site where N and K co-limitation existed. N limitation commonly occurs in a wide range of wet and moist ecosystems, e.g., grassland, fen, and mire (Antheunisse et al., 2006; Wassen et al., 1998, 1995). Compared to anthropogenically impacted rivers in Europe, of which the floodplain generally shows an absence of limitation, nitrogen limitation can be potentially interpreted as an indicator for a well-functioning, relatively undisturbed floodplain (Antheunisse et al., 2006). However, nutrient ratios in plant material can serve only as a rough indicator for nutrient deficiency in a system (Wassen et al., 1998; Wassen et al., 2021). We, therefore, suggest to further study in detail the nutrient cycling in the Narew river floodplain, especially in relation to water level dynamics, since seasonal nutrient boosts related to water level dynamics may well exist in the dynamic Narew floodplain.

Remarkably, in earlier studies in the adjacent floodplain of the Biebrza river, vegetation in the river-flooded zone showed no N limitation, whereas the fen vegetation in the non-river-flooded zone was limited by N or co-limited by N and P (Wassen et al., 1995; Wassen et al., 1998). We also observed a spatial pattern in nutrient limitation in the tropical monsoon Songkhram River, where high productivity bamboo vegetation occurring close to the river was N and P co-limited, while low productivity grassland experiencing less influence by the river was N-limited (Walalite et al., 2018). Apparently, different rivers may exhibit different nutrient limitation patterns, which is puzzling since flood duration and frequency are underlying factors determining nutrient availability and vegetation community in a floodplain ecosystem (Antheunisse et al., 2006). This provides even more reason to study nutrient dynamics in relation to river dynamics in different floodplains.

4.6 Conclusions

The Narew river floodplain appears to be a relatively pristine example of a European floodplain ecosystem. Our results showed that the distribution of plant communities in the river floodplain was related to the site's longitudinal and traversal position on the floodplain, flood characteristics, and site physical characteristics. Although the observed high concentrations of soil extractable N may indicate less pristine conditions than expected, our study demonstrated a spatial variety of different water sources with different water chemistry at different places in the floodplain and a predominantly N-limited environment that is different from anthropogenically disturbed European floodplains. These characteristics underline the value of the Narew floodplain as a relatively pristine floodplain that may serve as a reference system for studying ecohydrological relationships.

4.7 Acknowledgments

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Chapter 5

Nutrients in tropical and temperate rivers and floodplains - comparison of the Rivers Songkhram (Thailand) and Narew (Poland)

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Abstract: Ecological processes in floodplains may function differently across climate regions. We compared the river discharge, water chemistry, and nutrient budget and balance of floodplain vegetation in a temperate climate (River Narew, Poland) with those in a tropical climate (River Songkhram, Thailand). Both rivers show a discharge regime with a flood pulse, following snowmelt (Narew) or monsoon rainfall (Songkhram), with peak discharges roughly 25 times higher in the River Songkhram. Electrical Conductivity (EC) values of both rivers are generally comparable, while nutrient concentrations are somewhat higher in the temperate River Narew (with total phosphorus (TP) approximately 1.5 and total inorganic nitrogen (TIN) approximately 2.2 times higher than in Songkhram). However, annual nutrient river loads are much higher in the River Songkhram due to its much higher peak discharges. Nutrient fluxes from the catchments are highest during the flood pulse. A comparison of the nutrient budget of floodplain vegetation suggests that soil is the most important source of nutrients for most vegetation types, i.e., Narew sedge (N), Narew forest floor (N and P), Songkhram bamboo (N and P), and Songkhram grass (P). Additionally, floodwater is the main input source of P for the Narew sedge and a secondary input source for Songkhram grass. We found a significantly higher nutrient concentration (N, P, K) in biomass from the Narew floodplains than in biomass from the Songkhram floodplains. Vegetation close to the river tends to have a higher productivity, emphasizing the nutrient-filtering function of floodplain vegetation. For both rivers, nutrient input into the floodplains by floodwater is higher than nutrient export from the floodplains, indicating that both floodplains have a nutrient sink function. These findings demonstrate that the floodwater pulse is a source of nutrient input for floodplain vegetation in both temperate and tropical climates, with the soil playing a vital role in the nutrient budgets and balance.

Keywords: Nutrient budget, Flood Pulse, Temperate river, Tropical monsoon river

5.1 Introduction

River floodplains are fertile landscape components that provide ecosystem services such as water retention, nutrient accumulation, carbon sequestration, and productive vegetation that can be harvested. The ecological functioning of river floodplains is complex, and it is thought that variations in the ecological process of the floodplains are caused by the catchment's hydrology, geology, water chemistry, vegetation, topography, and climate (Spink et al., 1998; Montgomery 1999; Tockner et al., 2000). Globally, undisturbed floodplains are becoming rare, and this is why it is of utmost importance to study the remaining relatively pristine rivers and their floodplains.

For pristine river catchments, the vegetation in the floodplains benefits from the nutrient-rich floodwater, resulting in high productivity, which is observed in both temperate and tropical climates (e.g., Olde Venterink et al., 2002; Walalite et al., 2018). The growing season of vegetation depends on the regional climate, which determines the hydrological regimes and the temperature to grow vegetation. For instance, vegetation in boreal or arctic floodplains only grows during the short summer period (< 3 months), whereas in temperate floodplains, the growing season lasts longer, and in tropical areas, there is no distinct growing season because the temperature is suitable for vegetation growth all year round. Furthermore, vegetation directly benefits during or after a flood since the river brings nutrients. Therefore, the hydrological regime and temperature together determine nutrient dynamics and vegetation production in floodplain ecosystems (Spink et al., 1998).

Flood pulse is defined as a regular, predictable flooding characteristic of river floodplains. According to the Flood Pulse Concept (Junk et al., 1989), floodwater brings nutrients that drive nutrient cycles to the floodplain ecosystem. Based on this concept, floodplain ecosystems are seen as relatively high production systems because they import nutrients derived from the parent river and then convert and store nutrients in the floodplain's vegetation. Transitions between wet and dry periods accelerate nutrient cycling processes. In particular, decomposition of organic material will release nutrients and can return these to the vegetation. The processes of storage and release of nutrients in the floodplain are influenced by this flood pulse characteristic and are thus crucial to understanding the growing cycle of the vegetation. However, these processes appear to be different for individual floodplains (e.g., Spink et al., 1998; Capon 2003; Parolin et al., 2016), urging the need to study river floodplains under different climatic conditions.

Within floodplains, different zones in vegetation productivity are observed. The spatial pattern of vegetation and its nutrient cycling processes in floodplains is the effect of topography and flood pulse combined with various sources of floodwater, i.e., river water, atmospheric water, and groundwater. This leads to the zonation of vegetation type and production. It has been shown for some temperate floodplains that the transition zone at the edge of the floodplain shows lower productivity than vegetation near the river. The high productivity zone near the river is the result of additional nutrients from the river water (e.g., Keizer et al., 2018), while the transitional zonation is caused by the mixing of river water and groundwater with rain or snow, which has lower nutrient concentrations (Wassen et al., 2003; Olde Venterink et al., 2006). In tropical monsoon floodplains, a high productivity zone also benefits from floodwater (e.g., Walalite et al., 2018). Zonation of vegetation productivity in a tropical floodplain was shown to be caused by a filtration function of the vegetation closer to the river (e.g., Walalite et al., 2018, 2016) and dilution by monsoon rain further away from the river.

Floodplains in the temperate climate are well studied, especially in North America and Europe. In the temperate Biebrza River in Poland, it was demonstrated how floodplains contribute to nutrient accumulation (Wassen 1995; Olde Venterink et al., 2002). Although floodplains can act as a sink for nutrients, they can also turn into a source, depending on their position in the catchment and the nutrient status of the river water (Spink et al., 1998). The functioning of floodplains in the tropics has been studied less, although notable exceptions are the floodplains of the Amazon (Junk 1997; Wittmann et al., 2004), Orinoco (Lewis et al., 2000), Kafue (e.g., Rees 1978; Zurbruegg et al., 2012; Zuijdgeest et al., 2015) and Okavango (e.g., McCarthy and Ellery 2010; Arias et al., 2016). In earlier research, we demonstrated that the floodplains of a tropical monsoon river absorb nutrients, particularly N and P, from floodwater during the flood period while releasing soil organic carbon for downstream sections (Walalite et al., 2018). However, few studies have focused on comparing the functioning of floodplains in a tropical and temperate climates.

This paper tries to contribute to a further understanding of nutrient transport, nutrient accumulation, and nutrient release in tropical river floodplains and temperate river floodplains. In particular, we aim to understand the sink-source relations of nutrients in river floodplains. We compare the river discharge, hydrochemistry, and nutrient status of two rivers and their floodplains. We evaluate the importance of nutrient input by floodwater and its contribution to the nutrient budget of the floodplains. Although our study areas have completely different climate regimes, we found similar floodplain vegetation patterns. We seek to understand if these patterns are caused by similar processes, and we do so by analyzing the seasonal pattern of discharge, nutrient concentration, and nutrient loads of both rivers in relation to the floodplain.

5.2 Study areas

The European Narew River basin is situated in north-eastern Poland (22°12’ to 24°27’ E and 52°36’ to 54°16’ N), and the Southeast Asian River Songkhram is situated in north-eastern Thailand (103°12’ to 104°35’ E and 16°55’ to 18°23’ N) (Fig. 5.1).

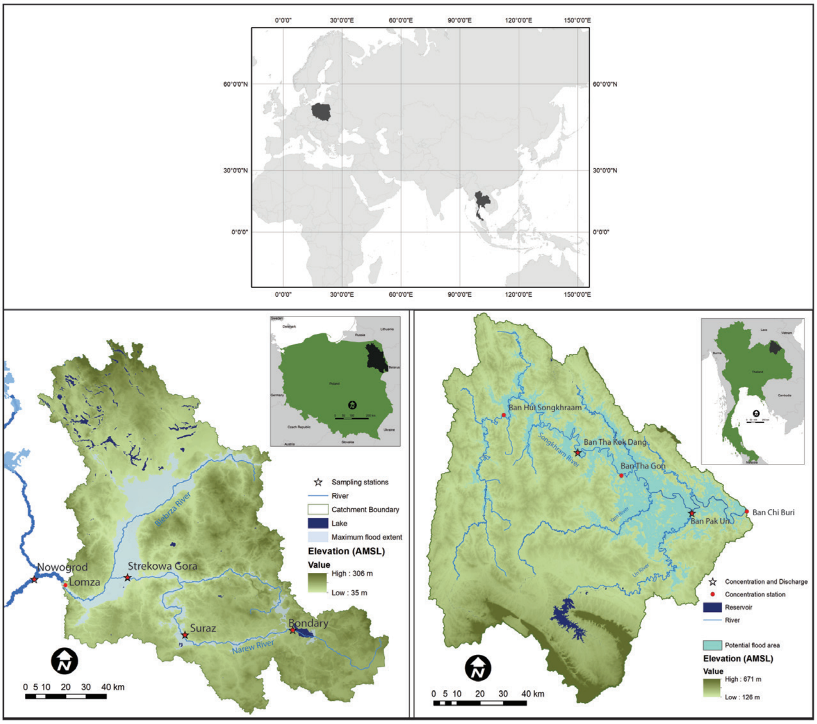

Fig. 5.1 Location of the River Narew catchment in northeast Poland and the River Songkhram in northeast Thailand.

The River Narew has a temperate climate with a yearly average temperature of 7.2°C and a mean annual precipitation of 617 mm (Gielczewski 2003). The drained area of the river basin at Lomza gauge station is around 15,000 km^2. This river is defined as a temperate snowmelt-fed river system (Mirosław-Świątek and Okruszko 2011) characterized by the maximum flood during spring (in March and April). Water level and discharge decrease in summer and autumn, and remain low during the frosty winter.

The River Songkhram has a tropical climate with a yearly average temperature of 26°C and a yearly average precipitation of 1960 mm (Walalite et al., 2016). The drainage area of this river basin is around 13,000 km^2. This river is a tropical monsoon rain-fed river. The monsoon season occurs from May to October, and flooding in the Songkhram floodplain occurs following the monsoon season. The peak flood generally occurs in late August, after which water discharge and water level gradually decrease towards the dry season that lasts from November until April.

The floodplains of both rivers show a relatively natural flood pulse, as well as natural patterns of floodplain vegetation communities and productivity. In the Narew floodplain, the general pattern consists of tall sedge vegetation in a wide belt adjacent to the river, and swamp forests occur at the edge of the floodplain, where the floodplain meets the elevated hinterland. In the Songkhram floodplain, there are also two main vegetation zones: dense bamboo vegetation adjacent to the river and grass vegetation further away from the river (Walalite et al., 2016). The Narew floodplain is dominated by organic peat soil, and the Songkhram floodplain soil is dominated by mineral soil.

5.3 Methods

5.3.1 Comparison of hydrochemistry and discharge patterns between the two rivers

To understand the seasonal pattern of flow characteristics and its relationship with hydrochemistry, we first analyzed the discharge and hydrochemical variables of the two rivers. We then compared discharge patterns and nutrient concentrations, which were mainly dissolved inorganic nitrogen and total phosphorus. To give a general view of the hydrochemistry, additional variables besides nutrients are also presented, i.e., electrical conductivity (EC), the potential of hydrogen (pH), dissolved oxygen (DO), and water temperature.

For the River Narew, the discharge and water chemistry variables, i.e., temperature, EC, pH, DO, TP, NO_2^-, NO_3^-, and NH_4^+, were obtained from the Chief Inspectorate of Poland's Environmental Protection. We selected data from four gauge stations distributed from upstream to downstream (Fig. 5.1), namely Bondary (BND), Suraz (SRZ), Strekowa Gora (St. Gora), and Nowogrod up to Pisa (NWP). The variables were measured on a monthly basis, and data were available from 1991 to 2017, except for Suraz; for this station, data were available from 2001 to 2016. A summary of the number of hydrochemical measurements can be found in Appendix 1. Daily discharge data were available from 1991 to 2018 for two stations, namely Strekowa Gora and Nowogrod up to Pisa. For Suraz, discharge data were available from 2015 to 2018 (Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)).

For the River Songkhram in Thailand, the hydrochemistry variables, i.e., temperature, EC, pH, DO, TP, NO_2^-, NO_3^-, and NH_3^+, were available for five stations. The stations, distributed from upstream to downstream (Fig. 5.1), were Ban Hui Songkhram (BHSK), Ban Tha Kok Dange (BTKD), Ban Tha Gon (BTG), Ban Pak Un (BPU), and Ban Chi Buri (BCBR). The hydrochemical data were available from 1996 to 2015, and these were provided by the Thai department of Pollution Control (unpublished data, personal communication). A summary of the number of measurements for each station can be found in Appendix 1. This river's daily discharge data were available only for Ban Tha Kok Dang from 1986 to 2010 and for Ban Pak Un station from 2013 to 2016 (Royal irrigation department of Thailand).

To compare the total inorganic nitrogen concentrations of these rivers, we used total inorganic nitrogen (TIN), which was the sum of the nitrogen from NO_2^-, NO_3^-, and NH_4^+ (for the River Narew), and NO_2^-, NO_3^-, and NH_3^+ (for the River Songkhram). Samples were taken from the River Narew monthly, while this was done every three months for the River Songkhram.

5.3.2 Nutrient loads and specific nutrient loads estimation

Nutrient load estimation: we assessed the outflow of nutrients from the catchments and the floodplain systems by estimating the rivers' nutrient loads and specific nutrient loads. For the River Narew, we estimated nutrient loads at three stations, i.e., Suraz, Strekowa Gora, and Nowogrod/Pisa. We omitted the Bondary station because this station is situated close to a reservoir. As for the availability of discharge data for the River Songkhram, we estimated nutrient loads at Ban Tha Kok Dang and Ban Pak Un stations, situated upstream and downstream of the main floodplains in the River Songkhram. The nutrient loading rates were estimated using an averaging estimation approach (Quilbé et al., 2006; Górniak 2018).

Monthly loads: we estimated the nutrient loads of each month using the average discharge and average concentration of nutrients measured in the month. The load of the month is given by:

$$\mathrm{L_m} = \overline{C_m} \times \overline{Q_m} \times n \times k \tag{1}$$

Where $\mathrm{L_m}$ = the month load (tons/month)

$\overline{C_m}$ = average nutrient concentration of the month (mg/l)

$\overline{Q_m}$ = average discharge of the month (m^3/s)

n = number of days in the month to convert from day to month

k = unit conversion coefficient (0.0864, to convert from gram per second to ton per day, so $86400 * 10^{-6}$)

Seasonal loads: we calculated the seasonal loads in the two rivers for two seasons based on the flow characteristics of the rivers. The flow characteristics of both rivers demonstrate a clear pattern of distinct seasonal high and low flows. The high flow season of the temperate River Narew is the winter/spring flow season, which runs from December to May of the following year, and the low flow summer/autumn season runs from June to November. The high-flow season of the River Songkhram starts in June and ends in November, and then the low-flow season begins in December and ends in May of the following year. The concentrations measured in each seasonal six-month period were averaged and were then considered to be the average concentration of the season. The average concentrations were then multiplied by the average discharge of the season. The seasonal load was calculated by:

$$\mathrm{L_S} = \overline{C_s} \times \overline{Q_s} \times n \times k \qquad (2)$$

Where $\mathrm{L_S}$ = the seasonal load (tons/season)

$\overline{C_s}$ = average nutrient concentration of the season (mg/l)

$\overline{Q_s}$ = average discharge of the season (m^3/s)

n = number of days in the season period

k = unit conversion coefficient (0.0864)

Annual loads: the annual load was the summation of the seasonal loads for both rivers.

Specific nutrient loads: specific nutrient load is the flux of nutrients from the upstream catchment area at a particular river outlet per unit area of the upstream watershed; this was calculated by dividing the annual nutrient load (in tons/year) by the area of the upstream watershed where the loads were estimated. The unit of the specific nutrient load is $kg/km^2/year$

5.3.3 Nutrient budgets estimation

Nutrient budget and balance model: in our simple nutrient budget and balance model, we assume that the increase in nutrients in vegetation biomass (*B*) equals the inflow of nutrients (*Ext* and *Soil*) subtracted by the outflow of nutrients from the system (Fig. 5.2):

$$\partial B_{N,P} = Ext_{N,P} + Soil_{N,P} - Outflow_{N,P} \qquad (3)$$

In which ∂B is the measured change in annual biomass expressed as Nitrogen (N) or Phosphorus (P), and *Ext* is the observed annual input of nutrients (N or P) from floodwater and the atmosphere. Following Wassen and Olde Venterink (2006), the input from groundwater is neglected. *Soil* is the amount of nutrients that vegetation takes up from the soil and is the only unknown in the equation. *Outflow* is the amount of nutrients leaving the floodplain by discharged water.

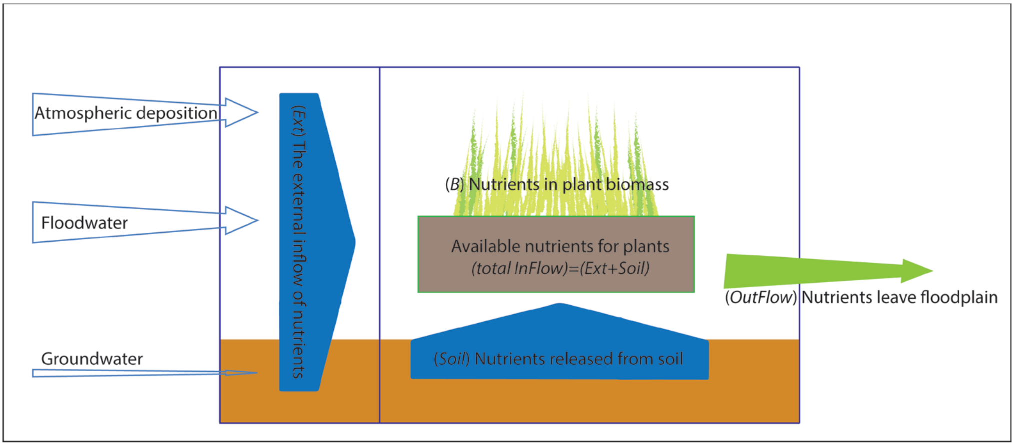

Fig.5.2 Conceptual model of nutrient flows in the floodplains ecosystem. The assumption is that the change in vegetation biomass (*B*) equals the inflows of nutrients (*Ext* and *Soil*) subtracted with the *outflows* of nutrients from the system.

Observations for calculating the nutrient budget and balance model: change in biomass (∂B) was measured by multiplying plant tissue nutrient concentration with the annual aboveground biomass production. In both the Narew floodplain and the Songkhram floodplain, two types of vegetation were distinguished. In the River Narew, floodplain sedge and floodplain forest floor vegetation were found. The species that dominated the floodplain sedge community were Phalaris arundinacea, Carex acuta, Glyceria maxima, and Carex elata, whereas the forest floor was dominated by herbaceous plants such as Urtica dioica and diverse forbs, grasses, and sedges. In the River Songkhram, floodplain vegetation was identified as flooded bamboo and flooded grass types (Walalite et al., 2018). For the Narew vegetation, we harvested the aboveground living biomass at the peak of the growing season, which is a reliable estimate for aboveground annual production in herbaceous temperate plant communities (Wassen et al., 2005). We applied the same method for the grass vegetation at Songkhram, and for the bamboo, we followed the approach of Walalite et al. (2018), in which only the yearly increase in biomass was measured by sorting fresh shoots from shoots of previous years.

For the River Songkhram, the external inflow of N by atmospheric deposition was 650 kg/km^2/year, whereas floodwater provided 2,170 and 1,240 kg/km^2/year to the flooded bamboo and grass zones, respectively, as was calculated by Walalite et al. (2016). The external inflow of atmospheric N deposition for Narew was estimated as 500-1000 kg/km^2/year, and N import from floodwater as 3,460 kg/km^2/year, based on measurements in the nearby Biebrza River floodplains (Wassen and Olde Venterink 2006). This is an adjacent tributary of the Narew, for which we assume an equal amount of external nutrient fluxes as for the Narew.

The external inflow of P by atmospheric deposition had not been reported for the Songkhram area, which is why we used information from Tipping et al. (2014), who reported an average P deposition for Asia of 20 kg/km^2/year. Floodwater provided 150 kg/km^2/year and 100 kg/km^2/year of P to the flooded bamboo and flooded grass zones, respectively (Walalite et al., 2016). For the River Narew, atmospheric P was 5 kg/km^2/year (Wassen and Olde Venterink 2006). In addition, floodwater provided 740 kg/km^2/year of P to the floodplain meadow at the Narew floodplain (Wassen and Olde Venterink 2006).

Outflow is calculated following equation (2) at a specific location in the river.

Plant tissue nutrient concentrations: Nutrient concentration in plant tissues was measured from collected plant material. For the River Songkhram, this included 15 samples of bamboo leaves and 27 samples of grass biomass (see Walalite et al., 2018), and for the River Narew, 18 samples of sedge biomass and 3 samples of forest floor vegetation biomass. The samples were dried at 70 °C for 48 hours. Subsequently, the dry plant material was ground and analyzed for nitrogen (N) and carbon (C), using a C/N analyzer. Part of the ground sample was digested in nitric acid (65% HNO_3) and analyzed for phosphorus (P) and potassium (K), using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

Following Olde Venterink et al. (2003), determining the type of nutrient limitation was based on critical values of N: P, N: K, and K: P ratios in aboveground plant material. N-limitation is indicated by N: P ratio < 14.5 and N: K ratio < 2.1, whereas P-limitation and co-limitation by both P and N was indicated by N: P ratios > 14.5 and K: P ratios > 3.4. K or in K+N co-limitation was indicated by N: K ratios > 2.1 and K: P ratios < 3.4.

5.4 Results

5.4.1 Hydrology and Hydrochemistry

Discharge patterns of two rivers: the discharge patterns of both rivers show a seasonal flood pulse (Table 5.1). In the River Narew (Poland), the peak discharge occurs in spring, around March and April, and the minimum discharge occurs in late summer, around August. The highest discharge occurred in March and April for SRZ and St. Gora stations, with approximately 26 and 55 m^3/s (Table 5.1). Thailand's Songkhram River demonstrates a flood pulse and peak discharge during the tropical monsoon season around August and September (Fig. 5.3). The average monthly discharge at the upstream station (BTKD) ranged from 3.1 – 493 m^3/s and the average monthly discharge at the downstream station (BPU) ranged from 2.5 – 1486 m^3/s (Table 5.1). During the dry season, from December to April, discharge in the River Songkhram was minimal. Peak discharges were roughly 25 times higher in the River Songkhram than in the River Narew. As the catchment area of the River Songkhram is around 30 to 40% smaller than that of the River Narew (Table 5.1), the specific peak discharge difference is even larger.

Differences between water chemistry and nutrient concentration of the two rivers: to understand the difference between the water chemistry and nutrient concentrations of the two rivers, the average EC and nutrient concentration were calculated from 4 (River Narew) and 5 (River Songkhram) stations, which were distributed from upstream to downstream (Table 5.2).

The average EC from the four selected stations of the River Narew ranged from 301 to 450 μS/cm and tended to increase downstream. The River Songkhram showed a higher range of average EC, from 345 to 952 μS/cm, and had the highest values midstream. In general, EC values were comparable for both rivers (ca. 300-450), except for stations 2 and 3 on the River Songkhram (EC ca. 800-950). The average total phosphorus (TP) concentration of the Narew River water was highest (0.31 mg/l) at the most upstream station at Bondary, and lowest (0.18 mg/l) at the most downstream station. A similar trend was observed in the River Songkhram, where the highest average TP concentration (0.23 mg/l) was at the most upstream Ban Hui Songkhram station, and the lowest TP concentration (0.12 mg/l) was at Ban Pak Un station (Table 5.3). The average annual nitrate-nitrogen ($N\text{-}NO_3^-$) concentration (Table 5.2) of the River Narew was lowest (0.58 mg/l) at the most upstream station Bondary, and highest (1.26 mg/l) at St. Gora station. The $N\text{-}NH_4^+$

Table 5.1. Mean monthly discharge (m^3/s) of the temperate River Narew (Poland) and the tropical monsoon River Songkhram (Thailand). The numbers in bold indicate each station's two highest discharges.

Month	River Narew			River Sonkghram	
	Suraz (SRZ)	Strekowa Gora (St. Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
January	16.3	35.6	80.2	3.7	8.5
February	19.8	42.9	98.2	3.1	2.5
March	**26.3**	**54.5**	**127.9**	2.6	4.9
April	**26.2**	**55.7**	**136.1**	2.9	3.2
May	14.6	33	84.6	27.9	38.5
June	9.6	20.5	51.7	194	279.3
July	8.5	17.5	39.7	316.2	739.9
August	7.1	15.6	35	**450.3**	**1485.9**
September	8.2	18.2	39.8	**493.4**	**1213**
October	8.9	22	48.5	216.5	458.7
November	12.8	27.4	61.9	27.5	187.5
December	15	31.8	70.7	5.6	50.1
Average	14.4	31.2	72.9	145.3	372.7
Discharge area (km^2)	3,377	7,181	20,106	5,089	12,328

Table 5.2.Hydrochemical characteristics of the River Narew and the River Songkhram. Total inorganic nitrogen (TIN) was the sum of $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, and $N\text{-}NH_4^+$ (for the River Narew) and of $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, and $N\text{-}NH_3^+$ (for the River Songkhram). Stations are listed from upstream to downstream.

River	Station Name	Annual average								
		Water Temp. (°C)	EC (μS/cm)	pH	O_2 (mg/l)	TP (mg-p/l)	$N\text{-}NO_3^-$ (mg/l)	$N\text{-}NO_2^-$ (mg/l)	$N\text{-}NH_4^+$/$N\text{-}NH_3$ (mg/l)	TIN (mg/l)
Narew	Bondary (BND)	9.79	301	7.9	9.4	0.31	0.58	0.37	0.25	1.08
	Suraz (SRZ)	10.3	389	7.8	9.4	0.2	1.03	0.02	0.11	1.16
	Strekowa Gora (St. Gora)	9.97	450	7.8	8.9	0.24	1.26	0.02	0.48	1.7
	Nowogrod up to Pisa (NWP)	10.23	444	8	9.3	0.18	0.87	0.02	0.36	1.18
Sonkghram	Ban Hui Songkhram (BHS)	27.92	441	7	6.2	0.23	0.38	0.04	0.17	0.46
	Ban Tha Kok Dang (BTKD)	28.56	952	7.1	6.9	0.14	0.49	0.03	0.18	0.57
	Ban Tha Ghon (BTG)	28.42	818	7.1	6.8	0.14	0.51	0.02	0.16	0.57
	Ban Pak Un (BPU)	28.24	454	7	6.4	0.12	0.57	0.04	0.14	0.65
	Ban Chai Buri (BCBR)	27.95	345	7.2	6	0.13	0.55	0.03	0.17	0.64

concentrations for the River Narew ranged from 0.11 mg/l at Suraz station to 0.48 mg/l at St. Gora station. The $N\text{-}NO_2^-$ concentrations (Table 5.2) appeared to be consistently low along the river from upstream to downstream (~0.02 mg/l), with the exception of the most upstream Bondary station (0.37 mg/l). For the River Songkhram, the average $N\text{-}NO_3^-$ concentration ranged from 0.38 to 0.57 mg /l. Upstream stations tended to have a slightly lower concentration than downstream stations, and annual $N\text{-}NO_2^-$ concentrations were low along the whole river. In general, inorganic nutrient concentrations – both TP and TIN – were almost twice as high in the River Narew as in the River Songkhram (Table 5.2).

Combining hydrology and hydrochemistry: to elucidate the effect of seasonal flow characteristics and the dilution effect on nutrient concentration and EC, Fig. 5.3 shows the monthly dynamics for both rivers. For the River Narew, we found a decreasing trend of EC during peak discharge in April, with the highest ECs during winter. TP concentrations had the lowest values during peak discharge and the highest during the summer months (June-August). Interestingly, the dynamics in TIN align with the dynamics in the discharge pattern in the River Narew. The River Songkhram showed the

Fig. 5.3 Annual patterns of discharge (lines), EC, TP, and TIN (bars) of the River Narew (St. Gora station) and the River Songkhram (Ban Tha Kok Dang stations). The plots present average monthly values.

lowest EC, TP, and TIN values during peak discharge. In contrast to the River Narew, the TIN values do not align with the discharge dynamics. Here, TP fluctuated before and at the start of the rainy season (April-July), whereas TIN concentrations were clearly highest after the peak discharge (Fig. 5.3).

5.4.2 Nutrient loads

Seasonal loads for P and N were integrated from the observed monthly loads (Appendixes 5.2 and 5.3). For the River Narew, between 77-79% of TIN was exported during winter (Table 5.3). For the River Songkhram, 97% of the TIN load was exported during the peak flow (Jun-Nov). Total annual TIN load and specific loads in the River Songkhram were twice as high as in the River Narew (Table 5.4). Clearly, for both rivers, the downstream stations exported more TIN due to higher discharges.

Table 5.3 Average discharge, nutrient concentrations, and nutrient loads of the River Narew and the River Songkhram. The table shows values for winter/spring (Dec.-May.) and summer/autumn (Jun.-Nov.) of the River Narew and dry season (Dec.-May.) and rain season (Jun.-Nov.) for the River Songkhram.

		River Narew			River Songkhram	
	Period	Suraz (SRZ)	Strekowa Gora (St. Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
Avareage Q (m3/s)	Dec.-May.	16.08	42.25	99.62	7.65	17.96
	Jun. -Nov.	9.16	20.19	46.1	283	727.38
Average TIN concentration (mg/l)	Dec.-May.	1.58	2.09	1.47	0.46	0.62
	Jun. -Nov.	0.75	1.33	0.9	0.47	0.49
Average TP concentration (mg/l)	Dec.-May.	0.17	0.18	0.13	0.14	0.09
	Jun. -Nov.	0.23	0.3	0.23	0.2	0.14
TIN load (tons)	Dec.-May.	399.5	1390	2299.2	55.3	173.8
	Jun. -Nov.	108.1	424.7	659.2	2101.4	5633.1
TP load (tons)	Dec.-May.	42.5	117.2	195.9	16.6	26.7
	Jun. -Nov.	33.6	96.3	170.6	873.4	1644.2
TIN load (%)	Dec.-May.	79%	77%	78%	3%	3%
	Jun. -Nov.	21%	23%	22%	97%	97%
TP load (%)	Dec.-May.	56%	55%	53%	2%	2%
	Jun. -Nov.	44%	45%	47%	98%	98%

Table 5.4. Annual nutrients load and specific nutrient load of the River Narew and the River Songkhram.

River	Station Name	Discharge area (km^2)	Load (tons/year)		Specific load ($kg/km^2/year$)	
			TIN	TP	TIN	TP
Narew	Suraz (SRZ)	3,420	507.5	76.1	148.4	22.3
	Strekowa Gora (St. Gora)	7,167	1814.7	213.4	253.2	29.8
	Nowogrod up to Pisa (NWP)	20,106	2958.4	366.5	147.1	18.2
Songkhram	Ban Tha Kok Dang (BTKD)	5,089	2156.7	890	423.8	174.9
	Ban Pak Un (BPU)	12,328	5806.9	1,671.0	471	135.5

In contrast, there was almost no difference in the TP load between summer and winter in the River Narew (Table 5.3), while for the River Songkhram, 98% of all P load was exported during the peak flow, comparable to the TIN dynamics. Total annual TP and specific loads were around six times larger for the River Songkhram than for the River Narew. Moreover, downstream stations exported a higher annual TP load.

5.4.3 Nutrient budget for biomass

We found a significantly higher nutrient concentration (N, P, K) in the biomass from the Narew floodplains compared to the nutrient concentrations in the biomass from the Songkhram floodplain (t-test, $p<0.05$; Table 5.5.). In the Narew floodplain, the herbaceous plants in the forest where no flooding occurs showed significantly higher N and P concentrations than in the floodplain sedge vegetation. In the River Songkhram, the bamboo, which is affected by flooding more than the flooded grass zone, had a higher nutrient concentration in biomass tissues and was the only vegetation type having P-limitation.

Nutrient accumulation in the aboveground biomass, calculated as the product of nutrient concentration and aboveground production, showed that vegetation zones with flooding had

Table 5.5. Nutrient concentrations in aboveground vegetation, aboveground production (dry weight), and the estimated nutrient storage in aboveground biomass of the River Songkhram floodplain and the River Narew floodplain. The data of the Songkhram floodplain was compiled from (Walalite et al., 2018), and data of the Narew floodplain was compiled from Walalite et al. (submitted to Wetlands Ecology and Management).

		Mean ± SE			
Plant tissue concentration	Unit	Poland		Thailand	
		Sedge (n= 18)	Forest floor (n = 3)	Bamboo (n = 15)	Grass (n = 27)
C	mg/g-dw	426.3 ± 5.1a	391.7 ± 7.98b	408.7 ± 4.5b	425.2 ± 2.6a
N	mg/g-dw	21.01 ± 0.71b	27.33 ± 2.36a	18.7 ± 0.8c	6.31 ± 0.30d
P	mg/g-dw	2.44 ± 0.07b	4.81 ± 0.39a	1.26 ± 0.08c	0.68 ± 0.05d
K	mg/g-dw	14.27 ± 0.96a	17.9 ± 1.74a	10.5 ± 0.5b	7.45 ± 0.30c
N/P	-	6.68 ± 0.27$^{\text{N-limited}}$	5.71 ± 0.47 $^{\text{N-limited}}$	15.4 ± 0.7 $^{\text{P-limited}}$	10.7 ± 1.0 $^{\text{N-limited}}$
K/P	-	5.95 ± 0.42	3.72 ± 0.01	8.5 ± 0.4	12.6 ± 1.1
N/K	-	1.59 ± 0.13	1.53 ± 0.1	1. 83 ± 0.09	0.91 ± 0.08
Aboveground production	g/m^2/year	471 ± 78 (n sample = 5)	162 ± 15 (n sample = 3)	521 ±? (n sample = 1)	386 ± 58 (n sample = 18)
Nutrient accumulation in aboveground biomass		Sedge (n site = 5)	Forest floor (n site = 1)	Bamboo (n site = 1)	Grass (n site = 6)
N	kg/km^2/year	9894.2	4427.5	9742.7	2435.7
P	kg/km^2/year	1149.1	779.2	656.5	262.5
K	kg/km^2/year	6720.2	2899.8	5470.5	2875.7

The same letters per row indicate no significant difference (t-test, $P<0.05$)

accumulated higher amounts of nutrients in aboveground biomass (Table 5.5). The amount of nitrogen in the Narew floodplain sedge community and the Songkhram bamboo was comparable, 9,894 and 9,743 kg/km^2/year, respectively (Table 5.5). In contrast, the amount of nitrogen in the aboveground production of the herbaceous vegetation in the forest floor of the Narew floodplain and the flooded grass in the Songkhram floodplain were much lower, 4,428 and 2,436 kg/km^2/year, respectively. Phosphorus storage in the aboveground biomass of the Narew floodplain sedge community and the forest floor was 1149 and 779 kg/km^2/year, respectively. In comparison, this was higher than P in aboveground production in the Songkhram River bamboo and grass vegetation, both flooded, which was 657 and 263 kg/km^2/year.

Potassium storage in the aboveground biomass of the Narew floodplain sedge and forest floor were 6,720 and 2,900 kg/km^2/year, respectively. For the River Songkhram, potassium stored in the aboveground bamboo and flooded grass was 5,471 and 2,876 kg/km^2/year, respectively.

5.4.4 Integrated Nitrogen and Phosphorus Budget and Balance Model

Based on Equation (3), we calculated all annual N and P flows for the different vegetation types in both rivers. The $Soil_{N,P}$ was the only unknown in the equation. In Table 5.6 and Figures 5.4 and 5.5, all flows are listed for all four vegetation types, both in kg/km^2/year and in percentages.

In the Narew floodplain, nitrogen input from the soil was the main source for both floodplain sedge (56%) and forest floor community (79%), and nitrogen outflow from the Narew floodplain was low, 2% and 5%, respectively. On the Songkhram floodplain, the soil was the major N source for flooded bamboo (72%), while the soil provided only 35% of the N for flooded grass. As a result, the external input flow (atmosphere and flooded water) was important in the flooded grass and provided 65%. The outflow of N from the Songkhram floodplain was about twice as high as the

Table 5.6. Nitrogen and Phosphorus balance of floodplain vegetation in River Songkhram and River Narew floodplains in kg/km^2/year (left) and in percentage (right). The percentage of the inflow from different sources was compared to the total inflow (*Ext+Soil*), which was considered as 100%. Also, the percentage of the nutrients in vegetation and the outflow were compared to the total inflow. Blue indicates the inflow of nutrients from different sources, grey is the total inflow, and green indicates nutrients stored in aboveground vegetation and the outflow from the floodplains.

Nitrogen		Narew		Songkhram		Narew		Songkhram	
		Floodplain sedge	Forest-floor	Bamboo	Grass	Floodplain sedge	Forest-floor	Bamboo	Grass
Ext	N from Atmospheric	500 - 1000b	500 - 1000b	650a	650a	10%	21%	6%	22%
	N from Floodwater	3460b	-	2170a	1240a	34%	0%	21%	43%
	Sub-total	4460	1000	2820	1890	44%	21%	28%	65%
Soil	*(B+OutFlow)-Ext*	5687	3681	7394	1017	56%	79%	72%	35%
Total Inflow	*Ext+Soil*	10147	4681	10214	2907	100%	100%	100%	100%
B	N in Vegetation	9894	4428	9743	2436	98%	95%	95%	84%
OutFlow	N River specific load	253	253	471	471	2%	5%	5%	16%

Phosphorus		Narew		Songkhram		Narew		Songkhram	
		Floodplain sedge	Forest-floor	Bamboo	Grass	Floodplain sedge	Forest-floor	Bamboo	Grass
Ext	P from Atmospheric	5c	5c	20d	20d	0.40%	0.60%	3%	5%
	P from Floodwater	740	-	150	100	63.40%	0%	19%	25%
	Sub-total	745	5	170	120	64%	0.60%	21%	30%
Soil	*(B+OutFlow)-Ext*	422	792	622	278	36%	99%	79%	70%
Total Inflow	*Ext+Soil*	1167	797	792	398	100%	100%	100%	100%
B	P in Vegetation	1149	779	657	263	98%	98%	83%	66%
OutFlow	P River specific load	18	18	136	136	2%	2%	17%	34%

a: data from Walalite et.al, 2016-Songkhram river floodplains

b: data from Wassen &Venterink, 2006 -Biebraza river floodplain

c: data from Venterink et.al, 2002 -European floodplain high productive meadows

d: data from Tipping et. al, 2014 - Average atmospherics deposition of P in Asia

outflow from the Narew floodplain, 471 and 253 kg/km^2/year, respectively. In both river floodplains, the outflow of N was much lower than the inflow.

Clear differences were found in the P budget and balance. In the River Narew, floodwater was the major source of P for the sedge community; thus, it is more important than the input from the soil, and this is in clear contrast to the findings for N. In the Narew forest, P was only derived from the soil, as P from the atmosphere was extremely low and no input from floodwater was registered for the forest. The outflow of P from the Narew floodplain was low compared to the input from soil and floodwater. In the River Songkhram, as in the Narew forest, the soil was the main source of P, but here this was comparable for both vegetation types (79% and 70%). The outflow proportion of P from the Songkhram floodplain accounted for 17% and 34% of the total inflow budget for flooded bamboo and grass, respectively. This proportion was much higher than the N exported from the flooded bamboo and grass (5% and 17%). The exported amount of P was much higher (by a factor of 7.5) than in the Narew floodplain. It appears that the flooded grass vegetation type exported more P (136 kg/km^2/year) than it received from floodwater (100 kg/km^2/year). For the flooded bamboo, the exported amount (136 kg/km^2/year) was slightly lower than the input from floodwater (150 kg/km^2/year).

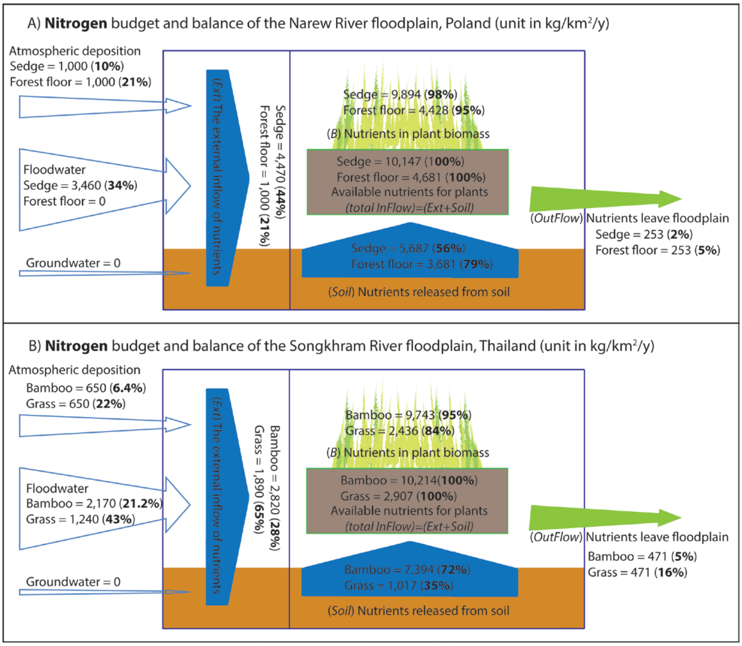

Fig. 5.4. Estimated N budgets and balance of floodplain vegetation in the River Narew (sedge and forest floor; A) and the River Songkhram (bamboo and grass; B). The percentage of the inflows from different sources was compared to the total inflow (*Ext+Soil*), which was 100%. Also, the percentage of the nutrients in vegetation and the outflow were compared to the total inflow.

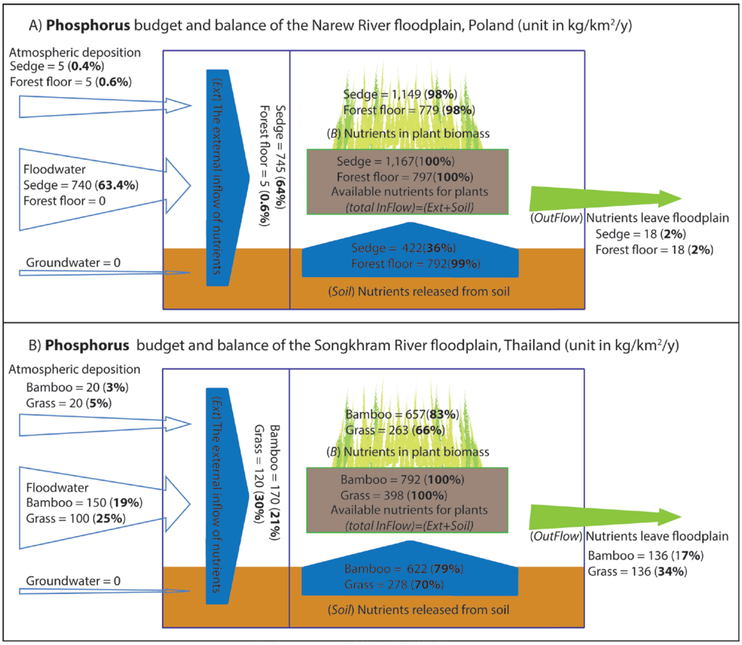

Fig. 5.5. Estimated P budgets and balance of floodplain vegetation in the River Narew (sedge and forest floor; A) and the River Songkhram (bamboo and grass; B). The percentage of the inflows from different sources was compared to the total inflow (*Ext+Soil*), which was 100%. Also, the percentage of the nutrients in vegetation and the outflow were compared to the total inflow.

5.5 Discussion

The aim of our paper was to better understand the relationship between riverine nutrient transport and nutrient accumulation and release in floodplains, for a tropical monsoon river and a temperate snowmelt river. Furthermore, we tried to shed light on the question of whether the comparable vegetation patterns in the two floodplains stem from similar processes, by analyzing the seasonal patterns of discharge, nutrient concentration, and nutrient loads of both rivers in relation to the floodplain.

5.5.1 The rivers

Both rivers show a clear flood pulse, with the discharge of the tropical monsoon River Songkhram showing far more seasonal variation in discharge than the temperate River Narew. Songkhram peak discharges are more than 25 times higher than those of the Narew, reflecting the much higher tropical monsoon rainfall compared to the temperate, mainly snowmelt-driven Narew peak discharges.

The River Narew shows a typical discharge pattern for a lowland river with a snowmelt water regime (Dingman 2015). In winter, snow accumulates with freezing temperatures, resulting in low flows and discharge mainly being fed by groundwater. In late winter and early spring (February and March), discharge increases to reach a maximum in April, reflecting significant snowmelt and rainfall feeding the river. The River Songkhram displays the typical flow characteristic of the monsoon river, with the discharge steeply increasing during and after the intense rainy season, which generally starts in May. During the dry season discharge is extremely low and almost stops completely. This flow pattern is generally observed in monsoon rivers (e.g., Sarma et al., 2009).

Surface runoff is the main mechanism that transports particulate and dissolved material to the river. It may be expected that concentrations of these materials increase during and shortly after the peak discharge, but our observations for EC, TP, and TIN from the two rivers show inconsistent variation patterns. Dissolved inorganic material, represented by EC, decreased during peak discharge in both river systems, reflecting dilution due to a large amount of atmospheric water input (rain, snow). Increasing EC during the summer (Narew) and dry season (Songkhram) also reflects that the rivers are fed by exfiltrating groundwater. TP, which includes particulate and dissolved phosphorus, also shows low concentrations during peak discharge in both rivers. The highest concentration of TP occurs during the lowest discharge of the River Narew, while the TP concentration of the River Songkhram fluctuates in the rising limb of the peak discharge. A similar dynamic pattern of phosphorus concentration was also reported in earlier research in the upper Narew by Banaszuk and Wysocka-Czubaszek (2005), who found that soluble reactive phosphorus (SRP) and TP concentrations generally decrease with increasing discharge. They also found that particulate phosphorus concentrations were higher during peak discharge after high rainfall events in summer, and during the elevated autumn flow. This was also the case in the tropical monsoon river Songkhram, where TP concentrations increased after heavy rainfall at the beginning of the rainy season. This may be explained by the resuspension of the bottom material from the river bed due to turbulence (Van der Grift et al., 2018) as well as runoff of particulate and dissolved phosphorus accumulated in the catchment soil during the dry period. It is likely that the decreasing TP concentration during peak discharges is caused by dilution.

In contrast to TP, the dynamics of TIN concentration in the River Narew showed a pattern that aligned with the discharge dynamic. The concentration of TIN was high during winter (highest in February) before it dropped in April when the discharge reached the maximum level. This suggests that dissolved inorganic nitrogen was transported from the catchment by snow-melted water and rainwater to the river during the rising stage of the flow. At the peak discharge in April, overbank flow occurred, with the floodplain receiving water from the river. Floodplain vegetation and other aquatic organisms consume nitrogen, resulting in decreased TIN concentration until the river discharge reaches its minimum in August. Subsequently, TIN concentration increased again, following higher river discharge, probably due to autumn rains. This suggests that TIN is transported by water (surface runoff and groundwater) from the catchment area to the river. However, this was not the case for TIN in the monsoon River Songkhram. Increasing TIN concentrations were observed in the rising stage of the discharge, and the decrease during peak discharge was similar to the TP concentration dynamic pattern in this river. EC and TP concentrations for both rivers tend to decrease downstream. It should also be noted that nitrogen concentrations are lower in the River Songkhram than in the River Narew, while a downstream increase was found for the River Narew. The average annual TP concentration of the River Narew was around 1.5 times higher than of the River Songkhram, and the average TIN concentration was 2.2 times higher. This might reflect differences in agricultural land use, with high intensity farming in the Narew catchment and less intense agricultural land use in the Songkhram catchment.

More natural land cover typically releases lower nutrients than agricultural land use (e.g., Weller et al., 2003; Ngoye and Machiwa, 2004). However, the land use of the River Narew and the River Songkhram basin was not much different regarding the proportion of agricultural land use. Most land of the Narew River basin is used for agriculture and forest, which account for 55% and 32%, respectively (Gielczewski 2003). In the Songkhram River basin, agricultural land use and forest/ planted trees cover 50% and 33% of the basin area, respectively (Shrestha et al., 2020). The main agricultural land use of the Songkhram River basin is rice paddy, which covers 45% of the basin area. The rice paddy land used in northeast Thailand has the characteristic of retaining rainwater during the monsoon rain season to support rice growth. The retention capability of the rice paddy possibly reduces erosion and keeps nutrients in the catchment. The higher concentration of TP and TIN in the River Narew than in the River Songkhram may result from differences in agricultural practices and soil nutrient status in the catchments. Typically, in the Narew catchment, the prevalent agriculture is arable farming, in which the fields are plowed in autumn and then left bare until spring, thus making them vulnerable to erosion. Soil total nitrogen in the Narew floodplain was reported to be around 6g/kg dry weight (Antheunisse et al., 2006), which is around 3 times higher than the total nitrogen in the Songkhram floodplain (1.7g/kg dry weight) (Walalite et al., 2018). Similarly, extractable P in the Narew floodplain soil was higher than in the Songkhram floodplain soil, ranging from 8-20 mg/kg dry weight for Narew (Walalite et al., n.d., submitted to Wetlands Ecology and Management) and around 8-11 mg/kg dry weight for Songkhram (Walalite et al., 2018).

In contrast to the concentration of TP and TIN, the River Narew has much lower nutrient loads than the River Songkhram, which is explained by the much higher discharges in Songkhram. Total annual nitrogen loads and specific loads are twice as high for Songkhram as for Narew, with increased values downstream for both rivers. This emphasizes the considerable influence of high monsoonal precipitation on the nutrient loads in the River Songkhram.

5.5.2 The floodplains

We roughly estimated nutrient budgets and balances for the vegetation following earlier work by Wassen and Olde Venterink (2006). This approach allowed us to differentiate between various nutrient fluxes and storage in the floodplain systems. However, in the Narew floodplains, we did not have a direct measurement for nutrient concentration in floodwater due to an extreme drought that resulted in no flooding during our field campaign. For this reason, we hypothesized that nutrient input from floodwater would have been in the same range as for its tributary, the Biebrza, which has been investigated intensively (e.g., Wassen 1995; Olde Venterink et al., 2002). Furthermore, we did not measure nutrient release from the soil but estimated this part of the budget from the unknown in Equation (3). For these reasons, the numbers in the budget calculations should be treated with caution as these are only rough estimates and are partly based on assumptions and data obtained from other areas. Still, it seems safe to conclude that the results of our simple nutrient budget and balance model suggest that in both floodplains, the soil is an important nutrient source for the vegetation. However, the extent to which the soil adds to the nutrient budget is different for the vegetation zones.

For the bamboo vegetation adjacent to the river (Songkhram River) and forest floor vegetation (Narew River) far away from the river, the soil is the most important source of both nitrogen and phosphorus. This is not fully the case for the grass vegetation (Songkhram; further away from the river) and sedge (Narew; next to the river) vegetation, where the soil seems most important only for P in the Songkhram grass vegetation and for N in the Narew sedge vegetation. As expected, besides soil, floodwater also plays a key role as a source of N for floodplain vegetation. Nitrogen from floodwater contributed 34% of the N input for the Narew floodplain sedge vegetation, and 21% and 43% for the River Songkhram flooded bamboo and grasses, respectively. Floodwater was the main source of P, contributing 63% to the P budget of the Narew floodplain sedge vegetation, while it was less important for the Songkhram floodplain bamboo and grass (contribution of 19% and 25%, respectively). It is noteworthy that in the Narew floodplain there is a distinct difference in river influence with a dominance of river water in the tall sedge vegetation and no river flooding in the forest, whereas in the Songkhram floodplain, the difference in river dominance is less extreme as river floods occur in both the bamboo and the grass vegetation. The outflow of N and P in both the Narew floodplain sedge and the Songkhram floodplain bamboo vegetation were lower than the inflow by floodwater, suggesting a sink function of these vegetation types for N and P. Interestingly, nutrient concentration in the biomass is higher for the Narew floodplain sedge than for the Songkhram flooded bamboo and grass, which might be related to interspecific differences in growth traits (Roeling et al., 2018). Nitrogen and potassium storage in plant biomass is higher for the Narew sedge and Songkhram bamboo vegetation than for the non-flooded forest and less flooded grass vegetation. The fact that P does not follow this pattern with generally low storage in Songkhram compared to Narew is probably related to differences in the sediment. The repeated glaciations during the Quaternary in northern Eurasia left substantial amounts of P-rich unweathered sediments exposed, providing ecosystems with a steady supply of P compared to aged and weathered soils in the tropics (Reich and Oleksyn 2004; Hopper 2009).

5.5.3 Synthesis

Generally, when vegetation is flooded, higher amounts of nutrients are stored in the vegetation than in non-flooded or rarely flooded vegetation (Tockner and Stanford, 2002; Wassen et al., 2003b; Olde Venterink et al., 2006; Keizer et al., 2018). Vegetation in a flood zone closer to the main river channel clearly receives more nutrients than vegetation in zones further away. Our results emphasize the capacity of nutrient filtering and the nutrient retention function of floodplain vegetation. The above observations imply that the floodplains of both rivers tend to act as a sink for nutrients that are stored in both vegetation biomass and soil. This implies that the floodplains of both rivers absorb nutrients and retain them in the biomass and soil produced. Literature provides evidence for the processes that might be involved. Gordon et al. (2020) reviewed North American and European floodplains and concluded that floodplains in temperate climates remove N and P from river water. Prolonged contact with the parent river can decrease the concentration of NO_3^- and increase dissolved organic forms of N and P during a flood pulse. The floodplain can also increase NH_4^+, particulate N, and P, and dissolved reactive P (Tockner et al., 1999; Tockner et al., 2002; Hein et al., 2003). Increased particulate nutrients are even thought to be the key to the high productivity of vegetation in the floodplain (e.g., Keizer et al., 2018). Apparently, it is likely that in temperate floodplains, dissolved nutrients brought to the floodplain are transformed into particulate form and accumulate in soil and vegetation.

Similarly, in tropical river floodplains, as for example demonstrated by Zuijdgeest et al. (2015) for the pristine floodplain of the Zambezi River, the floodplain may act as a sink for particulate nutrients and a source of dissolved organic carbon during the flood. This was also found in previous studies in the Songkhram floodplain, which acts as a sink for dissolved nutrients and sediment and exports organic carbon during the flood (Walalite et al., 2018, 2016).

The growing season of floodplain vegetation is aligned with the flood pattern for the Narew floodplain. The vegetation starts to grow after the spring flood (Feb-Mar), allowing vegetation to benefit from the nutrient input from floodwater. In contrast, the bamboo and grass in the Songkhram floodplain may not directly benefit from the floodwater since the magnitude of the flood is exceedingly high and prohibits the growth of the floodplain vegetation during the flood (authors' personal observations). However, this prolonged period of water on the floodplain does allow the aquatic vegetation and algae to grow (Walalite et al., 2016). After the flood recedes, these aquatic organisms decay, and the bamboo and grasses benefit from this nutrient source later in the growing season.

Our analysis demonstrates that the seasonal flood pulse is an important mechanism that brings in additional nutrients for floodplain vegetation in both rivers. Although the floodplain vegetation benefits from nutrient input from floodwater, nutrients stored in the soil are seen to be important too. In our view, this works as follows: the floodplain vegetation consumes the nutrients brought in by the flood, then produces biomass and build up the soil organic matter leading to the retainment of nutrients in the floodplain. The floodplains of both rivers function as a sink for N and P, although this capability differed in extent, depending on the type of nutrient and the vegetation zone. We recommend further research into the processes and forms of nutrients in both river floodplains; such research should focus on disentangling the most important hydrogeochemical processes, e.g., nutrient cycling in both the floodplain soil and the vegetation, and how this nutrient cycling is related to the river dynamics.

5.6 Acknowledgements

We thank the Institute of Meteorology and Water Management (IMGW-PIB) for providing the hydrological data of the River Narew and the Chief Inspectorate of Poland's Environmental Protection for the Narew River's water quality data. We also thank the Royal irrigation department of Thailand for providing the hydrological data of the River Songkhram, Thailand, and the Thai Department of Pollution Control for providing water quality data on the River Songkhram. This research was partly supported by a grant from the Thai Government Science and Technology Scholarship Students program granted to Tanapipat Walalite.

5.7 Appendices

Appendix 5.1. Summary of the number of measurements for each station from the Narew River, Poland, and the Songkhram River, Thailand.

		Narew River, Poland				Sonkghram River, Thailand				
		Bondary (BND)	Suraz (SRZ)	Strekowa Gora (St.Gora)	Nowogrod - UpTo Pisa (NWP)	Ban Hui Songkhram (BHSK)	Ban Tha Kok Dang (BTKD)	Ban Tha Gon (BTG)	Ban Pak Un (BPU)	Ban Chai Buri (BCBR)
Period of measurement	Flow data	1991-2018	2005-2018	1991-2018	1991-2018	-	1986-2010	-	2013 - 2016	-
	Concentration data	1992-2016	2001-2016	1991-2017	1991-2017	1996-2015	1996-2015	1996-2015	1996-2015	1996-2015
	Average annual Q (m^3/s)	4	14	31	75	-	145	-	373	-
	Discharge area (km2)	1050	3420	7167	20106	-	5089	-	12328	-
Number of observations	Temp. (C)	356	73	328	328	57	58	56	56	56
	EC	322	73	287	268	57	57	56	56	56
	pH	304	55	331	308	57	58	56	56	56
	DO	322	73	308	308	57	58	56	56	56
	TP	322	72	302	307	53	54	52	52	52
	NO_3-N	345	73	331	311	54	56	53	54	54
	NO_2-N	276	72	257	267	54	55	53	53	53
	NH_4-N/NH_3-N	323	73	332	311	52	53	51	51	51

Appendix 5.2. Monthly average TP concentration (mg/l)

Month	River Narew			River Sonkghram	
	Suraz (SRZ))	Strekowa Gora (St.Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
Jan	0.16	0.19	0.12	0.03	0.05
Feb	0.14	0.17	0.12	0.13	0.16
Mar	0.18	0.14	0.11	0.02	0.05
Apr	0.13	0.18	0.13	0.46	-
May	0.17	0.2	0.13	0.1	0.07
Jun	0.21	0.34	0.26	0.61	0.42
Jul	0.28	0.36	0.25	0.11	0.14
Aug	0.29	0.37	0.23	0.06	0.06
Sep	0.23	0.29	0.26	0.02	0.01
Oct	0.18	0.22	0.18	-	-
Nov	0.21	0.24	0.22	0.18	0.09
Dec	0.22	0.17	0.13	0.09	0.14
average	0.2	0.24	0.18	-	-

Appendix 5.3. Monthly average TIN concentration (mg/l)

Month	River Narew			River Sonkghram	
	Suraz (SRZ))	Strekowa Gora (St.Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
Jan	1.94	2.46	1.83	0.41	0.46
Feb	2.39	2.52	1.96	0.62	0.97
Mar	2.11	2.41	1.5	0.14	0.31
Apr	1.17	1.74	1.15	-	-
May	0.61	1.34	0.85	0.46	0.58
Jun	0.57	1.26	0.77	0.7	0.88
Jul	0.32	1.14	0.72	0.1	0.18
Aug	0.51	1.1	0.73	0.28	0.3
Sep	0.67	1.2	0.96	0.08	0.05
Oct	0.84	1.45	0.97	-	-
Nov	1.57	1.84	1.29	1.18	1.04
Dec	1.27	2.08	1.52	0.66	0.76
average	1.16	1.71	1.19	-	-

Chapter 6

Synthesis and perspective

Tanapipat Walalite

6.1 Introduction

This thesis aimed to understand the ecological functioning of a tropical river floodplain in a tropical monsoon climate and compare this with a temperate river floodplain to find similarities and differences in the ecological functioning of river floodplains. Understanding ecological functioning is necessary for effective conservation and management strategies of floodplains to sustain the biogeochemical processes in the whole river system. I am especially interested in the role of vegetation in different zones in those floodplains that steer the nutrient flow, storage, and recycling. In order to achieve the aim, the floodplains of two rivers were studied, the Narew River in Poland, located in a temperate climate, and the Songkhram River in Thailand, located in a tropical monsoon climate.

Firstly, in section 6.2, the main findings of this thesis are summarized and discussed in light of the objectives and research questions. Next, in section 6.3, the ecological concepts introduced in chapter 1 are discussed for their relevance in explaining this thesis's findings. Furthermore, section 6.4 discusses the management perspective for river floodplains. Lastly, perspectives for future research are provided in section 6.5.

6.2 Summary of the findings

River floodplains located across the globe are experiencing different climates in which temperature and precipitation patterns influence river dynamics and ecological processes. Understanding the ecological functioning of river floodplains is crucial for efficient management strategies to protect or restore their complex ecosystems. Since individual floodplains may function differently, in this thesis, I addressed the central question: How do river floodplains situated in temperate and tropical climates differ in ecohydrological functioning? To answer this question, I studied the floodplains of two rivers in detail; one is the Narew River in Poland, located in a temperate climate. The other is the Songkhram River in Thailand, located in a tropical monsoon climate.

Chapter 2, a pioneer study of the hydrochemical functioning of the monsoon Songkhram River floodplain, reveals that water in the Songkhram river is poor in dissolved solids and nutrients during the flood. Water chemical concentrations decrease from upstream to downstream and from the river to the floodplain edge. The longitudinal trend is related to the weathering products of the catchment geology, which leads to sources of dissolved solids, especially in the upstream trajectory. During the monsoon season, a large amount of rainwater causes a dilution effect that results in decreased concentrations downstream. Meanwhile, the decreased concentrations of dissolved solids and nutrients from the river to the floodplain edge appear to be related to the vegetation pattern in the floodplain. Dense and highly productive bamboo vegetation occurring adjacent to the river channels acts as a filter that absorbs sediment and dissolved material from the river water before this is further distributed over the floodplain. These findings suggest that the river is a source of nutrients for the floodplain. In turn, the floodplain is a sink for nutrients. This study is the first that collected scientific data, which revealed the Songkhram river floodplain acts as a sink for dissolved nutrients during the flood.

In chapter 3, the Songkhram River floodplain's ecological functioning was investigated by integrating soil, water, and vegetation data. The floodplain vegetation consists of a distinct zone of highly productive bamboo vegetation adjacent to the river channel and grass-type vegetation behind the bamboo. Significant differences are observed between the bamboo and the grass zone in terms of nutrient concentration in soil, floodwater, and plant tissues. The total nitrogen, potassium, and organic matter concentration are higher in the bamboo soil than in the grass soil. The dense and highly productive bamboo demonstrated its ability to filter sediment and dissolved nutrients brought in by floodwater. The bamboo distributed closer to the river, where flooding is more prolonged and deeper, receives a higher nutrient input and shows higher productivity. In contrast, the grass zone distributed further away from the river, where flooding is shorter and shallower, receives a lower nutrient input and shows lower productivity. Both floodplain vegetation types show more nutrients (N and P) stored in their biomass than the nutrients that were potentially imported yearly by floodwater. The N and P stored in bamboo in above-ground biomass were resp. ca 9.76 g/m^2 and 0.66 g/m^2, which is 4.5 and 4.4 times higher than the nutrients imported yearly by floodwater. For the grass, N and P stored in the above-ground biomass were 2.12 g/m^2 and 0.26 g/m^2, which is 1.7 and 2.6 times higher than nutrients imported yearly by floodwater. This finding suggests that vegetation production is not primarily determined by dissolved nutrients brought in by floodwater but, to a larger extent, driven by particulate nutrients brought in by organic sediments in floodwater, which after sedimentation and subsequent mineralization, are a nutrient source for vegetation. Another important finding was that while the floodplain received nutrients from the river, it exported organic carbon to the river during the flood. The floodplain apparently retains (particulate) nutrients during the flood and stores the nutrients in the vegetation biomass. Additionally, during the flood, the receding floodwater exports the remaining organic carbon that is accumulated in the soil during the dry period and serves as a source of organic carbon for the downstream river course. The research in this chapter provides a further understanding of the ecological functioning of the tropical monsoonal Songkhram River floodplain.

Chapters 2 and 3 demonstrate the floodplain ecological functioning of the Songkhram River as an example of a tropical monsoon river. The floodplain acts as a sink for sediment and dissolved material and, in turn, produces organic carbon, which is exported to the river during the flood. Floodplain vegetation plays an important role in trapping and storing nutrients on the floodplain. The nutrient input from the river is high in the zone adjacent to the river, which leads to highly productive vegetation. This productive vegetation leads to dense vegetation structure, which slows down flow velocity and promotes the trapping of sediment.

In chapter 4, I presented an integration of data on hydrology, soil nutrients, water chemistry, and vegetation communities of the relatively undisturbed floodplain of the Narew River, Poland, as an example of the ecological functioning of a river in a temperate climate region. Three floodplain sites were investigated, situated upstream, mid-lower course, and downstream in the catchment. The research revealed that vegetation communities of the river floodplain are distributed over longitudinal and transversal gradients of the floodplain and related to flood characteristics, site physical characteristics, and available soil nutrients. Three types of vegetation communities were recognized longitudinal and transversal distributed 1) a distinct forest understory community with shrubs, herbs, and grasses, 2) a relatively species-rich tussock sedge community dominated by *Carex elata*, and 3) a tall sedge community dominated by *Carex acuta* and/or *Glyceria maxima*. The forest floor community was found at a location that was not influenced by river floodwater and was the most far away from the river. The tussock sedge was found distributed in the upstream floodplain sites, which were close to the river. This sedge was also found farther away from the main river channel in the mid-lower floodplain site. In contrast, the tall sedge community was found closer to the river in the mid-lower and lower floodplains, where the flood was deeper. The pattern of changing vegetation from upstream to downstream and near the river to farther away demonstrates longitudinal and transversal gradients of vegetation communities on the floodplain. Furthermore, this study found that the growth of all these floodplain vegetation was limited by nitrogen.

The study also demonstrated a spatial variation of water chemistry at different places within the floodplain. The water from the river had significantly higher concentrations of NO_3^-, Cl^-, and K^+ than water from puddles, an oxbow lake, and groundwater. The surface water found on the floodplain had significantly higher organic carbon than the river water.

The occurrence of water quality variation, vegetation gradients, and the nitrogen limitation environment in the floodplain suggests a relatively undisturbed floodplain compared to many other European rivers where polluted river water dominates floodplain water chemistry and overrules natural vegetation gradients. These characteristics underline the value of the Narew floodplain as a relatively pristine floodplain that may serve as a reference system for studying ecohydrological relationships.

This study contributes to our understanding of how relatively undisturbed temperate river floodplains ecologically function and can be used as a reference for future management of such river floodplains. Additionally, the understanding of the ecological functioning of this river floodplain allows a comparison with the tropical monsoon river floodplain described in chapters 2 and 3 in order to understand similarities and differences in the ecological functioning of river floodplains situated in different climate zones.

In chapter 5, I compared the hydrology, water chemistry, and nutrient (N and P) status of vegetation in the floodplains of the Narew River and the Songkhram River. This research provides an understanding of similarities and differences in the ecological functioning of these two river floodplains, situated in different climate zones (temperate and tropical monsoon). The results show that both rivers show flood pulse characteristics which is an important mechanism that brings in additional nutrients for floodplain vegetation. The discharge of the Narew River was relatively constant over the year, in comparison to the monsoonal Songkhram River showing highly variable discharges, with higher peaks during the flood period and very low discharges in the dry season. Although the nutrient (N, P) annual average concentrations of the Narew River water were higher than those of the Songkhram River, the nutrient loads of the Songkhram River were higher than the Narew River due to the higher peak discharge of the Songkhram River. The analysis of the nutrient budgets for the floodplain vegetation showed that both river floodplains during the flood period and on a yearly basis exported fewer nutrients (N and P) than the nutrients input by floodwater. The floodwater imported nutrients that accumulate in the floodplain soil and in above-ground floodplain vegetation biomass. These results indicate that both river floodplains act as a sink for nutrients and emphasize that the flood pulse is an important mechanism for transporting nutrients to floodplains for vegetation in these temperate and tropical rivers. Although both river floodplains were similar in flood pulse characteristics and acted as a sink for nutrients, nutrient input from floodwater and soil to the nutrient budget for vegetation differed between nutrient species and vegetation types. Nitrogen input from soil was the main source for the Narew floodplain sedge (56%) and forest floor community (79%). On the Songkhram floodplain, the soil was the major N source for the flooded bamboo (72%), while for flooded grass, this was only 35%. The differences in the phosphorus budget were even more clear. In the Narew floodplain, floodwater was the major source of P for the sedge community and more important than the input from the soil, in contrast to N. In the Songkhram floodplain, in contrast, the main source of P was from the soil for both vegetation types (79% and 70 %). This research demonstrated similarities in flood pulse characteristics but differences in nutrient budget, and therefore in the ecological functioning of the river floodplains in temperate and tropical climates. Vegetation in both floodplains benefits from nutrients (N, P) brought in by the floodwater pulse and acts as a sink for the nutrients (N, P). At the same time, the capability to absorb nutrients by the vegetation varied among the floodplains and vegetation types. The finding contributes to our understanding of how rivers and river floodplains, which are relatively undisturbed in the temperate and tropical monsoon, may be similar and different in terms of ecological function.

6.3 Relevance of ecological river concepts

In chapter 1 (introduction), I introduced 3 major ecological concepts for rivers and floodplains: 1) the river continuum concept (RCC) (Vannote et al., 1980), 2) the flood pulse concept (FPC) (Junk et al., 1989; Junk and Wantzen, 2004), and the riverine ecosystem synthesis model (RES) (Thorp et al., 2006). In this section, I will discuss whether these concepts can be applied to the finding of this thesis.

The RCC is a classic ecological concept for river ecological functioning, which focuses on the longitudinal gradient of the physical and biological in the river channel. In chapter 2, the Songkhram River exhibited the decreasing longitudinal trend of hydro-chemical concentrations in the river during the flood. This phenomenon corresponds to the physical gradient from upstream to downstream, as described in the RCC. The limited information gathered from the river indicates that this concept may be applied to explain the ecological functioning of the tropical monsoon river system. The observed decreasing trend of EC from upstream to downstream can be used as an indicator for the longitudinal gradient of the river environmental parameters, and this gradient is responded to by a shift in the biotic community along the river, as suggested by Jiang et al. (2011). In chapter 4, the river exhibits a longitudinal gradient of hydro-chemical concentrations from upstream to downstream of the temperate Narew River. The concentration of river water increased downstream, especially EC. Although opposed to the Songkhram river, this trend also corresponds to the physical gradient from upstream to downstream described in the RCC. Moreover, vegetation communities in the Narew River floodplain also demonstrated longitudinal differences in the upstream and downstream floodplain.

Besides longitudinal processes affecting water chemistry, the Narew River and the Songkhram River systems were also subject to transversal processes involving floodplain inundation water chemistry and its vegetation patterns. In this aspect, the RCC only explains the longitudinal pattern of the rivers and floodplain systems. The Flood Pulse Concept (Junk et al., 1989) explains the ecological functioning of large river-floodplain systems and includes lateral exchanges of water, sediment, and nutrients between the river and the floodplain. Both rivers in this thesis function as a transportation route and source for dissolved material, including nutrients for the floodplains, as postulated by the Flood Pulse Concept. Floodwater pulse is an important mechanism for transporting material to both rivers' floodplains. However, the vegetation in the temperate Narew River floodplains relies more on dissolved nutrients imported by floodwater, while vegetation in the Songkhram River floodplain seems to rely more on the recycling process of organic material that accumulated in the floodplain.

With respect to the riverine ecosystem synthesis model (RES) the floodplains exhibit a mosaic pattern of vegetation zonation. In the Songkhram River floodplain, clear zonation of bamboo and grass was identified in Chapters 2 and 3, while in the Narew River floodplain, different floodplain sedge communities were described in chapter 4. Although these vegetation patterns are influenced by the longitudinal and transversal gradients in hydrological and hydrochemistry, the observed vegetation zones in the floodplain are in line with the 'functional process zone' described in the riverine ecosystem synthesis model (RES).

6.4 Management perspective

Lowland rivers such as the Narew River and the Songkhram River are characterized by spatial and temporal connectivity between the main channel and the floodplain, although situated in different climates. The flow regime of the rivers exhibits a seasonal flood pulse, which is demonstrated to be an essential mechanism to transport nutrients and sediment to the floodplains and determine the ecological functioning of the systems. Thus, any interference that may alter the flow regime of the river may cause a change in the ecological functioning of the floodplains. Any conservation and management plan that aims to conserve or improve the ecological functioning of river floodplains should consider the relationship between the hydrological characteristics and spatial characteristics of the vegetation in the floodplains and the biogeochemical process therein.

River-floodplain conservation plans should consider the key factors that maintain the spatial pattern of the floodplain vegetation. The flood and flow regime of the floodplain is important for the zonation of floodplain vegetation. It has been demonstrated in chapter 3 for the monsoon River Songkhram and chapter 4 for the temperate River Narew that spatial patterns of vegetation in the floodplains developed in response to flood characteristics (duration, depth, and frequency). In the Songkhram River, the transversal zonation of floodplain vegetation is clear. The flooded bamboo is found adjacent to the river channel and experiences longer flood duration, higher depth, and higher frequency than the grass found further away. In the Narew River, the longitudinal and transversal patterns of vegetation were observed. Tussock sedge was found in the upstream part close to the river channel while in the mid-lower floodplain far from the river channel. In the mid-lower floodplain, the tussock sedge undergoes a shallower flood than the tall sedge that was found in the mid-lower floodplain. The floodplain vegetation takes up nutrients from the soil that originates from floodwater, resulting in the removal of dissolved nutrients (N and P) from the floodwater. Additionally, the physical structure of floodplain vegetation reduces flow velocity and promotes sedimentation, which leads to trapping particulate nutrients in the vegetation zone. Also, the vegetation takes up the nutrients in those sediments and stores them in their biomass. The mechanisms of uptake of soil's nutrients that originate from floodwater or nutrients from sediments that are transported by the floodwater lead to the capability of the floodplain to act as a sink for nutrients.

As demonstrated in chapter 5, the vegetation in both studied river floodplains shows their potential to act as a sink for nutrients (N, P). However, the capability to uptake and store nutrients by the vegetation varied among the floodplains and vegetation types. Managing floodplains should thus consider how the vegetation type interacts with the hydrological processes and their ecological function (sink or source for nutrients). Those interactions differ across the floodplains of each river.

The priority of restoration plans for deteriorated rivers and floodplains is to reconnect the floodplain to its parent river to manage nutrient transport, storage, and recycling in an integral way. Spatial variation of flood characteristics in floodplains should be designed to create spatial patterns or zonation of vegetation types which could function differently in removing particular nutrients from floodwater. This is because the capability to uptake and store nutrients of floodplain vegetation varies among types and forms of nutrients, types of vegetation, and hydrological regimes. Restoring hydrological characteristics that lead to certain spatial patterns in vegetation within the floodplain will enhance the capability to act as a sink for nutrients of the floodplain on a large scale.

Data collection and monitoring are important for making appropriate management plans. Good quality and quantity of available data are essential for understanding the functioning of rivers and floodplains and using this to design effective management strategies for nutrient transport, storage, and recycling. River floodplains should be considered as part of the river in a management plan. In general, river management plans mainly focus on monitoring water quality and quantity in the main river channel. Although being recognized for their ecological functions and services, river floodplains show scarce available data regarding their status and functions. Since the ecological processes on the floodplain are an interaction between soil, floodwater, and vegetation, the status of these floodplain ecosystem components should be monitored. Floodplain soil should be monitored for its nutrient status before and after flooding. Floodwater should be monitored for its characteristics in water quality, flow regime, depth, duration, and frequency. Vegetations in the floodplain should be monitored for their change in community pattern, nutrient status, and production. Lastly, changes in vegetation cover and land use in the floodplain, which may lead to a change in the ecological functions of the floodplain, should be assessed and evaluated (e.g., using remote sensing).

The lack of good quality and quantity of available data, especially in tropical regions, are significant obstacles to managing rivers and floodplains. In the Songkhram River, water quality data is available from five stations distributed from upstream to downstream, which seem to be adequate from a spatial perspective. However, the sampling frequency of the water quality appears to be only four times per year, which hampers the understanding of the temporal patterns in water quality. Monthly sampling in the river will allow relating the water quality data to other variables, which have annual dynamic patterns and have already been monitored, such as precipitation, discharge, and land used/land cover of the catchment. This will lead to a better understanding of the factors that influence the water quality from temporal and spatial perspectives that will enhance the management plans. Therefore, it is recommended that the responsible government agency increase the sampling frequency to at least every month. This recommendation also applies to other rivers in Thailand.

6.5 Perspectives for future research

This thesis contributes to fundamental knowledge of the functioning of a tropical monsoon and a temperate river floodplain. It extends our understanding of the ecological functioning of both rivers by demonstrating that the river continuum concept, the flood pulse concept, and the riverine ecosystem serve as a basis for explanation. However, the body of knowledge about the river and its floodplains, particularly those situated in tropical climate, is still incomplete. Since the ecological functioning of rivers and floodplains is determined by climate, hydrology, and geomorphology, these factors together drive biogeochemical processes and the response of ecosystems, which may vary considerably among individual rivers and floodplains. To obtain a comprehensive understanding of especially the scarce studied tropical river floodplains, research into the response of the biotic community with regard to those underlying factors in different rivers would be necessary.

Since the RCC and the FPC were published in 1980 and 1989, respectively, more ecological concepts have been developed concerning the spatial and temporal complexity of the riverine ecosystem. Ecological concepts, e.g., the riverine Productivity Model (RPM) (Thorp and Delong 1994), the riverine ecosystem synthesis model (RES) (Thorp et al., 2006), and the river wave concept (RWC) (Humphries et al., 2014), do consider spatial and temporal dynamics of the river landscape and view the river and floodplain as patches of mosaic in a landscape. This research has contributed further to these concepts, especially through the interaction between hydrology and the biogeochemical process in different vegetation zones. The role of the hydrology and biogeochemical interactions in different vegetation zones provides a framework to extend our understanding of the ecological functioning and process of river and river-floodplains and to understand how biotic communities respond to spatial and temporal dynamics of the river and river floodplains landscape. However, empirical studies in various floodplains across climate zones are needed.

It has been demonstrated in this thesis how river floodplains situated in different climates can exhibit similar ecological functions with different mechanisms therein. Future studies of floodplains across different climate regions will need to show to what extent they are similar and/or different in terms of ecological functioning.

References

Admiraal, W., van der Velde, G., Smit, H., Cazemier, W.G., 1993. The rivers Rhine and Meuse in The Netherlands: present state and signs of ecological recovery. Hydrobiologia 265, 97–128. https://doi.org/10.1007/BF00007264

Antheunisse, A.M., Loeb, R., Lamers, L.P.M., Verhoeven, J.T.A., 2006. Regional differences in nutrient limitation in floodplains of selected European rivers: implications for rehabilitation of characteristic floodplain vegetation. River Res. Appl. 22, 1039–1055. https://doi.org/10.1002/rra.956

Antheunisse, A.M., Verhoeven, J.T.A., 2008. Short-term responses of soil nutrient dynamics and herbaceous riverine plant communities to summer inundation. Wetlands 28, 232–244. https://doi.org/10.1672/06-33.1

Arias, M.E., Cochrane, T.A., Norton, D., Killeen, T.J., Khon, P., 2013. The Flood Pulse as the Underlying Driver of Vegetation in the Largest Wetland and Fishery of the Mekong Basin. Ambio 42, 864–876. https://doi.org/10.1007/s13280-013-0424-4

Arias, M.E., Wittmann, F., Parolin, P., Murray-Hudson, M., Cochrane, T.A., 2016. Interactions between flooding and upland disturbance drives species diversity in large river floodplains. Hydrobiologia 1–13. https://doi.org/10.1007/s10750-016-2664-3

Arnebrant, K., Ek, H., Finlay, R.D., Söderström, B., 1993. Nitrogen translocation between Alnus glutinosa (L.) Gaertn. seedlings inoculated with Frankia sp. and Pinus contorta Doug, ex Loud seedlings connected by a common ectomycorrhizal mycelium. New Phytol. 124, 231–242. https://doi.org/10.1111/j.1469-8137.1993.tb03812.x

Arthington, A.H., Naiman, R.J., McClain, M.E., Nilsson, C., 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Freshw. Biol. 55, 1–16. https://doi.org/10.1111/j.1365-2427.2009.02340.x

Baldwin, D.S.S., Mitchell, A.M.M., 2000. The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river–floodplain systems: a synthesis. Regul. Rivers Res. Manag. 16, 457–467. https://doi.org/10.1002/1099-1646(200009/10)16:5<457::AID-RRR597>3.3.CO;2-2

Banaszuk, P., Wysocka-Czubaszek, A., 2005. Phosphorus dynamics and fluxes in a lowland river: The Narew Anastomosing River System, NE Poland. Ecol. Eng. 25, 429–441. https://doi.org/10.1016/J.ECOLENG.2005.06.013

Banerjee, S., Secchi, S., Fargione, J., Polasky, S., Kraft, S., 2013. How to sell ecosystem services: a guide for designing new markets. Front. Ecol. Environ. 11, 297–304. https://doi.org/10.1890/120044

Barendregt, A., Gietczewski, M., 1998. Linkage of environmental variation with vegetation in the catchment area of Narew river. Zesz. Probl. Postępów Nauk Rol. 458.

Basu, B.K., Pick, F.R., 1996. Factors regulating phytoplankton and zooplankton biomass in temperate rivers. Limnol. Oceanogr. 41, 1572–1577.

Batzer, D.P., Noe, G.B., Lee, L., Galatowitsch, M., 2018. A Floodplain Continuum for Atlantic Coast Rivers of the Southeastern US: Predictable Changes in Floodplain Biota along a River's Length. Wetlands 38, 1–13. https://doi.org/10.1007/s13157-017-0983-4

Bayley, P.B., 1995. Understanding Large River Floodplain Ecosystems. Bioscience 45, 153–158. https://doi.org/10.2307/1312554

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data 5, 180214. https://doi.org/10.1038/sdata.2018.214

Beltman, B., Willems, J.H., Güsewell, S., 2007. Flood events overrule fertiliser effects on biomass production and species richness in riverine grasslands. J. Veg. Sci. 18, 625–634. https://doi.org/10.1111/j.1654-1103.2007.tb02576.x

Bergerot, B., Lasne, E., Vigneron, T., Laffaille, P., 2008. Prioritization of fish assemblages with a view to conservation and restoration on a large scale European basin, the Loire (France). Biodivers. Conserv. 17, 2247–2262. https://doi.org/10.1007/s10531-008-9331-6

Beumer, V., Van Wirdum, G., Beltman, B., Griffioen, J., Grootjans, A.P., Verhoeven, J.T.A., 2008. Geochemistry and flooding as determining factors of plant species composition in Dutch winter-flooded riverine grasslands. Sci. Total Environ. 402, 70–81. https://doi.org/10.1016/j.scitotenv.2008.03.044

Bhat, N.A., Wanganeo, A., Raina, R., 2015. Seasonal dynamics of phytoplankton community in a tropical wetland. Environ. Monit. Assess. 187, 4136. https://doi.org/10.1007/s10661-014-4136-4

Billen, G., Silvestre, M., Grizzetti, B., Leip, A., Garnier, J., Voss, M., Howarth, R., Bouraoui, F., Lepisto, A., Kortelainen, P., Johnes, P., Curtis, C., Humborg, C., Smedburg, E., Kaste, O., Ganeshram, R., Beusen, A., Lancelot, C., 2011. Nitrogen flows from European watersheds to coastal marine waters, in: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment : Sources, Effects, and Policy Perspectives. Cambridge University Press, Cambridge, pp. 271–297.

Blake, D.J.H., Sunthornratana, U., Promphakping, B., Sarkkula, J., Kummu, M., Ta-oun, M., Waleetorncheepsawat, P., Boonyothayan, S., Tharme, R., Osbeck, M., Janprasart, S., Buaphuan, S., Sarkkula, J., Kummu, M., Ta--Oun, M., Waleetorncheepsawat, P., Boonyothayan, S., Tharme, R., Osbeck, M., Janprasart, S., 2011. E-Flow in the Nam Songkhram River Basin.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H., Valett, H.M., 1998. The Functional Significance of the Hyporheic Zone in Streams and Rivers. Annu. Rev. Ecol. Syst. 29, 59–81.

Brierley, G.J., Fryirs, K.A., 2008. River futures : an integrative scientific approach to river repair, NV-1 onl. ed, The science and practice of ecological restoration. Island Press ;, Washington, DC.

Bufkova, I., Prach, K., 2006. Linking vegetation pattern to hydrology and hydrochemistry in a montane river floodplain, the Å umava National Park, Central Europe. Wetl. Ecol. Manag. 14, 317–327. https://doi.org/10.1007/s11273-005-3817-8

Capon, S.J., 2003. Plant community responses to wetting and drying in a large arid floodplain. River Res. Appl. 19, 509–520. https://doi.org/10.1002/rra.730

Caraco, N.F., Cole, J.J., 1999. Human impact on nitrate export: An analysis using major world rivers. Ambio 28, 167–170.

Chormanski, J., Okruszko, T., Ignar, S., Batelaan, O., Rebel, K.T., Wassen, M.J., 2011. Flood mapping with remote sensing and hydrochemistry: A new method to distinguish the origin of flood water during floods. Ecol. Eng. 37, 1334–1349. https://doi.org/10.1016/j.ecoleng.2011.03.016

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V, Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1998. The value of the world's ecosystem services and natural capital (Reprinted from Nature, vol 387, pg 253, 1997). Ecol. Econ. 25, 3–15. https://doi.org/10.1016/S0921-8009(98)00020-2

Cushing, C.E., Mcintire, C.D., Cummins, K.W., Minshall, G.W., Petersen, R.C., Sedell, J.R., Vannote, R.L., 1983. Relationships among Chemical, Physical, and Biological Indexes Along River Continua Based on Multivariate Analyses. Arch. Fur Hydrobiol. 98, 317–326.

Department of, mineral resources, 2012. Geological map of Thailand, scale 1:2,500,000.

Dingman, S.L., 2015. Physical hydrology, Third. ed, TA - TT -. Waveland Press, Long Grove, Illinois.

Doering, M., Uehlinger, U., Tockner, K., 2013. Vertical hydrological exchange, and ecosystem properties and processes at two spatial scales along a floodplain river (Tagliamento, Italy). Freshw. Sci. 32, 12–25. https://doi.org/10.1899/12-013.1

Ellery, W.N., Ellery, K., Mccarthy, T.S., 1993. Plant-Distribution in Islands of the Okavango Delta, Botswana - Determinants and Feedback Interactions. Afr. J. Ecol. 31, 118–134. https://doi.org/10.1111/j.1365-2028.1993.tb00526.x

Exelis, V.I.S., 2014. ENVI 5.0.

Finlayson, C.M., 2005. Plant ecology of Australia's tropical floodplain wetlands: A review. Ann. Bot. 96, 541–555. https://doi.org/10.1093/aob/mci209

Finlayson, C.M., Cowie, I.D., Bailey, B.J., 1990. Characteristics of a Seasonally Flooded Freshwater System in Monsoonal Australia, in: Whigham, D.F., Good, R.E., Kvet, J. (Eds.), Wetland Ecology and Management: Case Studies. Springer Netherlands, Dordrecht, pp. 141–162. https://doi.org/10.1007/978-94-009-2115-3_18

Franklin, S.B., Gibson, D.J., Robertson, P.A., Pohlmann, J.T., Fralish, J.S., 1995. Parallel Analysis - a Method for Determining Significant Principal Components. J. Veg. Sci. 6, 99–106. https://doi.org/10.2307/3236261

Gielczewski, M., 2003. The Narew River Basin: A model for the sustainable management of agriculture, nature and water supply. Universiteit Utrecht.

Gielczewski, M., Stelmaszczyk, M., Piniewski, M., Okruszko, T., 2011. How can we involve stakeholders in the development of water scenarios? Narew River Basin case study. https://doi.org/10.2166/wcc.2011.027

Gordon, B.A., Dorothy, O., Lenhart, C.F., 2020. Nutrient retention in ecologically functional floodplains: A review. Water (Switzerland). https://doi.org/10.3390/w12102762

Górniak, A., 2018. Ecohydrological determinants of seasonality and export of total organic carbon in Narew River with high peatland contribution (north-eastern Poland). Ecohydrol. Hydrobiol. https://doi.org/10.1016/J.ECOHYD.2018.03.003

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

Grygoruk, M., Miroslaw-Swiatek, D., Chrzanowska, W., Ignar, S., 2013. How Much for Water? Economic Assessment and Mapping of Floodplain Water Storage as a Catchment-Scale Ecosystem Service of Wetlands. Water 5, 1760–1779. https://doi.org/10.3390/w5041760

Hanna instruments, 2016. HI-3811-100 Replacement reagent for Alkalinity [WWW Document]. URL http://ponpe.com/download/HANNA/brochure/hi3811.pdf (accessed 8.1.15).

Hein, T., Baranyi, C., Herndl, G.J., Wanek, W., Schiemer, F., 2003. Allochthonous and autochthonous particulate organic matter in floodplains of the River Danube: the importance of hydrological connectivity. Freshw. Biol. 48, 220–232. https://doi.org/10.1046/J.1365-2427.2003.00981.X

Hopper, S.D., 2009. OCBIL theory: towards an integrated understanding of the evolution, ecology and conservation of biodiversity on old, climatically buffered, infertile landscapes. Plant Soil 2009 3221 322, 49–86. https://doi.org/10.1007/S11104-009-0068-0

Humphries, P., Keckeis, H., Finlayson, B., 2014. The River Wave Concept: Integrating River Ecosystem Models. Bioscience 64, 870–882. https://doi.org/10.1093/biosci/biu130

ICPDR, 2009. Danube River Basin Management Plan (2009) | ICPDR - International Commission for the Protection of the Danube River [WWW Document]. URL http://www.icpdr.org/main/activities-projects/danube-river-basin-management-plan-2009 (accessed 9.22.20).

IMGW-PIB, ARCADIS, 2020. Maps II planning cycle (2016-2021) [WWW Document]. URL https://powodz.gov.pl/pl/mapy (accessed 5.1.21).

Jiang, X., Xiong, J., Xie, Z., Chen, Y., 2011. Longitudinal patterns of macroinvertebrate functional feeding groups in a Chinese river system: A test for river continuum concept (RCC). Quat. Int. 244, 289–295. https://doi.org/10.1016/j.quaint.2010.08.015

Johnson, B.L., Richardson, W.B., Naimo, T.J., 1995. Past, Present, and Future Concepts in Large River Ecology. Bioscience 45, 134–141. https://doi.org/10.2307/1312552

Junk, W., Bayley, P., Sparks, R., 1989. The flood pulse concept in river-floodplain systems, in: Dodge, D.P. (Ed.), Proceedings of the International Large River Sysmposium (LARS), Proceedings of the International Large River Sysmposium (LARS). Canadian Special Publication of Fisheries and Aquatic Sciences 106. Canadian Special Publication of Fisheries and Aquatic Sciences 106, Ottawa, pp. 110–127.

Junk, W.J., 1997. Structure and Function of the Large Central Amazonian River Floodplains: Synthesis and Discussion BT - The Central Amazon Floodplain: Ecology of a Pulsing System, in: Junk, W.J. (Ed.), The Central Amazon Floodplain. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 455–472. https://doi.org/10.1007/978-3-662-03416-3_23

Junk, W.J., Piedade, M.T.F., 1993. Biomass and primary-production of herbaceous plant communities in the Amazon floodplain. Hydrobiologia 263, 155–162. https://doi.org/10.1007/BF00006266

Junk, W.J., Piedade, M.T.F., Schöngart, J., Wittmann, F., 2012. A classification of major natural habitats of Amazonian white-water river floodplains (várzeas). Wetl. Ecol. Manag. 20, 461–475. https://doi.org/10.1007/s11273-012-9268-0

Junk, W.J., Wantzen, K.M., 2004. The flood pulse concept: new aspects, approaches, and applications—an update, in: Welcomme, R.L., Petr, T. (Eds.), Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries, Volume 2. Food and Agriculture Organization & Mekong River Commission, FAO Regional Office for Asia and the Pacific, Bangkok, pp. 117–149.

Keddy, P.A., Fraser, L.H., Solomeshch, A.I., Junk, W.J., Campbell, D.R., Arroyo, M.T.K., Alho, C.J.R., 2009. Wet and Wonderful: The World's Largest Wetlands Are Conservation Priorities. Bioscience 59, 39–51. https://doi.org/10.1525/bio.2009.59.1.8

Keizer, F.M., Schot, P.P., Okruszko, T., Chormanski, J., Kardel, I., Wassen, M.J., 2014. A new look at the Flood Pulse Concept: The (ir)relevance of the moving littoral in temperate zone rivers. Ecol. Eng. 64, 85–99. https://doi.org/10.1016/j.ecoleng.2013.12.031

Keizer, F.M., Van der Lee, G.H., Schot, P.P., Kardel, I., Barendregt, A., Wassen, M.J., 2018. Floodplain plant productivity is better predicted by particulate nutrients than by dissolved nutrients in floodwater. Ecol. Eng. 119, 54–63. https://doi.org/10.1016/J.ECOLENG.2018.05.024

Khammongkol, K., Trisurat, Y., Duengkae, P., Sungkaew, S., 2013. The Study of Riparian Forest Structure in Mun River Basin. Thai J. For. 32, 97–109.

Kumarasamy, P., James, R.A., Dahms, H.-U., Byeon, C.-W., Ramesh, R., 2014. Multivariate water quality assessment from the Tamiraparani river basin, Southern India. Environ. Earth Sci. 71, 2441–2451. https://doi.org/10.1007/s12665-013-2644-0

Land Development Department, 2014. Land used of prvinces in north-eastern Thailand [WWW Document]. URL http://www.ldd.go.th/web_OLP/report_research_NE.html. (accessed 11.6.15).

Langhans, C., Govers, G., Diels, J., 2013. Development and parameterization of an infiltration model accounting for water depth and rainfall intensity. Hydrol. Process. 27, 3777–3790. https://doi.org/10.1002/hyp.9491

Lewis, W.M., Hamilton, S.K., Lasi, M.A., Rodríguez, M., Saunders, J.F., 2000. Ecological Determinism on the Orinoco Floodplain: A 15-year study of the Orinoco floodplain shows that this productive and biotically diverse ecosystem is functionally less complex than it appears. Hydrographic and geomorphic controls induce a high degree. Bioscience 50, 681–692. https://doi.org/10.1641/0006-3568(2000)050[0681:EDOTOF]2.0.CO;2

Lillesand, T.M., Kiefer, R.W., Chipman, J.W., 2008. Remote Sensing and Image Interpretation. Willey & Sons, USA.

Loeb, R., Boxman, A.W., Lamers, L.P.M., Lucassen, E.H.E.T., Smolders, A.J.P., Roelofs, J.G.M., Antheunisse, A.M., Miletto, M., 2006. Biogeochemical constraints on the ecological rehabilitation of wetland vegetation in river floodplains 187, 165–186. https://doi.org/10.1007/1-4020-5367-3_11

Marcinkowski, P., Grygoruk, M., 2017. Long-term downstream effects of a dam on a lowland river flow regime: Case study of the upper narew. Water (Switzerland) 9, 783. https://doi.org/10.3390/w9100783

Marszelewski, W., Piasecki, A., 2020. Changes in Water and Sewage Management after Communism: example of the Oder River Basin (Central Europe). Sci. Rep. 10, 1–14. https://doi.org/10.1038/s41598-020-62957-1

McCarthy, T.S., Ellery, W.N., 1997. THE OKAVANGO DELTA. Trans. R. Soc. South Africa 53, 157–182. https://doi.org/10.1080/00359199809520384

McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P.M., Hart, S.C., Harvey, J.W., Johnston, C.A., Mayorga, E., McDowell, W.H., Pinay, G., 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6, 301–312. https://doi.org/10.1007/s10021-003-0161-9

Mcjannet, D., Wallace, J., Keen, R., Hawdon, A., Kemei, J., 2012. The filtering capacity of a tropical riverine wetland: II. Sediment and nutrient balances. Hydrol. Process. 26, 53–72. https://doi.org/10.1002/HYP.8111

Mehto, A., Chakrapani, G.J., 2013. Spatio-temporal variation in the hydrochemistry of Tawa River, Central India: effect of natural and anthropogenic factors. Environ. Monit. Assess. 185, 9789–9802. https://doi.org/10.1007/s10661-013-3291-3

Merck KGaA, 2013. 1.11109.0001 MColortest Alkalinity Test Acid capacity to pH 8.2 and pH 4.3. Merck KGaA, 64271 Darmstadt, Germany.

Mermillod-Blondin, F., 2011. The functional significance of bioturbation and biodeposition on biogeochemical processes at the water?sediment interface in freshwater and marine ecosystems. J. North Am. Benthol. Soc. 30, 770–778. https://doi.org/10.1899/10-121.1

Mertes, L.A.K., 1997. Documentation and significance of the perirheic zone on inundated floodplains. Water Resour. Res. 33, 1749–1762. https://doi.org/10.1029/97WR00658

Meybeck, M., Helmer, R., 1989. The Quality of Rivers - from Pristine Stage to Global Pollution. Glob. Planet. Change 75, 283–309.

Meyerhoff, J., Dehnhardt, A., 2007. The European Water Framework Directive and economic valuation of wetlands: the restoration of floodplains along the River Elbe. Eur. Environ. 17, 18–36. https://doi.org/10.1002/eet.439

Mirosław-Świątek, D., Okruszko, T., 2011. Modelling of hydrological processes in the Narew Catchment. Springer.

Miroslaw-Swiatek, D., Okruszko, T., Kubrak, J., Kardel, I., 2007. The Use of Hydrological Characteristics for Wetland Habitats Protection in Water Management of the Upper Narew River System, in: Integrated Water Management. Springer Netherlands, pp. 283–293. https://doi.org/10.1007/978-1-4020-6552-1_21

Montgomery, D.R., 1999. PROCESS DOMAINS AND THE RWER CONTINTUUM. J. Am. Water Resour. Assoc. 35, 397–410. https://doi.org/10.1111/j.1752-1688.1999.tb03598.x

Moomaw, W.R., Chmura, G.L., Davies, G.T., Finlayson, C.M., Middleton, B.A., Natali, S.M., Perry, J.E., Roulet, N., Sutton-Grier, A.E., 2018. Wetlands In a Changing Climate: Science, Policy and Management. Wetlands 1–23. https://doi.org/10.1007/s13157-018-1023-8

Murray-Hudson, M., Combs, F., Wolski, P., Brown, M.T., 2011. A vegetation-based hierarchical classification for seasonally pulsed floodplains in the Okavango Delta, Botswana. African J. Aquat. Sci. 36, 223–234. https://doi.org/10.2989/16085914.2011.636904

Ngoye, E., Machiwa, J.F., 2004. The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Phys. Chem. Earth, Parts A/B/C 29, 1161–1166. https://doi.org/10.1016/J.PCE.2004.09.002

Okruszko, T., Duel, H., Acreman, M., Grygoruk, M., Flörke, M., Schneider, C., 2011. Broad-scale ecosystem services of European wetlands—overview of the current situation and future perspectives under different climate and water management scenarios. Hydrol. Sci. J. 56, 1501–1517. https://doi.org/10.1080/02626667.2011.631188

Olde Venterink, H., Kardel, I., Kotowski, W., Peeters, W., Wassen, M.J., 2009. Long-term effects of drainage and hay-removal on nutrient dynamics and limitation in the Biebrza mires, Poland. Biogeochemistry 93, 235–252. https://doi.org/10.1007/s10533-009-9300-5

Olde Venterink, H., Pieterse, N.M., Belgers, J.D.M., Wassen, M.J., de Ruiter, O.D., 2002. N, P and K budgets along nutrient availability and productivity gradients in wetlands. Ecol. Appl. 12, 1010–1026. https://doi.org/10.2307/3061033

Olde Venterink, H., Vermaat, J.E., Pronk, M., Wiegman, F., van der Lee, G.E.M., van den Hoorn, M.W., Higler, L.W.G. (Bert), Verhoeven, J.T.A., 2006. Importance of sediment deposition and denitrification for nutrient retention in floodplain wetlands. Appl. Veg. Sci. 9, 163–174.

Olde Venterink, H., Wassen, M.J., Verkroost, A.W.M., de Ruiter, P.C., 2003. Species richness-productivity patterns differ between N-, P-, and K-limited wetlands. Ecology 84, 2191–2199.

Parolin, P., 2002. Submergence tolerance vs. escape from submergence: two strategies of seedling establishment in Amazonian floodplains. Environ. Exp. Bot. 48, 177–186. https://doi.org/10.1016/S0098-8472(02)00036-9

Parolin, P., Ferreira, L. V, Piedade, M.T.F., da Cunha, C.N., Wittmann, F., Arias, M.E., 2016. Flood Tolerant Trees in Seasonally Inundated Lowland Tropical Floodplains, in: Goldstein, G., Santiago, L.S. (Eds.), Tropical Tree Physiology: Adaptations and Responses in a Changing Environment. Springer International Publishing, Cham, pp. 127–147. https://doi.org/10.1007/978-3-319-27422-5_6

Parolin, P., Wittmann, F., 2010. Struggle in the flood: tree responses to flooding stress in four tropical floodplain systems. AoB Plants 2010, plq003. https://doi.org/10.1093/aobpla/plq003

Perakis, S.S., Hedin, L.O., 2002. Nitrogen loss from unpolluted South American forests mainly via dissolved organic compounds (vol 415, pg 416, 2002). Nature 418, 665. https://doi.org/10.1038/nature00959

Peres-Neto, P.R., Jackson, D.A., Somers, K.M., 2005. How many principal components? stopping rules for determining the number of non-trivial axes revisited. Comput. Stat. Data Anal. 49, 974–997. https://doi.org/10.1016/j.csda.2004.06.015

Piniewski, M., Okruszko, T., Acreman, M.C., 2014. Environmental water quantity projections under market-driven and sustainability-driven future scenarios in the Narew basin, Poland. Hydrol. Sci. J. 59, 916–934. https://doi.org/10.1080/02626667.2014.888068

Quilbé, R., Rousseau, A.N., Duchemin, M., Poulin, A., Gangbazo, G., Villeneuve, J.-P., 2006. Selecting a calculation method to estimate sediment and nutrient loads in streams: Application to the Beaurivage River (Québec, Canada). J. Hydrol. 326, 295–310. https://doi.org/10.1016/J.JHYDROL.2005.11.008

Rees, W.A., 1978. The Ecology of the Kafue Lechwe: Soils, Water Levels and Vegetation. J. Appl. Ecol. 15, 163. https://doi.org/10.2307/2402928

Reich, P.B., Oleksyn, J., 2004. Global patterns of plant leaf N and P in relation to temperature and latitude. Proc. Natl. Acad. Sci. U. S. A. 101, 11001–11006. https://doi.org/10.1073/PNAS.0403588101

Roeling, I.S., Ozinga, W.A., van Dijk, J., Eppinga, M.B., Wassen, M.J., 2018. Plant species occurrence patterns in Eurasian grasslands reflect adaptation to nutrient ratios. Oecologia 186, 1055–1067. https://doi.org/10.1007/s00442-018-4086-6

Sarma, V.V.S.S., Gupta, S.N.M., Babu, P.V.R., Acharya, T., Harikrishnachari, N., Vishnuvardhan, K., Rao, N.S., Reddy, N.P.C., Sarma, V. V., Sadhuram, Y., Murty, T.V.R., Kumar, M.D., 2009. Influence of river discharge on plankton metabolic rates in the tropical monsoon driven Godavari estuary, India. Estuar. Coast. Shelf Sci. 85, 515–524. https://doi.org/10.1016/J.ECSS.2009.09.003

Satrawaha, R., Prathepha, P., Andrews, R., Petney, T., 2009. Fundamental hydrochemical parameters of the Songkhram River in Northeast Thailand: foundation data for the study of an endangered tropical wetland ecosystem. Limnology 10, 7–15. https://doi.org/10.1007/s10201-008-0254-4

Schipper, A.M., Zeefat, R., Tanneberger, F., Van Zuidam, J.P., Hahne, W., Schep, S.A., Loos, S., Bleuten, W., Joosten, H., Lapshina, E.D., Wassen, M.J., 2007. Vegetation characteristics and eco-hydrological processes in a pristine mire in the Ob River valley (Western Siberia). Plant Ecol. 193, 131–145. https://doi.org/10.1007/s11258-006-9253-x

Seal Analytical, 2000. Bran + Luebbe Auto Analyzer III Applications and Operation Manual.

Sedell, J.R., Richey, J.E., Swanson, F.J., 1989. The river continuum concept: a basis for the expected ecosystem behavior of very large rivers, Proceedings of the International Large River Symposium. Can. Spec. Publ. Aquat. Sci., Proceedings of the International Large River Sysmposium (LARS). Canadian Special Publication of Fisheries and Aquatic Sciences 106. https://doi.org/0-660-13259-1

Shrestha, M., Shrestha, S., Shrestha, P.K., 2020. Evaluation of land use change and its impact on water yield in Songkhram River basin, Thailand. Int. J. River Basin Manag. 18, 23–31. https://doi.org/10.1080/15715124.2019.1566239

Sjodin, A.L., Lewis, W.M., Saunders, J.F., 1997. Denitrification as a component of the nitrogen budget for a large plains river. Biogeochemistry 39, 327–342. https://doi.org/10.1023/A:1005884117467

Southwell, M., Thoms, M., 2011. Patterns of Nutrient Concentrations across Multiple Floodplain Surfaces in a Large Dryland River System. Geogr. Res. 49, 431–443. https://doi.org/10.1111/j.1745-5871.2011.00699.x

Spink, A., Sparks, R.E., Van Oorschot, M., Verhoeven, J.T.A., 1998. Nutrient dynamics of large river floodplains. River Res. Appl. 14, 203–216. https://doi.org/10.1002/(sici)1099-1646(199803/04)14:2<203::aid-rrr498>3.0.co;2-7

Statzner, B., Higler, B., 1986. Stream hydraulics as a major determinant of benthic invertebrate zonation patterns. Freshw. Biol. 16, 127–139. https://doi.org/10.1111/j.1365-2427.1986.tb00954.x

Statzner, B., Higler, B., 1985. Questions and Comments on the River Continuum Concept. Can. J. Fish. Aquat. Sci. 42, 1038–1044.

Steiger, J., Gurnell, A.M., 2003. Spatial hydrogeomorphological influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France. Geomorphology 49, 1–23. https://doi.org/10.1016/S0169-555X(02)00144-7

Szewczyk, M., Dembek, W., Kamocki, A., 2003. RESPONSE OF RIPARIAN VEGETATION TO THE DECREASE OF FLOODING: NAREW NATIONAL PARK, POLAND, in: Towards Natural Flood Reduction Strategies. Warsaw.

Thailand Royal Irrigation department, 2016. HYDROLOGY AND WATER MANAGEMENT CENTER FOR UPPER NORTHEASTERN REGION - RID [WWW Document]. URL http://hydro-3.rid.go.th/ (accessed 3.15.16).

Thiha, Satrawaha, R., Wongpakam, K., 2012. Monitoring trends in the extent of major floods in the lower reach of Songkhram River Basin, Northeastern Thailand. Limnology 13, 163–170. https://doi.org/10.1007/s10201-011-0352-6

Thomas, J., Joseph, S., Thrivikramji, K.P., Manjusree, T.M., Arunkumar, K.S., 2014. Seasonal variation in major ion chemistry of a tropical mountain river, the southern Western Ghats, Kerala, India. Environ. Earth Sci. 71, 2333–2351. https://doi.org/10.1007/s12665-013-2634-2

Thorp, J.H., Delong, M.D., 1994. The Riverine Productivity Model - an Heuristic View of Carbon-Sources and Organic-Processing in Large River Ecosystems. Oikos 70, 305–308. https://doi.org/10.2307/3545642

Thorp, J.H., Thoms, M.C., Delong, M.D., 2006. The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. River Res. Appl. 22, 123–147. https://doi.org/10.1002/rra.901

Tipping, E., Benham, S., Boyle, J.F., Crow, P., Davies, J., Fischer, U., Guyatt, H., Helliwell, R., Jackson-Blake, L., Lawlor, A.J., Monteith, D.T., Rowe, E.C., Toberman, H., 2014. Atmospheric deposition of phosphorus to land and freshwater. Environ. Sci. Process. Impacts 16, 1608–1617. https://doi.org/10.1039/C3EM00641G

Tockner, K., Malard, F., Uehlinger, U., Ward, J. V., 2002. Nutrients and organic matter in a glacial river—floodplain system (Val Roseg, Switzerland). Limnol. Oceanogr. 47, 266–277. https://doi.org/10.4319/LO.2002.47.1.0266

Tockner, K., Malard, F., Ward, J. V., 2000. An extension of the flood pulse concept. Hydrol. Process. 14, 2861–2883. https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2861::AID-HYP124>3.0.CO;2-F

Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F., Ward, J. V., 1999. Hydrological connectivity, and the exchange of organic matter and nutrients in a dynamic river-floodplain system (Danube, Austria). Freshw. Biol. 41, 521–535. https://doi.org/10.1046/j.1365-2427.1999.00399.x

Tockner, K., Schiemer, F., Ward, J. V., 1998. Conservation by restoration: The management concept for a river-floodplain system on the Danube river in Austria. Aquat. Conserv. Mar. Freshw. Ecosyst. 8, 71–86. https://doi.org/10.1002/(SICI)1099-0755(199801/02)8:1<71::AID-AQC265>3.0.CO;2-D

Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends. Environ. Conserv. 29, 308–330. https://doi.org/10.1017/S037689290200022X

Tockner, K., Ward, J. V, Arscott, D.B., Edwards, P.J., Kollmann, J., Gurnell, A.M., Petts, G.E., Maiolini, B., 2003. The Tagliamento River: a model ecosystem of European importance. Aquat. Sci. 65, 239–253. https://doi.org/10.1007/s00027-003-0699-9

Townsend, C.R., 1989. The Patch Dynamics Concept of Stream Community Ecology. J. North Am. Benthol. Soc. 8, 36–50. https://doi.org/10.2307/1467400

USGS, 2013. Using the USGS Landsat 8 Product [WWW Document]. URL http://landsat.usgs.gov/Landsat8_Using_Product.php (accessed 9.25.14).

USGS, 2006. Shuttle Radar Topography Mission, 3 Arc Second scene STRM_f03_p128r048, STRM_f03_p128r047, STRM_f03_p128r048 filled finished 2.0, Global Land Cover Facility. University of Maryland, College Park, Maryland.

van der Grift, B., Osté, L., Schot, P., Kratz, A., van Popta, E., Wassen, M., Griffioen, J., 2018. Forms of phosphorus in suspended particulate matter in agriculture-dominated lowland catchments: Iron as phosphorus carrier. Sci. Total Environ. 631–632, 115–129. https://doi.org/10.1016/J.SCITOTENV.2018.02.266

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The River Continuum Concept. Can. J. Fish. Aquat. Sci. 37, 130–137. https://doi.org/10.1139/f80-017

Vet, R., Artz, R.S., Carou, S., Shaw, M., Ro, C.-U., Aas, W., Baker, A., Bowersox, V.C., Dentener, F., Galy-Lacaux, C., Hou, A., Pienaar, J.J., Gillett, R., Forti, M.C., Gromov, S., Hara, H., Khodzher, T., Mahowald, N.M., Nickovic, S., Rao, P.S.P., Reid, N.W., 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. Atmos. Environ. 93, 3–100. https://doi.org/10.1016/j.atmosenv.2013.10.060

Vitousek, P.M., Sanford, R.L., 1986. Nutrient Cycling in Moist Tropical Forest. Annu. Rev. Ecol. Syst. 17, 137–167. https://doi.org/10.1146/annurev.es.17.110186.001033

Walalite, T., Dekker, S.C., Keizer, F.M., Kardel, I., Schot, P.P., deJong, S.M., Wassen, M.J., 2016. Flood Water Hydrochemistry Patterns Suggest Floodplain Sink Function for Dissolved Solids from the Songkhram Monsoon River (Thailand). Wetlands 36, 995–1008. https://doi.org/10.1007/s13157-016-0814-z

Walalite, T., Dekker, S.C., Schot, P.P., Wassen, M.J., 2018. Unraveling the ecological functioning of the monsoonal Songkhram river floodplain in Thailand by integrating data on soil, water, and vegetation. Ecohydrol. Hydrobiol. 18, 10–21. https://doi.org/10.1016/J.ECOHYD.2017.09.005

Walalite, T., Kardel, I., Schot, P.P., Dekker, S.C., Okruszko, T., Wassen, M.J., n.d. Ecohydrological analysis of the relatively pristine floodplain of the Narew River, Poland.

Walker, J.K.M., Cohen, H., Higgins, L.M., Kennedy, P.G., 2014. Testing the link between community structure and function for ectomycorrhizal fungi involved in a global tripartite symbiosis. New Phytol. 202, 287–296. https://doi.org/10.1111/nph.12638

Ward, J. V, Tockner, K., Aroscott, D.B., Claret, C., 2002. Riverine landscape diversity. Freshw. Biol. 47, 517–539. https://doi.org/10.1046/j.1365-2427.2002.00893.x

Ward, J. V, Tockner, K., Schiemer, F., 1999. Biodiversity of floodplain river ecosystems: Ecotones and connectivity. Regul. Rivers-Research Manag. 15, 125–139. https://doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3<125::AID-RRR523>3.0.CO;2-E

Wassen, M., Peeters, W., Olde Venterink, H., 2003. Patterns in vegetation, hydrology, and nutrient availability in an undisturbed river floodplain in Poland. Plant Ecol. 165, 27–43. https://doi.org/10.1023/A:1021493327180

Wassen, M.J., 1995. Hydrology, water chemistry and nutrient accumulation in the Biebrza fens and floodplains (Poland). Wetl. Ecol. Manag. 3, 125–137. https://doi.org/10.1007/BF00177694

Wassen, M.J., Barendregt, A., Palczynski, A., de Smidt, J.T., de Mars, H., 1990. The Relationship Between Fen Vegetation Gradients, Groundwater Flow and Flooding in an Undrained Valley Mire at Biebrza, Poland. J. Ecol. 78, 1106. https://doi.org/10.2307/2260955

Wassen, M.J., Joosten, J.H.J., 1996. In search of a hydrological explanation for vegetation changes along a fen gradient in the Biebrza Upper Basin (Poland). Vegetatio 124, 191–209.

Wassen, M.J., Olde Venterink, H., 2006. Comparison of nitrogen and phosphorus fluxes in some European fens and floodplains. Appl. Veg. Sci. 9, 213–222. https://doi.org/10.1658/1402-2001(2006)9[213:CONAPF]2.0.CO;2

Wassen, M.J., Olde Venterink, H., de Swart, E., 1995. Nutrient Concentrations in Mire Vegetation as a Measure of Nutrient Limitation in Mire Ecosystems. J. Veg. Sci. 6, 5–16. https://doi.org/10.2307/3236250

Wassen, M.J., Olde Venterink, H., Lapshina, E.D., Tanneberger, F., 2005. Endangered plants persist under phosphorus limitation. Nature 437, 547–550. https://doi.org/http://www.nature.com/nature/journal/v437/n7058/suppinfo/nature03950_S1.html

Wassen, M.J., Schrader, J., van Dijk, J., Eppinga, M.B., 2021. Phosphorus fertilization is eradicating the niche of northern Eurasia's threatened plant species. Nat. Ecol. Evol. 2020 51 5, 67–73. https://doi.org/10.1038/S41559-020-01323-W

Wassen, M.J., Van Der Vliet, R., Verhoeven, J.T.A., 1998. Nutrient limitation in the Biebrza fens and floodplain (Poland). Acta Bat. Neerl 47, 241–253.

Weller, D.E., Jordan, T.E., Correll, D.L., Liu, Z.J., 2003. Effects of land-use change on nutrient discharges from the Patuxent River watershed. Estuaries 2003 262 26, 244–266. https://doi.org/10.1007/BF02695965

Wiens, J.A., 2002. Riverine landscapes: taking landscape ecology into the water. Freshw. Biol. 47, 501–515. https://doi.org/10.1046/j.1365-2427.2002.00887.x

Wittmann, F., Junk, W.J., Piedade, M.T.., 2004. The várzea forests in Amazonia: flooding and the highly dynamic geomorphology interact with natural forest succession. For. Ecol. Manage. 196, 199–212. https://doi.org/10.1016/j.foreco.2004.02.060

Wittmann, F., Zorzi, B.T., Tambelini Tizianel, F.A., Santiago Urquiza, M.V., Faria, R.R., e Sousa, N., Modena, E. de S., Gamarra, R.M., Martins Rosa, A.L., 2008. Tree Species Composition, Structure, and Aboveground Wood Biomass of a Riparian Forest of the Lower Miranda River, Southern Pantanal, Brazil. FOLIA Geobot. 43, 397–411. https://doi.org/10.1007/s12224-008-9022-9

Wu, Y., Blodau, C., 2015. Vegetation Composition in Bogs is Sensitive to Both Load and Concentration of Deposited Nitrogen: A Modeling Analysis. Ecosystems 18, 171–185. https://doi.org/10.1007/s10021-014-9820-2

YSI Environmental, 2009. YSI 556 MPS Multi Probe System, Operations Manual [WWW Document]. URL https://www.ysi.com/File Library/Documents/Manuals/655279-YSI-556-Operations-Manual-RevD.pdf (accessed 12.25.14).

Zielinski, P., Górniak, A., Suchowolec, T., 2003. Changes in water chemistry along the course of two rivers with different hydrological regimes. Polish J. Environ. Stud. 12, 111–117.

Zohary, T., Padisak, J., Naselli-Flores, L., 2010. Phytoplankton in the physical environment: beyond nutrients, at the end, there is some light. Hydrobiologia 639, 261–269. https://doi.org/10.1007/s10750-009-0032-2

Zuijdgeest, A.L., Zurbrügg, R., Blank, N., Fulcri, R., Senn, D.B., Wehrli, B., 2015. Seasonal dynamics of carbon and nutrients from two contrasting tropical floodplain systems in the Zambezi River basin. Biogeosciences 12, 7535–7547. https://doi.org/10.5194/BG-12-7535-2015

Zurbruegg, R., Wamulume, J., Kamanga, R., Wehrli, B., Senn, D.B., 2012. River-floodplain exchange and its effects on the fluvial oxygen regime in a large tropical river system (Kafue Flats, Zambia). J. Geophys. Res. 117, G03008. https://doi.org/10.1029/2011JG001853

Summary

Ecohydrological Functioning of a Tropical Monsoon and a Temperate River Floodplain

River floodplains are highly productive, especially when compared to many other terrestrial or aquatic ecosystems. Most river floodplains in Europe and North America have been heavily modified by human activities. Also, in Southeast Asia, the remaining undisturbed floodplains are rapidly disappearing. In order to maintain these valuable systems, control measures are necessary to prevent their further loss and, thus also, the loss of their valuable ecosystem services for humans. Effective control measures require insight into the ecological functioning of the floodplains. Although their ecological functioning in the temperate climate zone is fairly well known, the processes in tropical floodplains in tropical climates, particularly in the monsoon region of Southeast Asia, have been much less studied. Knowledge of these rivers and ecosystems in tropical areas is important in order to provide targeted support for management measures there as well. This thesis aims to contribute to this knowledge, in particular, knowledge about the role of biogeochemical processes in relation to vegetation.

This thesis contains six chapters. Chapter 1 introduces three river concepts that can be helpful in the study of rivers and river ecosystems. The discharge hydrology and the vegetation and nutrient dynamics of tropical rivers and rivers in a temperate climate are also discussed. Subsequently, the aims and research questions of the various chapters are presented, and finally, the study areas are introduced: the Songkhram River in Thailand and the Narew River in Poland. Chapter 2 presents a pioneering study of the tropical monsoon river Songkhram. Subsequently, in chapter 3, the ecological functioning of the Songkhram floodplain is analyzed in detail using data on the nutrient status of soil, water, and vegetation. Chapter 2 and chapter 3 together provide insight into the ecohydrological functioning of a tropical river floodplain in Thailand. For comparison, Chapter 4 presents an ecohydrological analysis of the Narew River as an example of the ecological functioning of a relatively pristine riverplain in Europe's temperate climate. Subsequently, in chapter 5, the ecological functioning of the Narew and the Songkhram is compared in terms of hydrology, hydrochemistry, nutrient budget, and nutrient balance of the vegetation.

Chapter 2, a study of the hydrochemical functioning of the Songkhram river and floodplain, shows that the water in the Songkhram river during the flood is poor in dissolved substances and nutrients and that the concentrations decrease downstream. This longitudinal trend is related to the weathering products of the basin's geological deposits and a dilution effect of a large amount of rainwater during the monsoon season. A transverse trend of decreasing solute and nutrient concentrations from the river to the edge of the floodplain has also been identified. This is related to the dense and highly productive bamboo vegetation found along the river and its tributaries. Bamboo acts as a filter that removes dissolved material and captures sediment from the river before it can spread further across the river plain. This study suggests that the river is a source of nutrients for the river plain itself. It is the first study to collect scientific data showing that the Songkhram river plain acts as a sink for dissolved nutrients during flooding.

In chapter 3, the ecological functioning of the Songkhram floodplain and its vegetation is further investigated. The vegetation consists of a clearly spatially marked zone of highly productive bamboo vegetation along the river and grassy vegetation behind it. The dense and highly productive bamboo was able to filter sediment and dissolved nutrients from the floodwaters brought in from the river. In the bamboo zone along the river, the floods are longer and deeper, and the increased supply of nutrients leads to high productivity. The grass zone, on the other hand, which is further from the river and where the floods are shorter and shallower, receives less nutrients and has lower productivity. Both types of vegetation store more nutrients (N and P) in their biomass than the nutrients that can be supplied annually by the floodwater. In addition, it was found that while the river floodplain receives nutrients from the river, it exports organic carbon to the river during the flood. The floodplain is thus a source of organic carbon for the downstream part of the river course. The Songkhram floodplain thus acts as a reservoir for sediment and dissolved material and in turn produces organic carbon, which is exported to the river during flooding. Vegetation plays an important role in retaining and storing nutrients.

In Chapter 4, an integration of hydrology, soil nutrients, water chemistry, and plant community data from the relatively undisturbed riverplain of the Narew river in Poland is presented as an example of river ecological functioning in a temperate climate. This study showed that plant community distribution is distributed over longitudinal and transverse gradients, which are related to flood characteristics and available soil nutrients. Plant growth is limited by nitrogen in all communities. In addition, this study also reveals a spatial variation of water chemistry in the floodplain that is not only related to the flooding with river water but also to the presence of upwelling groundwater and rainwater. The variation in water quality, vegetation gradients, and the fact that there is nitrogen limitation in the floodplain indicates a relatively undisturbed riverplain compared to many other European rivers where polluted river water dominates the water chemistry and dominates the natural vegetation gradients in their floodplains. This study contributes to our understanding of how relatively undisturbed river floodplains of temperate rivers function ecologically and may be useful as a reference and source of inspiration for future floodplain management and restoration of deteriorated floodplains. In addition, the understanding of ecological functioning gained here allows a comparison with the tropical monsoon riverplain, listing similarities and differences between floodplains in different climate zones.

Chapter 5 is done for the hydrology, water chemistry, and nutrient status (N and P) of the vegetation in the Narew and Songkhram. This analysis provides insight into the ecological functioning of these two systems. Both rivers show a discharge regime with a flood pulse. It occurs in the Narew after the snow melts in spring and in the Songkhram after the monsoon rains. The peak discharge in the Songkhram is roughly 25 times higher than in the Narew. Nutrient concentrations are slightly higher in the Narew river water. The flood pulse is an external source of nutrients for the vegetation in the floodplain in both the tropical river and the temperate river, with soil appearing to play an essential role in nutrient budgets and balance. The vegetation in both floodplains benefits from nutrients (N, P) supplied by the flood pulse and acts as a sink for the nutrients. However, the nutrient-absorbing capacity of the vegetation differs in both areas per vegetation type.

In Chapter 6, the findings are integrated, the results are discussed in relation to the three river concepts, and management recommendations and recommendations for further research are made. The flow regime of the rivers exhibits a seasonal flood pulse, which has been shown to be an essential mechanism for the transport of nutrients and sediment to the riverplain and determines the ecological functioning of the systems. The flood and flow regime is important for vegetation zoning, and the spatial patterns of vegetation in the Narew and Songkhram have evolved in response to flood characteristics (duration, depth, and frequency). These vegetations absorb nutrients from the soil that come from the flood water, removing dissolved nutrients (N and P) from the flood water. In addition, the physical structure of the vegetation reduces the flow rate and promotes sedimentation, causing nutrients to sediment in the vegetation zones, which the vegetation reabsorbs and stores in biomass. Although a number of important processes that occur in the soil and vegetation of floodplains have not been investigated, this research makes it clear that the floodplain acts as a sink for nutrients. While both floodplains are similar in the sense that the annual runoff peak causes the flooding and the floodplains act as a nutrient sinks, there are also distinct differences.

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The discharge of the Narew is relatively constant throughout the year, compared to the monsoon river Songkhram which showed highly variable discharges, with higher peaks during the flooding period after the monsoon rains and very low discharges in the dry season. In the Narew, snow melt and spring rains cause the discharge peak, but the differences between peak discharge and low discharge periods in the summer are much smaller. Although the annual average concentrations of the nutrients N and P in the water of the Narew River are higher than those of the Songkhram River, the nutrient load of the Songkhram River is higher than that of the Narew River due to the higher peak discharge of the Songkhram River.

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Also, the supply of nutrients from flood water and the supply of nutrients from the soil to the vegetation differed between the areas, the vegetation types, and also between the nutrients N and P. Soil nitrogen supply was the main source for the sedge vegetation and the swamp forest vegetation in the Narew. In the Songkhram, the soil was also the main N source for the bamboo vegetation (roughly 70%), while for the grassy vegetation, it was only 35%. Even clearer was the differences in the phosphorus budget. In the Narew, flood water was the main source of P for the sedge community and more important than the supply from the soil, unlike N. In contrast, in the Songkhram, the soil was the main source of P for both bamboo and grassy vegetation (roughly 70 -80%). There are thus similarities and differences in flood characteristics and nutrient budget, and thus in the ecological functioning of the floodplains of these rivers in temperate and tropical climates.

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Thus, floodplain conservation, management and restoration plans must take into account the river's discharge regime, the nutrient load of the river and floodwaters, and site-specific conditions, such as the morphology of the riverplain, the geology, and hydrology of the adjacent landscape and the catchment, vegetation zoning and the interaction between these factors. In order to make specific recommendations for the management of rivers and their floodplains, it is therefore recommended to perform empirical studies per area similar to the ecohydrological studies in this thesis. Sufficient attention to the interaction between the river, groundwater hydrology, and vegetation is essential. The highly dynamic situation in floodplains and the hydrogeochemical interactions taking place in floodplains make this kind of research very labor intensive. Comparative analyzes based on such studies will eventually also make it possible to further develop the various river concepts into an integrative vision of the functioning of rivers with their floodplains in different climate zones.

Samenvatting

Ecohydrologie van de overstromingsvlaktes van een tropische moesson rivier en een gematigd klimaat rivier

De overstromingsvlaktes van rivieren zijn zeer productief, zeker in vergelijking met veel andere terrestrische of aquatische ecosystemen. De meeste rivier-overstromingsvlaktes in Europa en Noord-Amerika zijn sterk veranderd door menselijke activiteiten. Ook in Zuidoost-Azië, verdwijnen de resterende ongestoorde overstromingsvlaktes snel. Om deze waardevolle systemen in stand te houden zijn beheersmaatregelen nodig om het verdere verlies ervan en daarmee ook verlies van hun voor de mens waardevolle ecosysteemdiensten te voorkomen. Doeltreffende beheersmaatregelen vereisen inzicht in het ecologisch functioneren van de overstromingsvlaktes. Hoewel hun ecologisch functioneren in de gematigde klimaatzone redelijk goed bekend is, zijn de processen in overstromingsvlaktes van rivieren in een tropisch klimaat, met name in de moessonregio van Zuidoost-Azië, veel minder bestudeerd. Kennis van deze rivieren en ecosystemen in tropische gebieden is belangrijk om ook daar gerichte ondersteuning van beheersmaatregelen te kunnen leveren. Dit proefschrift beoogt een bijdrage te leveren aan deze kennis, met name kennis over de rol van biogeochemische processen in relatie tot de vegetatie.

Dit proefschrift bevat zes hoofdstukken. In hoofdstuk 1 worden een drietal rivierconcepten geïntroduceerd die behulpzaam kunnen zijn bij de bestudering van rivieren en rivier-begeleidende ecosystemen. Tevens worden de afvoerhydrologie en de vegetatie- en nutriënten-dynamiek besproken van tropische rivieren en rivieren in een gematigd klimaat. Vervolgens worden de doelen en onderzoeksvragen van de diverse hoofdstukken gepresenteerd en tot slot worden de studiegebieden geïntroduceerd: de Songkhram rivier in Thailand en de Narew rivier in Polen. Hoofdstuk 2 presenteert een pioniersstudie van de tropische moessonrivier Songkhram. Vervolgens wordt in hoofdstuk 3 het ecologisch functioneren van de Songkhram overstromingsvlakte in detail geanalyseerd aan de hand van gegevens over de nutriëntenstatus van bodem, water en vegetatie. Hoofdstuk 2 en hoofdstuk 3 geven samen inzicht in het ecohydrologisch functioneren van een tropische rivier-overstromingsvlakte in Thailand. Ter vergelijking geeft hoofdstuk 4 een ecohydrologische analyse van de Narew rivier, als voorbeeld van het ecologisch functioneren van een relatief ongerepte riviervlakte in het gematigde klimaat van Europa. Vervolgens wordt in hoofdstuk 5 het ecologisch functioneren van de Narew en de Songkhram vergeleken in termen van hydrologie, hydrochemie, nutriëntenbudget en nutriëntenbalans van de vegetatie.

Uit hoofdstuk 2, een onderzoek naar het hydrochemisch functioneren van de Songkhram riviervlakte, blijkt dat het water in de Songkhram rivier tijdens de overstroming arm is aan opgeloste stoffen en voedingsstoffen en dat de concentraties stroomafwaarts afnemen. Deze longitudinale trend houdt verband met de verweringsproducten van de geologische afzettingen van het stroomgebied en een verdunningseffect van een grote hoeveelheid regenwater tijdens het moessonseizoen. Tevens is een transversale trend van afnemende concentraties opgeloste stoffen en nutriënten van de rivier naar de rand van de overstromingsvlakte geïdentificeerd. Deze hangt samen met de dichte en zeer productieve bamboevegetatie die is aangetroffen langs de rivier en haar nevengeulen. Bamboe werkt als een filter dat opgelost materiaal verwijdert en sediment uit de rivier opvangt voordat het zich verder over de riviervlakte kan verspreiden. Deze studie suggereert dat de rivier een bron van voedingsstoffen is voor de riviervlakte zelf. Het is de eerste studie die wetenschappelijke gegevens heeft verzameld waaruit blijkt dat de Songkhram riviervlakte tijdens overstroming fungeert als een put voor opgeloste voedingsstoffen.

In hoofdstuk 3 wordt het ecologisch functioneren van de Songkhram overstromingsvlakte en de vegetatie verder onderzocht. De vegetatie bestaat uit een duidelijk ruimtelijk gemarkeerde zone van zeer productieve bamboevegetatie langs de rivier en daarachter een grasachtige vegetatie. De dichte en zeer productieve bamboe bleek in staat om sediment en opgeloste voedingsstoffen te filteren uit het overstromingswater dat uit de rivier aanvoerde. In de bamboezone langs de rivier zijn de overstromingen langer van duur en dieper en leidt de grotere toevoer van voedingsstoffen tot een hoge productiviteit. De graszone daarentegen, die verder van de rivier af ligt en waar de overstromingen korter en ondieper zijn, ontvangt minder voedingsstoffen en heeft een lagere productiviteit. Beide types vegetatie slaan meer nutriënten (N en P) op in hun biomassa dan de nutriënten die jaarlijks door het overstromingswater kunnen worden aangevoerd. Bovendien bleek dat de riviervlakte weliswaar voedingsstoffen van de rivier ontvangt, maar organische koolstof naar de rivier exporteerde tijdens de overstroming. De overstromingsvlakte is dus een bron van organische koolstof voor het de stroomafwaarts gelegen deel van de rivierloop. De Songkhram overstromingsvlakte fungeert dus als reservoir voor sediment en opgelost materiaal en produceert op zijn beurt organische koolstof, die tijdens de overstroming naar de rivier wordt geëxporteerd. De vegetatie speelt een belangrijke rol bij het vasthouden en opslaan van nutriënten.

In hoofdstuk 4 wordt een integratie van gegevens over hydrologie, bodemnutriënten, waterchemie en plantengemeenschappen van de relatief ongestoorde riviervlakte van de Narew in Polen gepresenteerd, als voorbeeld van het ecologisch functioneren van een rivier in een gematigd klimaat. Uit dit onderzoek bleek dat de verspreiding van plantengemeenschappen verdeeld is over longitudinale en transversale gradiënten, die gerelateerd zijn aan overstromingskenmerken en beschikbare bodemvoedingsstoffen. De plantengroei wordt in alle gemeenschappen beperkt door stikstof. Daarnaast legt deze studie ook een ruimtelijke variatie aan waterchemie bloot in de overstromingsvlakte die niet alleen samenhangt met de overstroming met rivierwater, maar ook met de aanwezigheid van opwellend grondwater en regenwater. De aanwezige variatie in waterkwaliteit, vegetatiegradiënten en het feit dat er stikstofbeperking heerst in de riviervlakte wijzen op een relatief ongestoorde riviervlakte in vergelijking met veel andere Europese rivieren waar vervuild rivierwater de waterchemie domineert en de natuurlijke vegetatiegradiënten overheerst. Deze studie draagt bij aan ons begrip van hoe relatief ongestoorde rivier-overstromingsvlaktes en uiterwaarden van gematigde rivieren ecologisch functioneren en kan nuttig zijn als referentie en inspiratiebron voor toekomstig beheer van uiterwaarden. Bovendien maakt het hier verworven inzicht in het ecologisch functioneren een vergelijking mogelijk met de tropische moesson-riviervlakte, waarbij overeenkomsten en verschillen tussen overstromingsvlaktes in verschillende klimaatzones op een rijtje worden gezet.

In hoofdstuk 5 wordt dit gedaan voor de hydrologie, de waterchemie en de nutriëntenstatus (N en P) van de vegetatie in de Narew en de Songkhram. Deze analyse geeft inzicht in het ecologisch functioneren van deze twee systemen. Beide rivieren vertonen een afvoerregime met een overstromingspuls. Deze treedt in de Narew op na de sneeuwsmelt in het voorjaar en in de Songkhram na de moessonregens. De piekafvoer is in de Songkhram ruwweg 25 maal zo hoog als in de Narew. De nutriëntenconcentraties zijn iets hoger in het rivierwater van de Narew. De hoogwaterpuls is een externe bron van voedingsstoffen voor de vegetatie in de overstromingsvlakte in zowel de tropische rivier als de gematigde klimaat rivier, waarbij de bodem een essentiële rol lijkt de spelen in de voedingsstoffenbudgetten en -balans. De vegetatie in beide overstromingsvlaktes profiteert van nutriënten (N, P) die door de hoogwaterpuls worden aangevoerd en fungeert als een put voor deze nutriënten. Het nutriënten-opnemend vermogen van de vegetatie verschilt echter in beide gebieden per vegetatietype.

In Hoofdstuk 6 worden de bevindingen geïntegreerd, worden de resultaten bediscussieerd in relatie tot de drie rivierconcepten en worden beheers-aanbevelingen gedaan en aanbevelingen voor verder onderzoek.

Het stroomregime van de rivieren vertoont een seizoensgebonden overstromingspuls, waarvan is aangetoond dat het een essentieel mechanisme is voor het transport van voedingsstoffen en sediment naar de riviervlakte en bepalend is voor het ecologisch functioneren van de systemen. Het overstromings- en stroomregime is belangrijk voor de zonering van de vegetatie en de ruimtelijke patronen van de vegetatie in de Narew en de Songkhram hebben zich ontwikkeld als respons op overstromingskenmerken (duur, diepte en frequentie). Deze vegetaties nemen voedingsstoffen op uit de bodem die afkomstig zijn van het overstromingswater, waardoor opgeloste voedingsstoffen (N en P) uit het overstromingswater worden verwijderd. Bovendien vermindert de fysieke structuur van de vegetatie de stroomsnelheid en bevordert het de sedimentatie, waardoor voedingsstoffen sedimenteren in de vegetatiezones, die de vegetatie weer opneemt en opslaat in biomassa. Alhoewel een aantal belangrijke processen die optreden in de bodem en de vegetatie van overstromingsvlaktes niet zijn onderzocht, maakt dit onderzoek wel duidelijk dat de overstromingsvlakte fungeert als een put voor nutriënten.

Hoewel beide overstromingsvlaktes vergelijkbaar zijn in de zin dat de jaarlijkse afvoerpiek de overstroming veroorzaakt en de overstromingsvlaktes fungeren als een put voor voedingsstoffen zijn er ook duidelijke verschillen.

De afvoer van de Narew is gedurende het jaar relatief constant, in vergelijking met de moessonrivier de Songkhram die zeer variabele afvoeren vertoonde, met hogere pieken tijdens de overstromingsperiode na de moessonregens en zeer lage afvoeren in het droge seizoen. In de Narew veroorzaken sneeuwsmelt en voorjaarregens de afvoerpiek, maar de verschillen tussen piekafvoer en lage afvoerperiodes in de zomer zijn veel minder groot. Hoewel de jaargemiddelde concentraties van de nutriënten N en P in het water van de Narew rivier hoger zijn dan die van de Songkhram rivier, is de nutriëntenvracht van de Songkhram hoger dan die van de Narew vanwege de hogere piekafvoer van de Songkhram rivier.

Ook verschilde de toevoer van nutriënten uit overstromingswater en de levering van nutriënten uit de bodem aan de vegetatie tussen de gebieden, tussen de vegetatietypen en ook tussen de nutriënten N en P. Stikstoflevering uit de bodem was de belangrijkste bron voor de zeggevegetatie en de moerasbos-vegetatie in de Narew. In de Songkhram was de bodem eveneens de belangrijkste N-bron voor de bamboe vegetatie (ruwweg 70%), terwijl dit voor de grasachtige vegetatie slechts 35% was. Nog duidelijker waren de verschillen in het fosforbudget. In de Narew was overstromingswater de belangrijkste bron van P voor de zeggegemeenschap en belangrijker dan de aanvoer vanuit de bodem, in tegenstelling tot N. In de Songkhram daarentegen was de bodem de belangrijkste bron van P voor zowel de bamboe als de grasachtige vegetatie (ruwweg 70-80%). Er zijn dus overeenkomsten en verschillen in overstromingskarakteristieken en nutriëntenbudget, en dus in het ecologisch functioneren van de overstromingsvlaktes van deze rivieren in gematigd en tropisch klimaat.

In plannen voor behoud, beheer en herstel van overstromingsvlaktes moet dus rekening worden gehouden met het afvoerregime van de rivier, de nutriëntenbelasting van de rivier en het overstromingswater en locatie-specifieke omstandigheden, zoals de morfologie van de riviervlakte, de geologie en hydrologie van het aangrenzende landschap en het stroomgebied, de vegetatiezonering in de overstromingsvlakte en de interactie tussen deze factoren. Om specifieke aanbevelingen te kunnen doen voor het beheer van rivieren en hun overstromingsvlaktes wordt derhalve aanbevolen om per gebied empirische studies uit te voeren vergelijkbaar met de ecohydrologische studies in dit proefschrift. Voldoende aandacht voor de interactie tussen de rivier, de grondwaterhydrologie en de vegetatie is daarbij essentieel. De hoog-dynamische situatie in overstromingsvlaktes en de hydrogeochemische interacties maken dit soort onderzoek zeer arbeidsintensief. Vergelijkende analyses op basis van dergelijke studies zal het op termijn ook mogelijk maken om de verschillende rivierconcepten door te ontwikkelen tot een integrerende visie op het functioneren van rivieren met hun overstromingsvlaktes in verschillende klimaatzones.

บทสรุปภาษาไทย

กลไกการทำงานทางนิเวศอุทกวิทยา ของที่ราบลุ่มแม่น้ำ-น้ำท่วมถึง ในภูมิอากาศมรสุมเขตร้อน และภูมิอากาศเขตอบอุ่น

ระบบนิเวศที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงเป็นระบบนิเวศที่มีความอุดมสมบูรณ์สูงเมื่อเทียบกับระบบนิเวศบนบก หรือระบบนิเวศน้ำทั่วไป พื้นที่ที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงส่วนมากในประเทศที่พัฒนาแล้ว เช่นในยุโรป และอเมริกาเหนือ ได้ถูกแปลงสภาพจากเดิมไปแล้วโดยกิจกรรมของมนุษย์ และในเอเชียตะวันออกเฉียงใต้ก็เช่นเดียวกัน ที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงตามธรรมชาติที่เหลืออยู่กำลังสูญหายไปอย่างรวดเร็ว เพื่อที่จะรักษาระบบนิเวศที่มีคุณค่านี้ มาตรการอนุรักษ์เป็นสิ่งจำเป็นสำหรับการป้องกันไม่ให้มีการสูญเสียเพิ่มเติม และลดการสูญเสียนิเวศบริการที่มีค่าสำหรับมนุษย์ไป มาตรการอนุรักษ์ที่มีประสิทธิภาพจำเป็นต้องมีข้อมูลเชิงลึกเกี่ยวกับการทำงานของระบบนิเวศในที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงเหล่านี้ สำหรับระบบนิเวศที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงที่ตั้งอยู่เขตภูมิอากาศอบอุ่นนั้น องค์ความรู้เกี่ยวกับกลไกการทำงานของระบบนิเวศนั้นมีการศึกษาและเป็นที่เข้าใจกันอย่างกว้างขวาง สวนทางกับการศึกษาที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงที่อยู่ในเขตภูมิอากาศแบบร้อนชื้นโดยเฉพาะอย่างยิ่งในเขตมรสุมของเอเชียตะวันออกเฉียงใต้ที่พบว่ามีงานศึกษาที่น้อยกว่า นอกจากนี้ที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงแต่ละแห่งยังแสดงลักษณะและกระบวนการทางนิเวศวิทยาที่แตกต่างกัน ดังนั้นองค์ความรู้เกี่ยวกับแม่น้ำและระบบนิเวศที่ราบน้ำท่วมถึงในเขตร้อนจึงจำเป็นต้องได้รับการพัฒนาเพิ่มเติมเพื่อสนับสนุนการดำเนินการอนุรักษ์ที่มีประสิทธิภาพ

วิทยานิพนธ์นี้มีวัตถุประสงค์เพื่อพัฒนา เพิ่มเติมองค์ความรู้เกี่ยวกับระบบนิเวศที่ราบลุ่มแม่น้ำและที่ราบน้ำท่วมถึงในเขตร้อน และเปรียบเทียบกับระบบนิเวศแบบเดียวกันนี้ในเขตอบอุ่น ซึ่งจะเป็นการสนับสนุนการออกแบบวางแผนกลยุทธ์สำหรับการจัดการและการดำเนินการอนุรักษ์ให้มีประสิทธิภาพ เนื่องจากการทำงานทางนิเวศวิทยาของที่ราบลุ่มแม่น้ำ-ที่ราบน้ำท่วมถึงในเขตภูมิอากาศที่แตกต่างกันอาจเหมือนหรือแตกต่างกัน กลยุทธ์การจัดการและการอนุรักษ์ที่มีประสิทธิภาพจะต้องเข้าใจกระบวนการทางชีวธรณีเคมีของที่ราบน้ำท่วมถึงซึ่งเป็นส่วนสำคัญของระบบแม่น้ำทั้งหมด

วิทยานิพนธ์นี้มีองค์ประกอบหลัก 6 บทดังต่อไปนี้ บทที่ 1 ในบทที่ 2 ได้นำเสนองานศึกษาบุกเบิกของพื้นที่ราบน้ำท่วมถึงในลุ่มแม่น้ำสงครามที่อยู่ในพื้นที่มรสุมเขตร้อน จากนั้นในบทที่ 3 ได้นำเสนอการวิเคราะห์การทำงานเชิงนิเวศวิทยาของที่ราบลุ่มแม่น้ำสงครามโดยละเอียดโดยใช้ข้อมูลสถานะธาตุอาหารในดิน น้ำ และพืชพรรณ โดยบทที่ 2 และบทที่ 3 รวมกัน ได้สร้างความเข้าใจเกี่ยวกับอุทกนิเวศวิทยาของที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงในเขตร้อน โดยมีพื้นฐานตัวอย่างมาจากที่ราบน้ำท่วมถึงของแม่น้ำในพื้นที่มรสุมเขตร้อนของประเทศไทย ในบทที่ 4 ได้นำเสนอการวิเคราะห์ทางอุทกนิเวศวิทยาของแม่น้ำ และที่ราบน้ำท่วมถึงของแม่น้ำนาเรฟ (River Narew) ในเขตอบอุ่น ประเทศโปแลนด์ เป็นตัวอย่างของการทำงานทางนิเวศวิทยาของที่ราบลุ่มแม่น้ำที่ค่อนข้างเก่าแก่ในเขตอบอุ่นของยุโรป จากนั้นในบทที่ 5 จะเปรียบเทียบการทำงานของระบบนิเวศของแม่น้ำ และที่ราบน้ำท่วมถึงแม่น้ำนาเรฟและที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงแม่น้ำสงคราม ในด้านอุทกวิทยา อุทกเคมี ปริมาณธาตุอาหาร และความสมดุลของธาตุอาหารของพืชในที่ราบลุ่มน้ำท่วมถึง

ในบทที่ 2 ได้นำเสนอการศึกษาเกี่ยวกับการทำงานด้านอุทกเคมี (hydrochemistry) ในพื้นที่ราบลุ่ม-น้ำท่วมถึงของแม่น้ำสงครามที่อยู่ในพื้นที่มรสุมเขตร้อนของประเทศไทย โดยการศึกษาเผยให้เห็นว่า ปริมาณวัสดุละลายน้ำ (Dissolved solid) และธาตุอาหารละลายน้ำ ในน้ำของแม่น้ำสงครามในช่วงน้ำท่วมนั้นมีความเข้มข้นไม่มากนัก และมีแนวโน้มที่ลดลงของความเข้มข้นจากต้นแม่น้ำถึงปลายน้ำและจากแม่น้ำถึงขอบที่ราบน้ำท่วมถึง รูปแบบแนวโน้มตามแนวยาวนั้นเกี่ยวข้องกับผลจากสภาพดินฟ้าอากาศ และลักษณะทางธรณีวิทยาของลุ่มแม่น้ำ และผลกระทบจากการเจือจางจากน้ำฝนจำนวนมากในช่วงฤดูมรสุม ส่วนรูปแบบแนวโน้มตามขวางของการลดลงของของแข็งที่ละลายน้ำและความเข้มข้นของสารอาหารจากแม่น้ำถึงขอบที่ราบน้ำท่วมถึงเกี่ยวข้องกับต้นไผ่ที่ขึ้นหนาแน่นริมขอบแม่น้ำ กอไผ่ทำหน้าที่เป็นตัวกรองและที่ขจัดของแข็งละลายน้ำ และดักจับตะกอนจากแม่น้ำก่อนที่จะกระจายลงสู่ที่ราบน้ำท่วมถึงต่อไป การศึกษานี้ชี้ให้เห็นว่าแม่น้ำเป็นแหล่งของธาตุอาหารสำหรับระบบนิเวศที่ราบลุ่มน้ำท่วมถึงและที่ราบน้ำท่วมถึงนี้เป็นแหล่งกักเก็บธาตุอาหารเหล่านั้น นับเป็นการศึกษาแรกที่รวบรวมข้อมูลทางวิทยาศาสตร์ และพบว่าที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงแม่น้ำสงครามทำหน้าที่เป็นแหล่งกักเก็บธาตุอาหารที่ละลายน้ำที่มากับน้ำหลากในช่วงน้ำท่วม

ในบทที่ 3 ข้าพเจ้าศึกษาเพิ่มเติมเกี่ยวกับการทำงานของระบบนิเวศ และพืชพรรณต่างๆ ของที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงของแม่น้ำสงคราม และผลการศึกษาแสดงให้เห็นว่าพืชพรรณในที่ราบน้ำท่วมถึงประกอบด้วยโซนของชุมชนพืชที่แตกต่างกัน โดยมีชุมชนของไผ่ที่ให้ผลผลิตสูงและอยู่ติดริมขอบของแม่น้ำและชุมชนพืชประเภทหญ้าที่อยู่ถัดมาด้านหลังแนวไผ่ กอไผ่ที่หนาแน่นและให้ผลผลิตสูงได้แสดงให้เห็นถึงความสามารถในการกรองตะกอนและสารอาหารที่ละลายในน้ำที่ท่วมมาจากแม่น้ำ ไผ่ที่กระจายอยู่ใกล้แม่น้ำ ซึ่งน้ำท่วมนานกว่าและลึกกว่า ได้รับสารอาหารสูงกว่าและแสดงถึงผลผลิตที่สูงขึ้น ในทางตรงกันข้าม พื้นที่หญ้าที่พบกระจายห่างจากแม่น้ำมากกว่า ระยะเวลาน้ำท่วมจะสั้นกว่าและระดับน้ำท่วมตื้นกว่า ได้รับสารอาหารน้อยกว่าและแสดงถึงผลผลิตที่ต่ำกว่า ชุมชนพืชในที่ราบน้ำท่วมถึงทั้งสองประเภทกักเก็บสารอาหาร (N และ P) ไว้ในมวลชีวภาพมากกว่าปริมาณที่พืชที่อาจได้รับจากการนำเข้ามาโดยน้ำหลากท่วมในแต่ละปี ในขณะที่พืชพรรณในพื้นที่น้ำท่วมได้รับสารอาหารจากแม่น้ำ การศึกษายังพบว่าที่ราบน้ำท่วมถึงนี้ เป็นแหล่งส่งออกของสารอินทรีย์คาร์บอนไปยังแม่น้ำในช่วงน้ำท่วม และทำหน้าที่เป็นแหล่งที่มาของคาร์บอนอินทรีย์สำหรับระบบนิเวศท้ายน้ำ การศึกษานี้ได้เพิ่มเติมคำอธิบายเกี่ยวกับการทำงานทางนิเวศวิทยาของที่ราบน้ำท่วมถึงของแม่น้ำสงครามที่อยู่ในพื้นที่มรสุมเขตร้อน

บทที่ 2 และ 3 รวมกันได้แสดงให้เห็นถึงการทำงานของระบบนิเวศของที่ราบลุ่มแม่น้ำ-น้ำท่วมถึง ของแม่น้ำสงครามและเป็นตัวอย่างของแม่น้ำมรสุมเขตร้อน ที่ราบน้ำท่วมถึงทำหน้าที่เป็นแหล่งซับเก็บตะกอนและวัสดุที่ละลายน้ำ และในทางกลับกัน จะผลิตสารอินทรีย์คาร์บอนและส่งออกไปยังแม่น้ำในช่วงน้ำท่วม พืชพรรณในที่ราบลุ่มน้ำท่วมถึงมีบทบาทสำคัญในการดักจับและกักเก็บสารอาหารในที่ราบน้ำท่วมถึงนี้

ในบทที่ 4 ข้าพเจ้าได้นำเสนอการบูรณาการของข้อมูลเกี่ยวกับอุทกวิทยา ธาตุอาหารในดิน เคมีของน้ำ และชุมชนพืชพรรณของที่ราบน้ำท่วมถึงที่ค่อนข้างไม่ถูกรบกวนของแม่น้ำนาเรฟ ประเทศโปแลนด์ซึ่งเป็นการแสดงตัวอย่างกลไกการทำงานทางนิเวศวิทยาของแม่น้ำและที่ราบน้ำท่วมถึงในเขตภูมิอากาศอบอุ่น การวิจัยพบว่าชุมชนพืชในที่ราบน้ำท่วมถึงมีลักษณะการเปลี่ยนแปลงไปตามแนวยาวของต้นน้ำถึงปลายน้ำ และตามแนวขวางจากริมแม่น้ำไปยังขอบของที่ราบน้ำท่วมถึง การเปลี่ยนแปลงการกระจายนี้เกี่ยวข้องกับลักษณะของน้ำท่วม ลักษณะทางกายภาพของพื้นที่ และธาตุอาหารในดินที่มีอยู่ การเติบโตของชุมชนพืชพรรณทั้งหมดถูกจำกัดโดยธาตุอาหารไนโตรเจน นอกจากนี้การศึกษายังแสดงให้เห็นการเปลี่ยนแปลงเชิงพื้นที่ของเคมีของน้ำในสถานที่ต่างๆ ภายในที่ราบน้ำท่วมถึง การเกิดขึ้นของการเปลี่ยนแปลงคุณภาพน้ำ การไล่ระดับการเปลี่ยนแปลงของสังคมพืช และสภาพแวดล้อมที่จำกัดของไนโตรเจนในที่ราบน้ำท่วมถึงแสดงให้เห็นถึงระบบนิเวศพื้นที่น้ำท่วมถึงที่ค่อนข้างไม่ถูกรบกวนเมื่อเทียบกับแม่น้ำอื่นๆ ในยุโรป ซึ่งมีน้ำในแม่น้ำที่เป็นมลพิษและส่งผลต่อเคมีของน้ำในที่ราบน้ำท่วมถึงและทำให้การรูปแบบการกระจายของพืชพรรณตามธรรมชาติหายไป การศึกษานี้ช่วยให้เราเข้าใจถึงการทำงานของที่ราบน้ำท่วมถึงในแม่น้ำเขตอบอุ่นที่ห่างไกลจากการถูกรบกวน และสามารถใช้เป็นข้อมูลอ้างอิงสำหรับการจัดการที่ราบน้ำท่วมถึงในอนาคตได้ นอกจากนี้การทำความเข้าใจเกี่ยวกับการทำงานทางนิเวศวิทยาของที่ราบลุ่มแม่น้ำนี้ช่วยให้สามารถเปรียบเทียบกับระบบนิเวศที่ราบน้ำท่วมถึงแม่น้ำมรสุมเขตร้อนที่ได้อธิบายไว้ในบทที่ 2 และ 3 เพื่อทำความเข้าใจความเหมือนและความแตกต่างของการทำงานทางนิเวศวิทยาของที่ราบลุ่มแม่น้ำที่ตั้งอยู่ในเขตภูมิอากาศที่แตกต่างกัน

ในบทที่ 5 ข้าพเจ้าได้ศึกษาเปรียบเทียบสถานะอุทกวิทยา อุทกเคมี และธาตุอาหาร (N และ P) ของพืชพรรณในระบบนิเวศที่ราบน้ำท่วมถึงของแม่น้ำนาเรฟในประเทศโปแลนด์ และแม่น้ำสงครามในประเทศไทย งานวิจัยนี้ให้ความเข้าใจเกี่ยวกับความเหมือนและความแตกต่างในการทำงานของระบบนิเวศของที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงทั้งสอง ซึ่งตั้งอยู่ในเขตภูมิอากาศที่แตกต่างกัน (เขตอบอุ่น และเขตมรสุมเขตร้อน) แม่น้ำทั้งสองแสดงลักษณะของชีพจรน้ำท่วม (Flood Pulse) หลังจากหิมะละลายในแม่น้ำนาเรฟหรือหลังฝนมรสุมในแม่น้ำสงคราม โดยในแม่น้ำสงครามมีปริมาณน้ำท่าสูงสุดประมาณ 25 เท่าของปริมาณน้ำท่าของแม่น้ำนาเรฟในขณะที่ความเข้มข้นของธาตุอาหารในน้ำของแม่น้ำนาเรฟ จะค่อนข้างสูงกว่าน้ำในแม่น้ำส่งคราม น้ำที่หลากท่วมที่ราบน้ำท่วมถึงเป็นแหล่งภายนอกของธาตุอาหารสำหรับพืชพรรณในที่ราบน้ำท่วมถึงทั้งในเขตอบอุ่นและเขตมรสุมเขตร้อน โดยดินมีบทบาทสำคัญที่สุดในการเป็นแหล่งธาตุอาหารสำหรับพืชพรรณในที่ราบน้ำท่วมถึง นอกจากนี้พืชพรรณยังได้รับประโยชน์จากธาตุอาหาร (N, P) ที่มากับกระแสน้ำหลากท่วมและทำหน้าที่เป็นแหล่งกักเก็บธาตุอาหาร (N, P) เหล่านี้ ในขณะเดียวกันความสามารถในการดูดซับธาตุอาหารของพืชนั้น แตกต่างกันไปตามพื้นที่ของที่ราบน้ำท่วมถึงและชนิดของสังคมพืชพรรณ การค้นพบนี้ช่วยให้เราเข้าใจว่าแม่น้ำและที่ราบน้ำท่วมถึง ซึ่งค่อนข้างไม่ถูกรบกวนในเขตอบอุ่น และมรสุมเขตเขตร้อน มีความคล้ายคลึงและแตกต่างกันในแง่ของการทำงานของระบบนิเวศอย่างไร

วิทยานิพนธ์นี้ก่อให้เกิดความรู้พื้นฐานเกี่ยวกับการทำงานทางนิเวศวิทยาของที่ราบลุ่มแม่น้ำ-น้ำท่วมถึงในเขตอบอุ่น และเขตมรสุมเขตร้อน พื้นที่ราบลุ่มแม่น้ำ-ทุ่งน้ำท่วมถึงของแม่น้ำที่อยู่ในพื้นที่ลุ่มต่ำอย่างแม่น้ำนาเรฟ และแม่น้ำสงคราม มีลักษณะสำคัญคือการเป็นระบบที่มีการเชื่อมต่อระหว่างแม่น้ำและที่ราบน้ำท่วมถึง แม้จะตั้งอยู่ในภูมิอากาศที่แตกต่างกัน ระบบการไหลของแม่น้ำแสดงรูปแบบชีพจรของน้ำท่วมตามฤดูกาลซึ่งเป็นกลไกสำคัญในการขนส่งธาตุอาหารและตะกอนไปยังที่ราบน้ำท่วมถึงและกำหนดการทำงานของระบบนิเวศที่ราบน้ำท่วมถึง รูปแบบการไหลของน้ำในที่ราบน้ำท่วมถึงมีความสำคัญต่อการกำหนดรูปแบบการกระจายบองสังคมพืชพรรณในที่ราบน้ำท่วมถึง วิทยานิพนธ์ฉบับนี้ได้แสดงให้เห็นแล้วว่ารูปแบบเชิงพื้นที่ของพืชพรรณในที่ราบลุ่มแม่น้ำนาเรฟ และแม่น้ำสงครามนั้นพัฒนาขึ้นตามลักษณะของน้ำท่วม (ระยะเวลา ความลึก และความถี่) พืชในที่ราบน้ำท่วมถึงนี้ใช้ธาตุอาหารจากดินที่ได้รับมาจากน้ำที่ท่วม โดยที่สารอาหารที่ละลายน้ำ (N และ P) ถูกดึงออกจากน้ำที่หลากเข้ามาท่วม นอกจากนี้ โครงสร้างทางกายภาพของพืชในที่ราบน้ำท่วมถึงยังลดความเร็วการไหลของน้ำและเพิ่มการตกตะกอน ซึ่งนำไปสู่การดักจับอนุภาคของธาตุอาหารของพืชพรรณแต่ละสังคม และใช้สารอาหารในตะกอนเหล่านี้และเก็บไว้ในมวลชีวภาพ กลไกการดูดซับธาตุอาหารของดินที่มาจากน้ำหลากหรือสารอาหารจากตะกอนที่น้ำหลากพัดพามาทำให้ที่ราบน้ำท่วมถึงสามารถทำหน้าที่เป็นแหล่งกักเก็บธาตุอาหารได้ ซึ่งแตกต่างกันไปตามเขตพืชพรรณทั่วที่ราบลุ่มแม่น้ำแต่ละสาย แผนการอนุรักษ์ การจัดการ และการฟื้นฟูของที่ราบน้ำท่วมถึงควรพิจารณาว่าชนิดของพืชมีปฏิสัมพันธ์อย่างไรกับกระบวนการทางอุทกวิทยาและหน้าที่ทางนิเวศของพวกมัน (เป็นแหล่งนำเข้าสะสมหรือแหล่งผลิตและส่งออกธาตุอาหาร)

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For me, doing a Ph.D. may be analogous to exploring a path in a jungle and climbing a mountain, looking for something that you are unsure of it existing. At the start, everything looked fine, but the finish was ambiguous. Once you walk into the jungle and try to find the right path, then everything looks hazy too. But, suddenly, you hear your fellows calling you from the top of a clip, and you have no idea how to get to the top. After struggling and toil, you are now standing at the top of your mountain clip. I think no words could fully describe the feeling once you have reached the top, looking back on the path while discovering the other side of the mountain.

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Tanapipat Walalite (Joon)
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About the author

Tanapipat Walalite was born on 29 August 1980 in Maha Sarakham province in northeast Thailand. He spent his childhood in his hometown, near the River Chi, before attending a high school (Kaennakhon Wittayalai) in Khonkhaen province. Tanapipat received his bachelor's degree in biology from Mahidol University in Bangkok in 2002. While attending the biology program at Mahidol University, he spent most of his attention on ecology and conservation. His bachelor's research project was about the effect of domestic buffalos and cattle on the wildlife community in a Karen village, Baan Meung Pam, Maehongson province, in the north of Thailand. After graduation, he worked as a researcher for Thailand's Biodiversity Research and Training Program (BRT) and spent his time on study small mammals in a limestone mountain of Kanchanaburi province in the west of Thailand. In 2007, he won a competition for a scholarship from the Ministry of Science and Technology to study aboard. After preparation for study abroad, in 2009, he attended an MSc program in Geo-information and Earth observation Science for Natural resource management at the department of ITC, University of Twente, Enschede, Netherlands. To complete his master's thesis, he went to a remote area in Borneo, Indonesia, for his fieldwork. His master's degree thesis is about assessing foliar nitrogen in a mangrove forest using hyperspectral remote sensing. He received his MSc degree in 2011. After his graduation, he returned to his hometown and became interested in river floodplains as his hometown is situated in a floodplain area and is subjected to flooding frequently. Tanapipat came back to the Netherlands and started his Ph.D. Research at the Copernicus Institute of Sustainable Development, Utrecht University, in 2013. At Utrecht, he has developed his research skill on a topic related to river floodplains.