

## **Modelling nutrient retention in floodplains**

Development of a concept to empirically derive the average inundated floodplain extent and incoming nutrient loads

DISSERTATION

zur Erlangung des akademischen Grades

Dr. rer. nat

im Fach

Geographie

eingereicht an der

Mathematisch-Naturwissenschaftlichen Fakultät II

der Humboldt-Universität zu Berlin

von

**Dipl. Geoökol. Stephanie Natho**

Präsident der Humboldt-Universität zu Berlin

Prof. Dr. Jan-Hendrik Olbertz

Dekan der Mathematisch-Naturwissenschaftlichen Fakultät II

Prof. Dr. Elmar Kulke

Gutachter:

1. Prof. Dr. Gunnar Nützmann

2. Prof. Dr. Mathias Zessner

3. Prof. Dr. Dagmar Haase

Tag der Verteidigung: 17.10.2013



*I dedicate this work  
to Torsten, my parents and the Elbe*



## Abstract

Although there are detailed studies on nutrient retention in single wetlands and floodplains, the role of riparian floodplains for nutrient retention is not investigated very well on a landscape scale, since knowledge on the most important parameters for nutrient retention, inundated floodplains and incoming load, is insufficient. Additionally, a method for describing these parameters as discharge dependent variables is missing. Therefore, the present work analyzes the flooding frequencies on floodplains of three study rivers, Elbe, Main and Rhine. The relation of inundated floodplain extent and current discharge conditions based on detailed results of the established Software FLYS is deduced empirically. Based on these subsequently generalized results, methods and concepts are improved iteratively to calculate average and finally event related average inundated floodplain extent respectively, incoming nutrient loads by considering the effects of the yearly respectively monthly hydrologic conditions of each river system. Therefore, available data (land use, active floodplain extent, discharge, water quality, slope) is used and processed to create a discharge dependent database which in turn serves as input data for different empirical retention models.

The calculated nutrient retention in floodplains varies with hydrological connectivity of the floodplain to the surface waters as well as with the current hydrologic condition of the river system. For this reason the finally developed concept of event related nutrient retention is suggested as the most realistic in combination with hydro-exponential retention models. The Elbe floodplains are the most natural, and in years with high floods nutrient retention in the floodplains contributes up to 9% respectively 10% of the monthly transported load of TP and  $NO_3-N$ , which is significant.

The transfer of the results to a German-wide application is possible due the generalization of the methods carried out.

With the presented results the hydrology dependent role of floodplains for nutrient balances in river systems can be quantified on a landscape scale.



## German Abstract

Obwohl es sehr detaillierte Studien zur Nährstoffretention in einzelnen Auen und Feuchtgebieten gibt, ist die Bedeutung von Auen für die Nährstoffbilanz auf Landschaftsebene wenig untersucht. Dies liegt an dem geringen Wissensstand über die wichtigsten Parameter der Nährstoffretention, nämlich die überflutete Auenfläche sowie die in die Aue strömende Nährstofffracht. Zusätzlich gibt es bislang keinen Ansatz, demzufolge beide Parameter abhängig vom Abfluss, und damit variabel für verschiedene zeitliche Einheiten, berechnet werden können.

Aus diesem Grund analysiert diese Arbeit die Überflutungshäufigkeiten der Auen von drei Flüssen, Elbe, Main und Rhein. Darauf aufbauend wird eine Abhängigkeit zwischen der überfluteten Fläche (anteilig von der aktiven Aue) und dem Abfluss empirisch abgeleitet, die auf detaillierten Berechnungen der etablierten Software FLYS basieren. Ausgehend auf diesen im Folgenden generalisierten Ergebnissen werden Methoden und Konzepte iterativ verbessert, um eine mittlere bzw. letztendlich Ereignis basierte mittlere überflutete Auenfläche sowie einströmende Nährstofffracht zu berechnen, die den Einfluss der monatlichen bzw. jährlichen Hydrologie jedes Flusses berücksichtigen. Hierfür werden allgemein verfügbare Daten (Landnutzung, aktive Aue, Abfluss, Wassergüte und Neigung) neu kombiniert und als Eingangsdaten für verschiedene empirische Retentionsmodelle aufbereitet.

Die berechnete Nährstoffretention in den Auen ist abhängig von der hydrologischen Konnektivität der Auen sowie der aktuellen hydrologischen Situation. Deshalb wird letztendlich das weiterentwickelte Konzept der Ereignis bezogenen Nährstoffretention angewendet und als am realistischsten in Kombination mit hydro-exponentiellen Retentionsmodellen erachtet. Für die naturnahe Elbe werden damit in Monaten mit Hochwässern bis zu 9 % bzw. 10 % Retention der transportierten TP bzw. der  $NO_3-N$  Fracht berechnet.

Die Übertragbarkeit dieser Ergebnisse auf eine deutschlandweite Kulisse ist durch die generalisierten Methoden geschaffen.

Die vorliegende Arbeit leistet damit einen Beitrag, die Bedeutung der Auen für die Nährstoffbilanz auf Landschaftsebene abhängig von hydrologischen Gegebenheiten zu quantifizieren.



# Contents

<b>Abstract</b>	<b>i</b>
<b>German Abstract</b>	<b>iii</b>
<b>Foreword</b>	<b>1</b>
<b>1 Introduction &amp; Motivation</b>	<b>2</b>
1.1 Legal framework . . . . .	2
1.2 Estimation of nutrient loads and introduction of new measures .	2
1.3 Wetlands and floodplains . . . . .	3
1.4 Definition of the main processes . . . . .	5
1.5 Modelling of nutrient retention . . . . .	6
1.6 Information on floodplain areas . . . . .	9
1.7 Role of floodplain soils . . . . .	12
1.8 Effect of reconnected wetlands and floodplains . . . . .	13
1.9 Summary & Motivation . . . . .	14
<b>2 Aims &amp; Concept</b>	<b>17</b>
<b>3 Outline</b>	<b>22</b>
<b>4 Active versus potential floodplains – small floods and their effect as a key to calculate nutrient retention on a landscape scale</b>	<b>25</b>
<b>5 Nutrient retention in riparian floodplains on landscape scale, the necessity for a monthly retention approach</b>	<b>43</b>
<b>6 Modelling spatial and temporal dynamics in floodplains: extent, nutrient loads and retention</b>	<b>55</b>
<b>7 Modelling nitrogen retention in differently degraded floodplains of three large rivers in Germany</b>	<b>62</b>
<b>8 Modelling event related nutrient retention in natural floodplains, examples of three large rivers in Germany</b>	<b>80</b>

<b>9 Discussion</b>	<b>101</b>
9.1 Discussion of Methods and Concepts . . . . .	101
9.1.1 Wetlands and inundated floodplains . . . . .	101
9.1.2 Temporal resolution . . . . .	102
9.1.3 Calculation of the average inundated floodplain extent . . . . .	104
9.1.4 Calculation of the average incoming nutrient load . . . . .	105
9.1.5 Selection of retention models . . . . .	106
9.2 Discussion of Results . . . . .	107
9.2.1 Event related retention rates . . . . .	107
9.2.2 Effect of inundated floodplains on nutrient retention . . . . .	109
9.2.3 Consideration of disservices . . . . .	110
9.2.4 Uncertainties and possibilities for improvement . . . . .	111
9.2.5 Implications for future work . . . . .	113
<b>10 English Summary</b>	<b>115</b>
<b>11 German Summary</b>	<b>117</b>
<b>Bibliography</b>	<b>120</b>
<b>List of Figures</b>	<b>133</b>
<b>List of Tables</b>	<b>137</b>
<b>Nomenclature</b>	<b>139</b>
<b>Acknowledgment</b>	<b>141</b>
<b>Appendix Estimating the Size of German Riparian Wetlands on Landscape Scale</b>	<b>142</b>

## Foreword

Floodplains are fascinating ecosystems which form transition zones between terrestrial and aquatic ecosystems. The amount of nutrient loads in the river, being lower than the emissions into the system, can only be understood, if the role of inundated floodplains is considered for retention processes in the river system. In recent times the multi-criterial benefits provided by floodplains are acknowledged, of which nutrient removal is one, although information on floodplains of German rivers is insufficient. Floodplains have been investigated in several projects within the Leibniz-Institute of Freshwater Ecology and Inland Fisheries. Although the working group Nutrient Balance in River Systems develops a model to calculate nutrient emissions in river systems under consideration of retention processes in the river itself, the role of floodplains for nutrient retention has not been considered explicitly, yet. Due to my hydrological and ecological background I was interested to ascertain, whether inundated floodplains can contribute significantly to the reduction of nutrient loads on a landscape scale.

# 1 Introduction & Motivation

## 1.1 Legal framework

Eutrophication of rivers and seas is an international problem which needs a solution across national borders. Therefore, river basins have to be considered as a spatial unit without being limited by national borders. Two strategies can be found to identify solutions. Whereas, international cooperation as the Baltic Sea Action Plan aim at reducing emissions and loads, the European Union (EU) established the Water Framework Directive (WFD) to improve water quality to finally reach a good ecological status for all surface waters and groundwater in Europe. Nutrient loads and nutrient concentration in the rivers can be reduced, either by measures aimed to reduce nutrient inputs (emissions) or by measures aimed to increase retention. Nutrient retention on inundated floodplains is shifting into the focus of politicians and river basin managers, but still many uncertainties have to be faced when the concrete contribution of floodplains on nutrient retention in river systems is accounted for.

## 1.2 Estimation of nutrient loads and introduction of new measures

By implementing the WFD into national law, the monitoring station network was expanded along the rivers to measure nutrient concentrations among other parameters on a regular basis. Monitoring nutrient concentrations (especially nitrogen (N) and phosphorus (P)) is one method to evaluate water quality, since their concentration levels provide information on the trophic status. Nutrient loads, however, provide information on the contribution of a river to the nutrient balance of a system, which is, for example, to the eutrophication of a sea. But nutrient loads cannot be measured directly (Zweynert 2008). They are the product of concentration of a substance and discharge. Very often, the nutrient load is presented without discussing the way it has been obtained. There are different sampling strategies and calculation methods available to obtain yearly in-stream nutrient loads (Kronvang & Bruhn 1996, Zessner et al.

2008, Zweynert 2008), depending on the availability of data and the considered substance. For most stations continuous discharges are available but nutrient concentrations are sampled monthly or fortnightly, which might lead to under- or overestimation of nutrient loads when nutrient peaks are missed or sampled respectively. Zessner et al. (2008) compared continuous measurements with differently frequent samplings for nitrate ( $NO_3-N$ ) and total phosphorus ( $TP$ ) at the Danube, showing that the wide spread method according to OSPAR (2008), based on 24 nutrient samplings per year under consideration of daily discharges, leads to deviations of around 12 respectively 25 % of the reference load.

Uncertainties regarding the calculation of nutrient loads have to be considered when evaluating the nutrient retention in floodplains.

Whereas loads can be calculated from measurements of discharge and concentration, emissions from the catchment into the river can only be modelled. Therefore several nutrient emission models (for N and P) were developed since the 1990's to visualize the effect of catchment characteristics on the river. Some of them also model the effect of measurements to meet the goals of the WFD, namely reducing nutrient loads. Considerable effort was undertaken in carrying out different measurements in the catchments of the EU to reduce nutrient emissions into surface waters. After having improved the quantity and performance of WWTP (Behrendt et al. 2002), the main source of nitrogen emissions can be attributed to diffuse emissions. For nitrogen and also for phosphorus the potential of further reductions by technical solutions is cost intensive and the effects are limited. Instead, regarding cost effectiveness of measures, new options are highlighted by several authors (Constanza et al. 1997, Gren 1993, Meyerhoff & Dehnhardt 2007, Mitsch & Gosselink 2000) which is the naturally given function of wetlands and thus riparian floodplains acting as nutrient sinks when intact and connected to the river system. But floodplains with natural flooding regimes belong to the most threatened ecosystems in the world (Brunotte et al. 2009, Opperman et al. 2009) and the land-use form wetland, based on biotope types, is rare on floodplains (Brunotte et al. 2009).

### 1.3 Wetlands and floodplains

Wetlands are transition zones between aquatic and land ecosystems with an excessive supply of water, either driven by groundwater, by surface water,

by rainwater, or by a combination. Defining wetlands is complex (Mitsch & Gosselink 1993). There is no agreed on definition on wetlands neither worldwide nor in Europe (Maltby et al. 2009, Mitsch et al. 2009). Even if the WFD demands a prohibition of regression for aquatic ecosystems and connected wetlands (matter and hydrology), no definition of wetlands is provided within the Framework. Different definitions are found in Mitsch & Gosselink (1993), stating, that most definitions include three main components: presence of water, either at the surface or within the root zone, unique soil conditions and vegetation adapted to wet conditions. The definition given by the Ramsar Convention Secretariat (2006) is very broad and even includes rivers and lakes up to a depth of 6 m. Difficulties in providing an exact definition of wetlands derive from the fact, that wetlands aggregate a wide range of different ecosystems and habitats (Maltby et al. 2009) - including artificial wetlands. Country specific nomenclatures for wetland types exist. Europeans differentiate wetland types, whether the soil is peat forming or not (for an overview see Hofmeister (2006)). Peat results from water logging conditions in the soil, when organic compounds cannot be mineralized completely and accumulate. In contrast, this fact is not considered in the United States (Mitsch et al. 2009). Temporal and spatial dynamics are high, leading to changing conditions (e.g. changing water levels due to seasonal or sudden environmental settings). The differentiation between wetlands and riparian floodplains remains unclear because the dynamics of water levels (surface flow and groundwater) are also high in floodplains, allowing different biotopes to coexist on a floodplain. Riparian floodplains or floodplains can be defined as "the surface or strip of relatively smooth land adjacent to a river channel, constructed by the present river in its existing regime and covered with water when the river overflows its banks" (Hamilton 2009). Others differentiate between the morphologic (historic) and the active floodplain, whereby the active or recent floodplain is defined as the floodplain extent which is at least inundated once in hundred years (Brunotte et al. 2009).

<p>This study assumes inundated floodplains to act as a "wetland". Hereby, the wetland is characterized by its hydric soil properties regardless of organic or anorganic soil content. The river itself is excluded from the inundated floodplain.</p>
--

## 1.4 Definition of the main processes

Knowledge on the nutrient retention function of wetlands has a long history and is established especially in the U.S. where surface flow treatment wetlands are installed to treat waste water (Kadlec & Wallace 2008, Kadlec et al. 2010, Spieles & Mitsch 2000). Of course, these wetlands are constructed; idealized wetlands and the comparison of obtained retention rates with rates from natural wetlands is limited. Nevertheless, denitrification and sedimentation are known to be the main driving processes for N- (as nitrate nitrogen ( $NO_3 - N$ )) and P-removal on a yearly basis for natural and constructed wetlands (Byström 1998, Spieles & Mitsch 2000). Denitrification is known to be the most important nitrogen removal process, especially where nitrate makes up the main compound transported in river water (which can be found in German rivers (Deutsch et al. 2006)).

When quantifying the contribution of N- retention in floodplains denitrification is considered as the main retention process.

During this process nitrate is reduced via a four-step mechanism to firstly nitrite, secondly nitrogen monoxide, thirdly nitrous oxide and finally to inert nitrogen (Groffman et al. 2009a, Trepel & Palmeri 2002, Verhoeven et al. 2006). Thereby, nitrogen is not only transformed into a gaseous compound, namely dinitrogen, but also removed from the observed system and transferred into the earth's dominant gas in atmosphere (Boyer et al. 2006). Incomplete denitrification is also reported and can lead to nitrous oxide emissions (Hefting et al. 2006), which are known to contribute to global warming. However, denitrification occurs under anoxic conditions and nitrogen supply, bacteria community, carbon availability and water temperature influence the denitrification rate (Boyer et al. 2006, Pinay et al. 2007). The lack of oxygen can be found when floodplains are inundated and water fills the pore space of the soil. Suggested thresholds for optimal denitrification conditions from models lie around 90 % saturation of the pore space in the soil (Marchetti et al. 1997 in Boyer et al. 2006). Nitrate as an oxidant is supplied by periods of inundation, as well as by the changing environment from anoxic to oxic conditions and following oxidation from ammonia to nitrate (coupling of nitrification and denitrification (Spieles & Mitsch 2000)). Bacteria respire oxidized nitrogen in the form of nitrate as oxidant to gain energy from organic compounds. These organic compounds are typical of wetlands when biomass is not mineralized

completely due to the lack of oxygen. Higher water temperature accelerates kinetics and increases denitrification rates (Kadlec et al. 2010, Pinay et al. 2007). Sedimentation plays a minor role for N-retention (Noe & Hupp 2009). But sedimentation is the main removal process for P since most P is transported as particulate P (Olde Venterink et al. 2002, SedNet 2005) adsorbed to mineral soil particles (Noe & Hupp 2005), especially to loam and clay (Kronvang et al. 2007). Depending on the hydrological dynamics, namely flow velocity, sedimentation can be a temporal retention since sedimented particles can repeatedly underlay re-mobilization. Under flooding conditions flow velocity is high in the river, leading to erosion of sandbanks and increasing sediment load. Additionally, erosion in the catchment becomes the dominant emission pathway, increasing the particular P load in the river. However, as different restoration projects have shown: if inundation occurs, flow velocities decrease (Olde Venterink et al. 2002) in the floodplain and sedimentation can be a very effective longterm removal (Kronvang et al. 2007, van der Lee et al. 2004). Low flow velocities leading to sedimentation in the floodplain depend on the hydraulic roughness which in turn results from the roughness of the vegetation. The roughness of the vegetation varies with the biotope type (Olde Venterink et al. 2002, Schneider 2010, van der Lee et al. 2004).

When quantifying the contribution of P-retention in floodplains sedimentation is considered as the main retention process.

## 1.5 Modelling of nutrient retention

The main mechanisms of denitrification and their factors are generally understood and described by many authors (e.g. Boyer et al. 2006, Groffman et al. 2006, 2009a) but the combination of the four most important settings, waterlogging, nitrogen supply, bacteria community and energy source (Boyer et al. 2006) vary with time and space, depending on environmental settings and hence makes the modelling and measurement of denitrification a complex task (Boyer et al. 2006, Groffman et al. 2006). Indirect measurements of denitrification can only be carried out and results from mesocosms and study wetlands have to be upscaled to basins (Groffman et al. 2009a). Since denitrification is a biogeochemical process, in which microorganisms are involved, measurements do not measure denitrification, but results from denitrification processes (see Groffman et al. (2006) for an overview of denitrification mea-

surements). Consequently retention models do not account for denitrification itself, but environmental settings, which affect the process of denitrification. There are various more or less complex deterministic and empirical retention models for aquatic and terrestrial ecosystems available (see Boyer et al. (2006) for an overview). Because of data availability this work focusses on yearly and monthly empirical retention models.

### **Modelling of nutrient retention in rivers**

To quantify the effect of floodplains on nutrient retention in a river system, the retention in the river has also to be known in comparison. There are several river retention models (Alexander et al. 2009, Behrendt & Opitz 2000, Boyer et al. 2006, Venohr 2006). Since the retention model developed by Behrendt & Opitz (2000) has been established for retention calculation in German rivers and modules for N- and P-retention calculations are both available (see below), it is applied in this work. Additionally, this approach is also applied for calculating nutrient retention in floodplains, which is presented in the next section. The riverine retention module for P depends on the hydraulic load (HL) as the main factor. HL as the reciprocal of the water residence time can be concluded from the water surfaces of rivers and lakes and the corresponding discharge respectively specific runoff (Behrendt & Opitz 2000, Venohr 2006). It represents the contact area between sediment and water (Behrendt & Opitz 2000) which is incorporated in many other retention models (Boyer et al. 2006, Groffman et al. 2009a). N-retention is modelled as the sum of sedimentation and denitrification since TN (total nitrogen) is considered in the model and with it dissolved inorganic nitrogen as the most important fraction of which nitrate forms the main compound. This approach was enhanced by Venohr (2006) to be modelled according to a Temperature and HL dependent approach (THL) on a yearly basis. Further extensions were carried out by Venohr et al. (2011), by adding global Radiation as the third input factor (THLR-approach) on a monthly basis to consider N-uptake and N-release by plants.

### **Modelling of nutrient retention in wetlands**

Three different approaches can be found in literature to quantify nutrient retention in wetlands and floodplains.

Firstly, nutrient retention can be described as a linear or exponential relationship, depending on either only nutrient load (Mander & Mauring 1994) or the combination of nutrient load and the wetland area (Byström 1998), and

additional parameters such as nutrient concentration (Arheimer & Wittgren 2002, Dortch & Gerald 1995), water temperature (Arheimer & Wittgren 2002) and/or residence time respectively hydraulic load (HL) (Dortch & Gerald 1995, Fisher & Acreman 2004). This approach is chosen when retention processes are described in concrete study wetlands where water surfaces are assumed to be constant over the studied period.

Secondly, based on the results of the first approach, retention proxies are combined with given constant floodplain extent to calculate nutrient retention on the catchment scale (Kronvang et al. 2004, Schulz-Zunkel et al. 2012). Thereby, a linear relationship is assumed between retention rate and wetland area. Schulz-Zunkel et al. (2012) considered the National Floodplain Inventory as a spatial basis for a first estimate of N- and P-retention in floodplains for German river systems only very recently. Here, floodplain characteristics (landuse, soil type) were applied to modify denitrification and sedimentation rates described in literature, which were then applied to upscale these values for landscape scale calculations. Kronvang et al. (2004) applied land-use characteristics of the catchment as an indicator for modifying denitrification, whereas one constant sedimentation rate is assumed.

Thirdly, retention can be considered as the difference of emissions from the catchment into the river and loads transported in the river. This connection was found by Behrendt (1996, 1999), Behrendt & Opitz (2000) who initially had developed a nutrient (N and P) emission inventory and found discrepancies between calculated nutrient emissions and measured nutrient loads in several European rivers. Based on these results Behrendt & Opitz (2000) derived an empirical retention model which has already been described in the section above because it defines retention as the sum of removal processes in the river system, including all water surfaces (lakes, rivers, wetlands, inundated floodplains). Thus, retention processes in the river and in the floodplain cannot be distinguished. Nevertheless, this retention model is also applied to calculate the role of floodplains for nutrient retention as a measure, when dyke relocation activities are carried out. Venohr et al. (2011) assume that the retention in inundated floodplains can be expressed by the same algorithm as for retention calculations in the river itself because retention processes are comparable. Here the crucial parameter water surface area for calculating the hydraulic load is assumed as a constant derived from land-use data or estimates. But the calculated effects of dyke relocation on nutrient retention have not been validated.

Since inundation of floodplains is temporally and spatially variable, the inundated floodplain extent as well as the incoming load have to be modelled as variables and not as constants which has not been done so far.

## 1.6 Information on floodplain areas

Knowledge on inundation extent and flooding frequencies of floodplains is low. Whereas, morphologic features such as natural terraces identify borders of the total floodplain, the actual inundation extent is as variable as the hydrology of the river. Only recently the active floodplain extent of 79 medium to large sized rivers was examined (Brunotte et al. 2009) by a first national floodplain inventory which was carried out under the leadership of BfN and BMBF by several scientific institutes (BMU & BfN 2009). The goal was to map the loss of floodplains for 79 German rivers with catchment sizes exceeding 1,000 km<sup>2</sup> as well as to quantify the loss of floodplain functions such as nutrient retention, carbon storage, and biodiversity among others (Scholz et al. 2012). By identifying the active floodplain, which can still be flooded at least by a statistical probability of once in 100 years, two floodplain types can be distinguished. The morphological floodplain represents the floodplain which had been formed originally by the river. It does not necessarily underlie the current hydrologic river regime. By comparing the extents of the morphologic and the active floodplain floodplain losses could be detected. Additionally the degree of connectivity was considered to classify river systems regarding their naturalness, relying on information on land use among other parameters (Brunotte et al. 2009). Today, natural floodplain forests are scarce (BMU & BfN 2009, Brunotte et al. 2009), since most floodplains are tile drained and under agricultural use. However, grasslands indicate higher flooding frequencies than arable land. Grassland is more frequent along floodplains of the Elbe than along floodplains of other rivers.

So far there is neither basin-wide information on the inundated floodplain extent nor on the incoming load as a yearly or monthly variable.

Thus, the National Floodplain Inventory (Brunotte et al. 2009) greatly contributed to the knowledge on the loss of floodplains and on the distribution of floodplains. Nevertheless, the mapped active floodplain does not represent the floodplain area relevant for nutrient retention for most of the time. Here,

the term relevant for nutrient retention has to be defined more precisely, since its relevance depends on time and space.

### **Hot spots and hot moments**

The contribution of floodplains to N- and P-retention by denitrification respectively sedimentation is highly dynamic because the driving factor inundation of the floodplain is highly variable in time and space. This variability of wetland and floodplains contributing to nutrient retention is described by many authors (Fisher & Acreman 2004, Hoffmann et al. 2011, Kieckbusch & Schautzer 2007). Cooper (1990) examined denitrification levels in riparian floodplains and described the phenomenon of small patches contributing more than half of the N-retention by denitrification although they only cover around 12 % of the floodplain soils. This phenomenon is also discussed by McClain et al. (2003) and Groffman et al. (2009a) as the hot spot hot moment concept. Hot spots show disproportionately high biogeochemical reaction rates relative to the surrounding matrix (McClain et al. 2003). On landscape scale the total riparian floodplain can be regarded as a hot spot (Groffman et al. 2009a). On a smaller scale, patches in floodplains can be distinguished in more and less reactive hot spots depending on environmental conditions e.g. the vicinity to nitrate input (McClain et al. 2003) or hydric soil conditions. McClain et al. (2003) introduced the temporal dimension of the hot spot concept by hot moments. Generally, when conditions in soil turn from unsaturated to saturated soils can become hot spots of denitrification if all conditions influencing denitrification are fulfilled. Under middle European climatic conditions these hot moments occur during typical late winter/spring floods, resulting in high denitrification rates in soils with lower rates during average conditions without inundation. Since temperature influences denitrification rates, higher denitrification rates can be found if water temperatures are higher (Pinay et al. 2007). In terms of the hot spot hot moment concept during a summer flood hot moments could overlay hot spots leading to even higher retention rates (McClain et al. 2003). Although sedimentation is a physical process, highest retention rates are also reported to occur in defined areas in the floodplain. Rupp et al. (2000) cited in Schulz-Zunkel et al. (2012) measured highest sedimentation rates in a 45m-wide buffer from the river. However, as stated above, due to dominant pluvial and nival flow regimes in Germany, the temporal consideration of hot spots, and thus hot moments is of great importance for calculating nutrient retention even on a landscape scale.

## Connectivity

Not only chemical, physical and biological parameters are considered as water quality criteria within the WFD but also the morphology plays an important role for a good ecological status. Morphology has changed dramatically in middle European rivers (BMU & BfN 2009, Brunotte et al. 2009, Cioc 2002, Kronvang et al. 2007, State Ministry of the Environment Baden-Württemberg 2007) because of a stringent flood control management as well as expansion of hydropower in the past. Whereas, in the last century rivers were still constructed as straight channels with disconnected and drained floodplains, river management now suggests more room for rivers and their restored floodplains (Opperman et al. 2009). Pressures on floodplains are more diverse than ever, though: human interests (agriculture, leisure, fishery, flood control etc.) collide, and also ecological interests (protection of endangered species and ecosystems, see Turner et al. (2003) for an overview) have to be considered. This is due to the fact that floodplains provide more ecosystem services than many other ecosystems (Constanza et al. 1997, Opperman et al. 2009), of which flood control is currently the most popular right now. However, the interest in floodplains as nutrient sinks is increasing (Dehnhardt & Bräuer 2008). It is known, that on landscape scale, riparian floodplains are hot spots of denitrification (Groffman et al. 2009a, McClain et al. 2003). Therefore, projects are planned and carried out, either to reconnect floodplains with the river hydrology to allow regular flooding by river water (Kronvang et al. 2007) or by rewetting former fens (Davidsson et al. 2002, Zak & Gelbrecht 2007). By dyke relocation the degree of connectivity is increased which in turn increases the flux of water and nutrients and thus the potential for nutrient retention (Mitsch & Gosselink 2000).

## Modelling the effect of small floods on floodplain inundation

The extent of inundated floodplains at floods which occur frequently during the year is not known, but floodplain restoration projects aim to relocate dykes to allow flooding to occur more often. Only recently, the Flood Risk Assessment Directive European Community (2007) has forced the countries to map floodplain extent which is in danger of being flooded until the end of 2013. Again this only accounts for floods with a statistical occurrence of once in 100 years. Ambitious Federal States also start to model inundation extents for more frequent floods. So far, this information is available only for some Federal Water Ways (Busch et al. 2009), for which the modelling was carried out with the

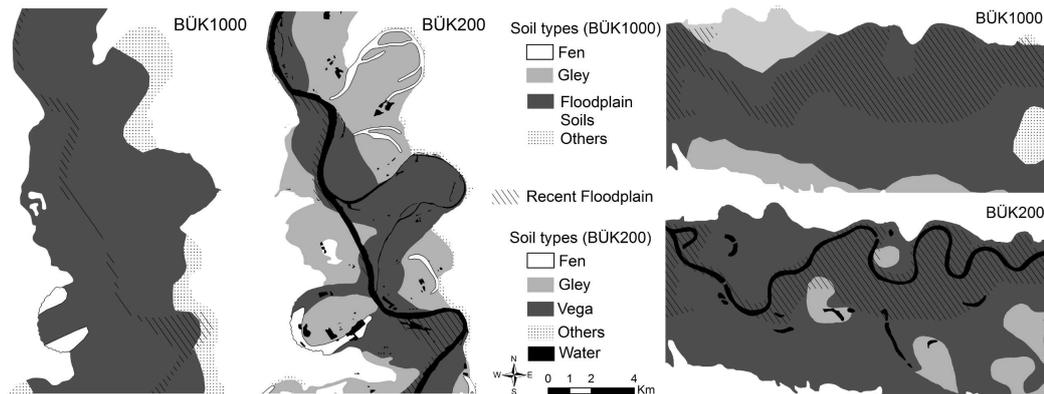
Software FLYS. The Federal Institute of Hydrology (BfG) has developed the River Hydrology Software FLYS 2.1.3 (in the following FLYS as a water level information and analysis tool for German Federal Waterways (Busch et al. 2009), for example Elbe, Rhine and Main. FLYS processes model results (1D) as well as basic (e.g. digital terrain maps (DTM)) and special (e.g. river channel line) geographic data. Inundated areas are calculated based on geometrical calculations. For details on validation, description on the methodology and uncertainties see Meißner and Kiel in BfG (2009). The active floodplain area is a central input data, representing maximum borders of the inundated area.

By applying the Software FLYS the effect of smaller floods on inundated floodplain extent can be quantified. The results can be a source for a general approach to consider variable inundated floodplain extent in empirical retention models

## 1.7 Role of floodplain soils

Hydrologic conditions of floodplains influence soil texture and subsequently the development of soil types on the floodplain (Bechthold 2007). Fluvial sorting during inundation is the crucial process and leads to predictable patterns showing the size distribution of sediments which are also reflected by successional stages of the vegetation and biotopes (Bechthold 2007, Scholz et al. 2012) because soil texture influences organic matter content, nutrient and moisture relations (Bechthold 2007). Hydric soils especially with high organic carbon contents are denitrification hot spots (Cooper 1990).

Because detailed information on landscape scale is scarce, only few approaches consider soil characteristics for modelling nutrient retention on landscape scale (Schulz-Zunkel et al. 2012). Information on soil characteristics are available digitally for Germany, but a German wide dataset is available with the scale 1:1.000.000 only (Bodenübersichtskarte (BÜK) 1000 (topographical map)). Here of course, detailed features such as carbon content cannot be provided in detail. Information on hydrologic characteristics of the soils is general. Consequently, soils in riparian areas are represented by Floodplain Soils or Gley or Fens (Figure 1.1). Finer soil maps, such as the BÜK 200 (German soil maps with the spatial resolution 1:200.000, BÜK 200) are still not available nationwide, but provide more detailed information on different floodplain soils. Additionally, soil maps provide only limited information on the current



**Figure 1.1:** Soil types according to differently detailed soil maps (BÜK 1000 and the BÜK 200) along floodplains of river stretches of the Rhine (left) and Elbe (right). The morphologic and the recent floodplains are also shown. Datasource: BÜK200, ©BGR, Berlin, 2011; floodplains, ©BfN, Bonn.

hydrologic situation and information on soil texture is aggregated so that detailed analysis are not possible. The distribution of hot moments in riparian floodplains can neither be reflected by large scale soil maps as the BÜK 200 and the BÜK 1000, since recent and morphologic floodplain do not differ regarding their soil types (Figure 1.1). Consequently, the implementation of soil characteristics as a parameter for evaluating retention on landscape scale can only be additive to land-use and digital elevation data.

## 1.8 Effect of reconnected wetlands and floodplains

Floodplains can be reconnected by dyke relocations including the permanent removal respectively relocation of dykes or the lowering of dyke sections. German examples of recent dyke relocations at large rivers are Bürgerweide in the vicinity of Worms and Kirschgartshausen in the vicinity of Mannheim, both located at the river Rhine, Lödderitzer Forst and Oberluch in the middle stretch and Lenzen located in the upper middle stretch of the river Elbe. Background information and results are published in regional papers but mostly not reviewed (IKSR 2006, Jährling 2009). So far, there is little knowledge on their effect on nutrient retention since monitoring programs, if initiated at all, have just started and inundation occurs not permanently but only occasionally. This in turn makes it more complicated to validate model results. The Integrated Rhine Programme (IRP) combines dyke relocations and the installation of polders to reduce flood peaks (State Ministry of the Environment Baden-Württemberg 2007), their effect on nutrient retention is not investigated. Normally these polders are intensively used by agriculture and forestry,

but in case of very high floods (statistically expected to occur once in 10 years) a delayed throughflow through these polders is managed to occur which reduces effectively the flood peak.

The effect of dyke relocations on the nutrient balance of river systems can also be negative, since agricultural use leads to a change of site characteristics of floodplains (Aldous et al. 2005). The application of fertilizer can be a source of nutrients and agriculturally used land in floodplains is drained, which changes hydrology and nutrient availability (see above) and hence conditions for denitrification (Groffman et al. 2009a). Despite these constraints, even drier and agriculturally used former floodplains are found to contribute to high denitrification rates, when organic material accumulates during dry periods, provides labile organic carbon for denitrification during inundation (Boyer et al. 2006). Altogether wetlands are reported to act as net nutrient sinks. However, in recent years, outcomes of studies dealing with rewetting have shown, that decomposed organic soils act as nutrient sources, especially for phosphorus, but also for ammonia and organic carbon (Aldous et al. 2007, Cabezas et al. 2012, Song et al. 2007, Zak et al. 2004). The degree of decomposition affects the extent of nutrient release (Zak & Gelbrecht 2007) and nutrient release can be only temporary (Aldous et al. 2007). Other studies have shown that rewetted peatlands show increased denitrification rates after flooding due to coupled processes of nitrification and denitrification (Davidsson et al. 2002). Consequently, the decomposition degree of peat should be analysed before rewetting takes place (Cabezas et al. 2012), to prevent disservices to occur.

## 1.9 Summary & Motivation

Summarizing the state of knowledge so far, riparian floodplains are now in the focus of politicians and river basin managers. Although pressure of floodplains to be used in different ways is even more diverse than in the past (Dehnhardt & Bräuer 2008), benefits provided by floodplains are acknowledged. One ecosystem service is the function to remove nutrients, such as N and P by denitrification and sedimentation and consequently to be an appropriate measure to reduce eutrophication-driven problems in oceans. The main removal processes occurring in floodplains are identified and the most important parameters which support high removal rates are also known. Modelling these processes is complex and on a landscape scale, modelling is limited due to availability of input data, although the data base has improved in the last years (Groffman et al. 2009a). Considering the data availability the application of less demand-

ing empirical models is often the better or only option. Most models need information on water surface area (representing the extent of the inundated floodplain), discharge and nutrient concentrations or loads in the inundated floodplain, which prove to be highly dynamic and not available on landscape scale so far, although gauges and monitoring stations provide this information for rivers.

Consequently, as stated above, several uncertainties have to be faced, when the nutrient removal in floodplains is quantified on a landscape scale. In the following the most important aspects are summarized:

- When comparing the share of nutrient removal in floodplains with "measured" loads, it is important to consider uncertainties in calculated loads derived from sampling frequency and calculation methodology between 10 % and 25 % depending on the substance (Zessner et al. 2008).
- The term wetland is not defined precisely (Maltby et al. 2009, Mitsch et al. 2009) and since hydrology is dynamic, floodplains are described to inhabit wetlands or vice versa; retention processes are described generally for wetlands and not for total floodplains. Consequently, in this thesis it is assumed that floodplains act as wetlands, when they are inundated by river water. River retention is excluded from the floodplain retention.
- Although the most important parameters influencing denitrification and sedimentation are known, rates are measured for single spots and for a defined time only. But retention varies highly in space and time. Thus observed retention values for individual locations are often not representative for the entire or other floodplains (Cooper 1990). When comparing modelled areal retention rates with measured, these uncertainties have to be considered.
- There are three different concepts of empirical retention models described in literature. 1. relationships between measured retention and wetland characteristics (Dortch & Gerald 1995) and others, 2. retention proxies for the considered area (Gren et al. 1995, Kronvang et al. 2004, Schulz-Zunkel et al. 2012) and 3. calculating net retention as losses in the river system (Behrendt & Opitz 2000). Applying and comparing these models on a larger scale for frequently inundated floodplains has not been done so far.
- Although there is a first inventory of German floodplains (Brunotte et al. 2009), the actual extent of the inundated floodplain is unknown.

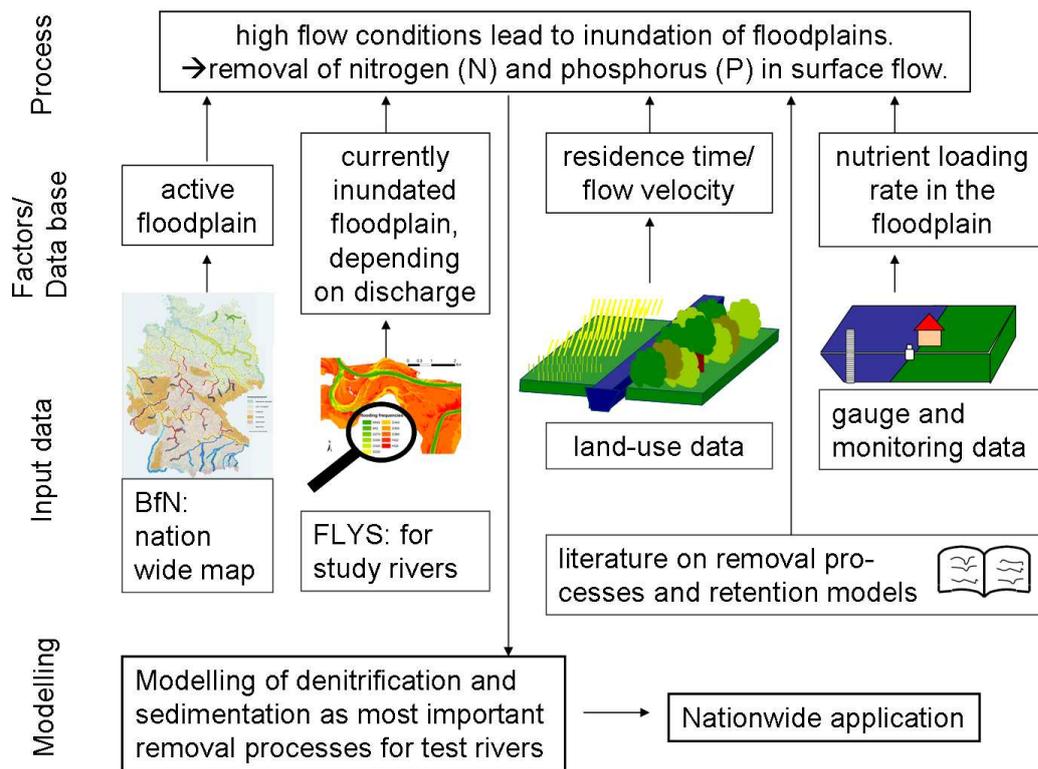
Despite or rather because of these fundamental uncertainties this present thesis deals with analysis and solutions of how to close knowledge gaps to quantify nutrient retention in riparian floodplains on a landscape scale, using empirical modelling.

## 2 Aims & Concept

The aim of this work is to quantify the effect of inundated floodplains on nutrient retention (N and P) by considering the main retention processes denitrification (for N) and sedimentation (for P). On the one hand, there is plenty of information on floodplains for German river basins on a landscape scale derived from several previous projects. On the other hand, there are different empirical retention models which describe retention processes. So far, a methodology to couple the existing data with the retention models is missing. *The main idea of this work is to develop a new concept and subsequent methodology which considers spatially and temporally variable inundated floodplain extents and incoming nutrient loads. Therefore data is derived from previous projects to create a database necessary for these retention models.*

1. The spatially and temporally highly variable quantification of nutrient retention in inundated floodplains is hypothesized to be properly modelled by empirical models.
2. The application of nutrient retention models necessitates the creation of a database, which provides information on flooding frequencies of riparian floodplains and incoming nutrient loads. It is hypothesized that with the combination of general information on the active floodplain extent and more specific model results of the software FLYS of study sites, a generalization of results is possible on a Germanwide application. Therefore three parameters within the floodplain are hypothesized to be sufficient to describe the role of floodplains for nutrient retention: land use, topography and soils.
3. It is hypothesized that floodplains play a major role for nutrient retention in comparison to rivers, which is assumed to be shown by the application of empirical models for rivers on the one hand and by the inundated floodplains on the other.

Finally a trade-off between model simplicity and input data complexity is accepted. Whereas uncertainties in simple empirical equations may derive from neglecting important factors, uncertainties in complex models can result from error propagation (Groffman et al. 2009a) or from inaccurate input data.



**Figure 2.1:** Concept of background information and input data

There are several different complex empirical models described in literature. Comparisons between linear, exponential and hydro-exponential models have been drawn for wetlands (Trepel & Palmeri 2002). But the effect of floodplains of large rivers such as the Elbe, Rhine and Main have not been examined with these models, yet. Furthermore floodplain area respectively wetland area have been considered constant so far. Consequently, a methodology has to be developed to derive this crucial input data before models can be applied (see also Figure 2.1). Therefore, the floodplain area, relevant for nutrient retention, is explored based on knowledge on the

- active floodplain area which is derived from the National Floodplain Inventory for selected (since the data is not freely available) floodplains
- inundation of the active floodplain of the three study rivers Elbe, Rhine and Main under respective hydrologic conditions. The actual inundation is determined in the present work by using the Software FLYS 2.1.3 (in the following FLYS). The three study rivers differ in respect to the discharge and the degree of naturalness of their floodplains.
- current discharges provided by gauges for the validation sections of the Software FLYS

The combination of this data (active floodplain extent, FLYS and gauges; see Figure 2.1) provides insights into the flooding frequency of the active floodplain. As presented in chapter 1, the National Floodplain Inventory maps the floodplain inundated statistically once in 100 years ( $HQ_{100}$ ). Hence, the total active floodplain is not inundated every year and hence not relevant for nutrient retention, when calculating retention on a yearly basis. The maximum extent of the inundated floodplain is covered sufficiently, but the information on the inundated area for smaller floods is not available. This is where the Software FLYS 2.1.3 comes in for Federal Waterways: Calculations are carried out for three rivers (Elbe, Rhine and Main), to explicitly explore the extent of smaller floods with the aim to determine the inundated area on different spatial scales (yearly, monthly, daily) which is relevant for nutrient retention. To apply nutrient retention models developed for wetlands processes occurring in inundated riparian floodplains are assumed to be similar to those processes occurring in wetlands.

The following assumptions are applied: Inundation of the particular floodplain part creates a contact zone between river water and surface. The roughness can be expressed by vegetation types (Schneider 2010) and influences flow velocities and thus sedimentation in the floodplain.

When water fills the pore spaces of floodplain soils during inundation denitrification occurs in saturated soils comparable to wetland soils. Hence, inundated floodplain extents can also be expressed as water surface area or wetland area, which allows the application of empirical models developed for nutrient retention in wetlands.

This variable, wetland area, is treated as constant in most empirical models, which calculate nutrient retention in surface flow wetlands on a yearly or monthly base. The aim of this work is to describe the wetland area as a spatial and temporal dependent variable, since hydrology changes over time. Therefore, a methodology has to be developed to approach the most precise yearly, respectively monthly average inundated floodplain area.

On the one hand, the locations of areas within the floodplains, which are inundated with defined statistical frequencies, are identified, on the other hand, areas with the same inundation frequency are aggregated independent of their location. In this way, characteristics of very frequently inundated areas can be determined (land use, topography, soils) as well as temporarily average inundated areas. Based on this methodology the incoming nutrient load (see Figure 2.1) is derived by means of

- monitoring data from gauges and water quality stations along the study rivers to calculate nutrient loads
- information on floodplain characteristics provided by FLYS, detailed land-use maps (1:25,000) and digital elevation maps

So far, most models carrying out nutrient retention calculation consider wetlands as single patches of hot spots in an inactive matrix, a surrounding being not relevant for nutrient retention. Within this work active riparian floodplains are regarded as a hotspot independent of land-use or biotope type. Instead, the extent depends on the current inundation and thus water surface area, driven by the river hydrology. Therefore, it has to be tested, whether a retention approach, which calculates retention based on the water surface area (and which was originally developed for calculating retention in the river on a landscape scale) is comparable with the wetland retention approaches reported in literature. Since this approach is already incorporated into the model MONERIS (Venohr et al. 2011) which calculates nutrient emissions and nutrient retention in river systems, results from this study provide information whether a transfer of this river retention approach to floodplain retention is possible and comparable to other wetland retention approaches. Comparisons between some approaches have already been performed between single wetlands (Trepel & Palmeri 2002) but not on a landscape scale for total riparian floodplain areas. Within the present study results of several approaches are compared and discussed.

Additionally, nutrient retention is calculated by the application of average retention rates for N and P respectively (as proxy values in  $kg \cdot ha^{-1} \cdot yr^{-1}$ ) on the active floodplain extent derived by Brunotte et al. (2009) and thus on a nationwide scale. But the active floodplain does not have necessarily to be relevant for nutrient retention on a yearly basis. Consequently, proxy values reported in literature resulting from certain hydrologic characteristics have to be transferred to the active floodplain carefully and are compared to the effect of calculating with average inundated floodplain areas. According to a literature research, analyzing landcover and wetland specific retention rates showed large variations and could not be attributed to certain wetland types.

To apply the approach nationwide, based on empirical models, information on land use, elevation and slope as well as soil is assumed to describe flooding frequencies. It is hypothesized that arable land within the floodplain indicates less frequent inundation than grassland, wetland or open areas. The relief and hence the slope defines the degree of connectivity of floodplains (BMU & BfN

2009). Soil maps tend to reflect historic and not necessarily current conditions, since anthropogen interventions have changed river channels. Nevertheless, riparian soils indicate morphologic floodplain extent. Information derived by the results of the Software FLYS are tested regarding the three parameters land use, slope and soil types. Results are then transfered for a first nationwide estimation of inundated floodplain area relevant for nutrient retention.

### 3 Outline

The main part of this thesis consists of five chapters, which represent five articles, previously published or submitted for publication. For better coherence and legibility, cross references have been adjusted and citation styles have been harmonised. The overall question all papers deal with, is the effect of nutrient retention in floodplains on a landscape scale. The main findings of paper 1 and 2 were presented during the Diffuse Pollution Conference held in Rotorua (New Zealand) in 2011. Results from paper 3 were presented during the Environmental Science and Technology Conference in Houston (U.S.) in 2012 and published in the corresponding proceedings. Paper 3 is a result of a cooperation with the Helmholtz Centre for Environmental Research (UFZ), comparing their approach to the approach presented in this work. Paper 5 presents the latest findings dealing with a new methodology for average floodplain calculations and has been submitted for publication. Additionally, in the appendix a poster is shown which was presented at the Planet under Pressure conference in London 2012.

- Paper 1 (chapter 4), *Active versus potential floodplains? small floods and their effect as a key to calculate nutrient retention on a landscape scale* is submitted for publication. It deals with the analysis of the flooding characteristics of potential floodplains along the rivers Elbe, Rhine and Main during the last 15 years. The extent of inundated floodplains was calculated using the Software FLYS for available discharges. By comparing the discharge frequency of the studied period to the long-term discharges the application of FLYS results are justified. The analysis allows the calculation of a yearly based mean inundated floodplain, since only a small part of the potential floodplain is relevant for nutrient retention. Based on this analysis, an empirical approach is developed to calculate the inundated floodplain extent depending on the morphology of the river section for each river. This approach is then coupled with a proxy based nutrient retention calculation for a first rough estimation of nutrient retention in inundated riparian floodplains. My contribution to this manuscript is 95 %, comprising the idea of this paper, the development of methods, carrying out analysis and the writing of the

manuscript. My contribution to the layout of manuscript, figures and tables is 100 %.

- Paper 2 (chapter 5), *Nutrient retention in riparian floodplains on landscape scale, the necessity for a monthly retention approach* is based on the results of the analysis and the developed approach presented in paper 1 to calculate a mean inundated floodplain. To calculate more reliable nutrient retention depending on the nutrient load transported in the river an approach is developed to apply differently complex empirical  $NO_3 - N$  retention models on a yearly basis for 1999 to 2002. The incoming load is calculated as a variable depending on the current discharge, the average floodplain extent and the average floodplain depth. The most complex model (hydro-exponential) led to the most realistic results, whereas especially the linear approach resulted in extremely high retention in humid years. The role of yearly based models for highly dynamic processes as flooding and retention is discussed and the application of a monthly retention approach is suggested. My contribution to this manuscript is 90 %, regarding the idea, the concept and the development of the methodology and the analysis. My contribution to writing and layouting is 95 %.
- Paper 3 (chapter 6), *Modelling spatial and temporal dynamics in floodplains: extent, nutrient loads and retention* describes the further development of the methodology based on paper 2, since the first approach resulted in very high incoming loads. In this more dynamic approach, the flow velocity is considered as a function derived from land use inducing roughness in the inundated floodplain in relation to the mean flow velocity in the river. Yearly and monthly retention models are applied for phosphorus and nitrogen to compare the effect of nutrient retention in the floodplains and in the rivers Rhine, Main and Elbe for the years 1997 to 2004. My contribution to the development of the methodology and to the analysis is 95 % and to the data processing 85 %. I contributed 100 % to the writing and layouting of the manuscript.
- Paper 4 (chapter 7), *Modelling nitrogen retention in differently degraded floodplains of three large rivers in Germany* applies the methodology developed in paper 3 for calculating the average incoming nutrient load to be applied as input data for two empirical retention models. The hydro-exponential approach examined in the previous studies and found

to lead to realistic results is compared to the hydro-exponential approach, originally developed to calculate riverine nitrogen retention as a module of the model MONERIS. The results are compared to a proxy based approach developed at the UFZ Leipzig, based on the active floodplain, for the three study rivers Rhine, Main and Elbe for a dry and a wet year respectively. The importance and the role of hot spots and hot moments within riparian floodplains is discussed. However, results of the model-based approach indicate that calculated retention rates are more in the upper end of reported values and up to three times higher than the applied proxy values. I contributed to about 65 % to the study concept, to the literature review and to the data analyses and processing as well as the discussion. My contribution to writing, layouting of the text and the tables and figures is about 85 %.

- Paper 5 (chapter 8), *Modelling event related nutrient retention in natural floodplains, examples of three large rivers in Germany* considers the issue of high retention rates, which were found in paper 4. First, an intensive literature study has been carried out, dealing with the possibilities and restrictions of how to transfer measured denitrification and sedimentation rates from point measurements to the landscape scale. New insights lead to a modification of the applied methodology to calculate the average inundated floodplain extent as well as the incoming nutrient load as event related variables. Phosphorus and nitrogen retention is then calculated by applying a hydro-exponential empirical retention approach. My contribution to the concept of the manuscript and methodology is 100 % and 95 % to the writing, analysing of data and development of graphics.
- In the appendix (Poster presentation with the title *Estimating the Size of German Riparian Wetlands on Landscape Scale*) a first transfer of the results based on proxy values coupled with a hydrology dependent inundated floodplain extent calculation is shown. Land use, soil types and slope in the reference floodplains of the Elbe, Main and Rhine were correlated with flooding frequencies derived from detailed FLYS calculations. Land use and slope were found to be the most important predictors for flooding frequencies which were transferred to other rivers for a calculation of a nation-wide floodplain retention for Germany.

## **4 Active versus potential floodplains – small floods and their effect as a key to calculate nutrient retention on a landscape scale**

S. Natho, M. Venohr

Keywords: flooding frequency; nutrient retention capacity; riparian floodplain; spatial and temporal dynamics; active floodplain

### **Abstract**

Riparian floodplains are known to retain nutrients such as nitrogen and phosphorus. The main processes are denitrification (for nitrogen) and sedimentation (for phosphorus), which depend on the nutrient load and the flow velocity or residence time, respectively. Both are related to the floodplain size and the current discharge conditions. However, it is not yet known, to which extent, how long and how often during a year riparian floodplains are inundated. Small floods are not relevant for flood risk management, but they are important for the nutrient cycle. Therefore this study examines the flooding frequency, the extent and the nutrient retention capacity of inundated riparian floodplains between Wittenberg and Wittenberge along the river Elbe in Germany, basing on freely available data. The results of inundated areas are produced by the Software FLYS 2.1.3. On the basis of these results we developed an empirical approach to predict the average yearly active floodplain as a share of the inundated floodplain on the potential floodplain depending on the morphology. This hydrology dependent approach was applied to calculate the active floodplain as an average inundated floodplain and coupled with a proxy based nutrient retention calculation. Due to morphologic characteristics, riparian floodplains upstream and downstream from Magdeburg show significant differences in flooding frequencies, average inundated floodplain extent and floodplain widths. Assuming this average inundated floodplain as relevant for nutrient retention, we could calculate an eight-fold higher retention for the downstream river section, despite a smaller potential floodplain, indicating how important regularly flooded areas are. The methodology developed can be transferred to other river systems. It provides information on floodplain extent relevant for nutrient retention but the coupling with proxy based

retention rates has to be improved to a more adaptable approach which considers variable nutrient load and concentration levels.

## 1. Introduction

The role of floodplains for water retention, but also for nutrient retention is widely accepted (Jansson et al. 1994, Trepel & Palmeri 2002, Verhoeven et al. 2006). Politicians and planners start considering riparian floodplains as cost effective measures to reduce not only flood peaks but also nutrient loads in rivers. Here riparian floodplains contribute to nutrient retention either when flooded by river water or when acting as buffer strips between diffuse nutrient emission from arable land and river (Jansson et al. 1994, Arheimer & Wittgren 2002, CIS 2003). Riparian floodplains also work as green corridors or green belts in the landscape, connecting ecologically important areas across country borders (Terry et al. 2006). Nitrate ( $NO_3-N$ ) and phosphorus (here as total phosphorus -  $TP$ ) retention are subject to different retention processes during flood events; whereas denitrification is the most important process for  $NO_3-N$  on a yearly basis (Spieles & Mitsch 2000, Saunders & Kalff 2001, Trepel & Palmeri 2002, Pinay et al. 2007), sedimentation is the most important process for  $TP$  retention (Kronvang et al. 1999, Behrendt & Opitz 2000, Olde Venterink et al. 2002, Verhoeven et al. 2006). Retention processes depend on interacting factors, such as soil characteristics, e.g. the organic carbon availability (Davidsson et al. 2002) and soil moisture (Pinay et al. 2007), as well as water temperature (Mitsch et al. 2000, Pinay et al. 2007) and retention time respectively flow velocity (Arheimer & Wittgren 2002) or hydraulic load (Venohr 2006) which is linked to floodplain size respectively water surface area and the given discharge. Apart from selected study floodplains the size of active floodplains for whole river basins is not known. Detailed knowledge is collected for study floodplains used for dyke back-shifting projects, for example along the Elbe and the Rhine (IKSR 2005, ICPER 2009, Scholz et al. 2009). As a first step towards an improved understanding, Brunotte et al. (2009) quantified the extent of recent riparian floodplains along German rivers with catchment sizes bigger than  $1000 km^2$ . Different digital maps such as land-use, soil and orthophotos were analyzed, allowing recent riparian floodplains to be accounted for as an active floodplain with a statistical inundation frequency of at least once in 100 years and their status of disturbance. This active floodplain is not necessarily relevant for nutrient retention every year, since inundation is too rare on the total area. To fulfill the standards of the EU directive on the assessment and

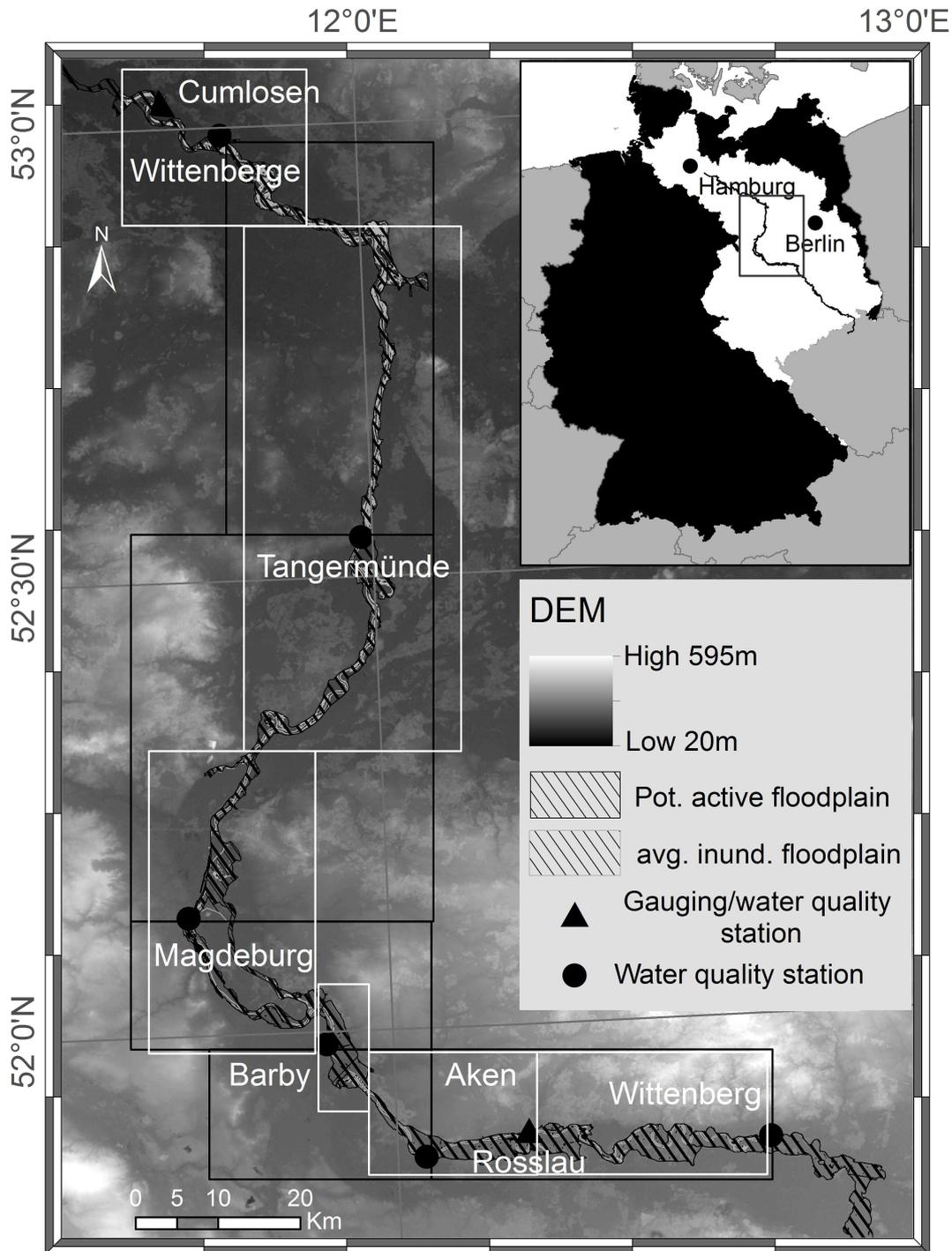
management of flood risks (European Community 2007) the Federal States have started to create flood risk maps for rivers with smaller catchments, also. Again, the focus is on the floodplain extent of 100 year floods, in the following referred to as the potentially active floodplain or potential floodplain.

On the basis of the presented knowledge three overall questions of this study can be formulated. To which extent, how long and how often during a year are these active floodplains inundated? What is the effect of more frequent and thus smaller floods on nutrient retention in floodplains? Is it possible to empirically quantify an average inundated floodplain on a yearly basis and couple this approach with proxy based retention rates to quantify nutrient retention? To answer these questions this study focuses on the flooding frequencies and the extent of inundated floodplains of the river Elbe, one of the main emitters of nutrients into the German Bay of the North Sea. Additionally existing monitoring data is examined to identify nutrient retention in floodplains based on discharge and nutrient concentrations at river monitoring stations which are sampled fortnightly at consecutive monitoring stations. To our knowledge there is no study published dealing with the detection of nutrient retention in floodplains based on such generally available data.

## 2. Methods

### 2.1 Study Area and Data

In this study the extent of inundated riparian floodplains along 330 km of the river Elbe in North Eastern Germany (11°30'0"E, 51°50'0"N; 12°45'0"E, 53°00'0"N) was calculated with the software FLYS 2.1.3 (2011) for different discharges on the base of eight gauging stations: Torgau, Wittenberg, Barby, Aken, Magdeburg, Tangermünde, Wittenberge and Neu Darchau. Five water quality stations (Wittenberg, Magdeburg, Aken, Tangermünde and Wittenberge) were considered to calculate nutrient loads and consequently to examine the influence of riparian floodplains on nutrient retention. Water quality sampling ( $NO_3-N$  and  $TP$  as mean daily concentrations) took place fortnightly. In cases where locations of the gauging and quality stations were not identical, nearest water quality stations were accounted for (for Aken: Rosslau and for Wittenberge: Cumlosen was accounted for; see Figure 4.1. Data from 1996 to 2004 (and where available to 2006) was taken for investigation.



**Figure 4.1:** Overview of the potential active (diagonal lines with black frame) and the long term average inundated (diagonal lines with grey frame) riparian floodplains from BfG along the river Elbe in Germany; FLYS 2.1.3 validation sections between Wittenberg and Wittenberge are differentiated white framed boxes. Areas, for which retention is calculated, are illustrated by black framed boxes. Digital elevation is presented by 90m SRTM raster in the background (USGS 2000)

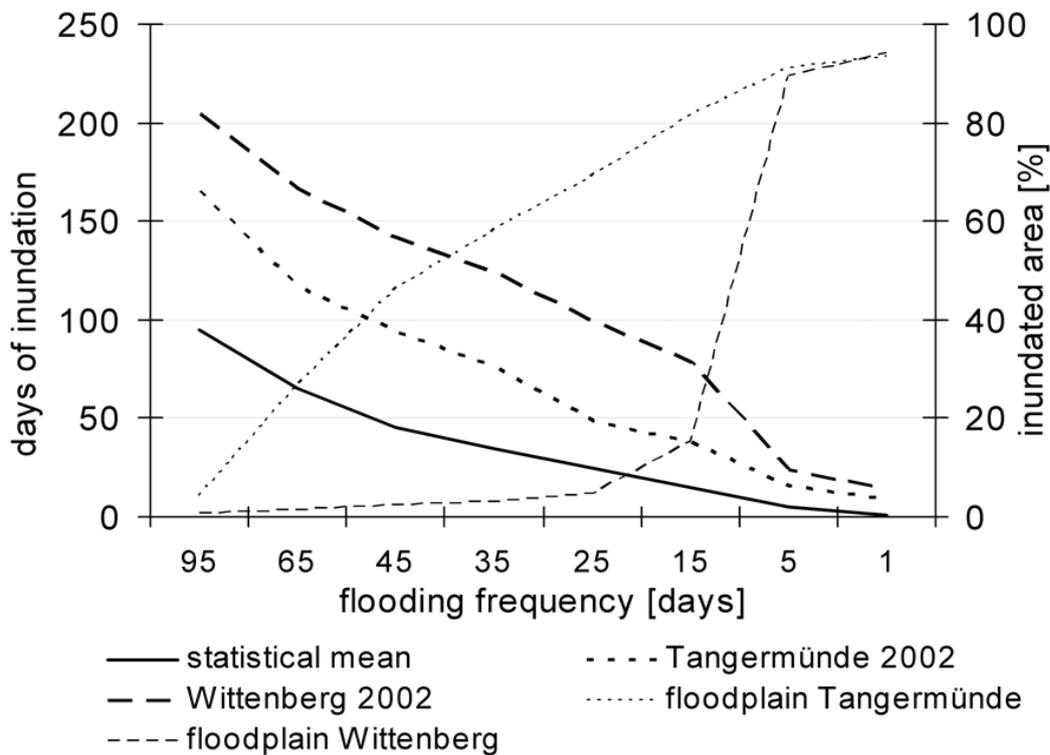
## 2.2 Software

The Federal Institute of Hydrology (BfG) has developed the River Hydrology Software FLYS as a water level information and analysis tool for The German Federal Waterways. The software can derive water levels at any point of the course of the river on the basis of known discharges (for details see Busch et al. (2009), BfG (2008)). On the basis of the potential riparian floodplain, river cross sections and other river characteristics (such as a digital terrain model (DTM) with a vertical centimeter resolution and a resampled grid resolution of 5m\*5m), FLYS processed 1D model results (e.g. SOBEK, BfG (2008)) for validation sections of each considered gauge. The module “Flood maps” calculates the extent of the river water table and if bank overflow occurs, and the respective area of the inundated floodplains also, providing GIS compatible file formats. The river sections FLYS considers valid for each gauge do not agree with the location of monitoring stations. For the calculation of this study the river sections were selected in such a way that one monitoring station is located at the inlet and respectively at the outlet of the considered floodplain (Figure 4.1).

The extent of river water levels was calculated with FLYS 2.1.3 for all gauges at different discharges: Discharges, statistically occurring once a year ( $HQ_1$ ), once in two years ( $HQ_2$ ) or once in five ( $HQ_5$ ) are considered as maximum values. These and mean discharges (MQ) and mean low discharges (MNQ) present minimum values, based on daily measurements of a long-term period, starting in 1890 or 1936 and ending in 2006. MQ represents the annual mean discharge and MNQ represents the lowest measured yearly discharges derived from long-term observations. Smaller floods could be accounted for by  $D270$ ,  $D300$ ,  $D320$ ,  $D330$ ,  $D340$ ,  $D350$ ,  $D360$ . “Dx” refers to the German Dauerlinie (duration curve), meaning, that on  $x$  days per year there is less discharge based on long term observations. Hence the statistical frequency of a  $D270$  is  $365 - 270 = 95$  days per year. In the following these long-term events are introduced as discharge frequency, which can also be expressed as a flooding event with a certain frequency and inundation extent. For discharge events higher than  $D320$  the inundation depths were calculated in 0.5 meter steps. The yearly frequency of the above mentioned discharges was calculated based on mean daily values between 1990 and 2005 as well as for hydrologically outstanding single years, as 2002, when long lasting floods occurred (see Figure 4.2).

English expression	Probability of event to be exceeded in %	in days	FLYS 2.1.3 /German nomenclature
Q95	95	347	D18
Q50	50	183	D183
Q5	5	18	D347
Q1	1	5	D360
Q10	10	35	D330
Q26	26	95	D270

**Table 4.1:** Introduction of FLYS 2.1.3 nomenclature (based on the duration curve) applied in this study in comparison to English expressions



**Figure 4.2:** Inundated area in % of the sections Tangermünde and Wittenberg related to the days of inundation based on the flooding events for the long-term mean as the statistical mean and the years 2002

## 2.3 Calculating retention with proxy values

First retention calculations were carried out for average inundated floodplains. Following the wide range of retention values reported in literature maximum, mean and minimum retention was calculated by applying proxy values which were applied in two recent studies. Whereas, Kronvang et al. (2004) considered land use in the catchment as relevant for proxy values (the more agricultural land, the higher the retention due to nutrient leakage), and Schulz-Zunkel et al. (2012) incorporated hydric soil characteristics. Gren et al. (1995) transferred a conservative retention of  $100 \text{ kg } NO_3\text{-N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  from measurements in Sweden to the Danube floodplains. All studies present retention rates typical of middle European rivers with dominant winter/spring flooding. The combination of both approaches resulted in the application of 5, 100 and  $350 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1} \text{ } NO_3\text{-N}$  retention and 0.5, 5 and  $55 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1} \text{ } TP$  retention. Floodplains are spatially heterogeneous ecosystems (Gren et al. 1995) due to morphological and thus different hydrological characteristics. This in turn leads to different retention rates within a floodplain (Schulz-Zunkel et al. 2012) which can be described by an average retention rate on a yearly basis. Consequently, the application of the mean retention rate presents a conservative estimate.

## 2.4 Flood and floodplain characteristics

### 2.4.1 Introducing the theoretical floodplain width

FLYS results showed that inundation on riparian floodplains does not increase linearly in width but via preferential flow paths such as oxbows. This individual flooding process can hardly be considered on a river basin scale. Instead, a simplified “theoretical width” was introduced to compare the flooding process on floodplains of different river sections:

$$width_{theoretical} = \frac{A_f}{L_r} \quad (4.1)$$

With  $A_{fl}$  as the inundated floodplain area and  $L_r$  as the length of the river stretch. This parameter summarizes inundation characteristics of a defined river stretch and allows the comparison between different long river stretches regarding their floodplain characteristics and conclusions on morphology and connectivity of floodplain. Hereby,  $L_r$  defines the spatial resolution and the aggregation level of floodplain characteristics.

Discharges along the river Elbe are affected by the discharge of tributaries.

Thus, a dimensionless parameter was introduced to compare discharges independent of their absolute size, expressing the discharge ( $Q$ ) at the sample time of nutrient concentrations ( $NO_3-N$  and  $TP$ ) relative to the mean discharge (MQ) of the respective gauging station.  $Q/MQ$  ratio classes were identified that represent (a) start of inundation, (b) inundation with low flow velocities and (c) inundation with higher flow velocities. It is stated that with increasing discharge, floodplain inundation is possible and leads to retention due to higher retention times (Tockner et al. 1999), whereas if discharge is too high and thus inundation is too deep (as derived from FLYS calculations), flow velocity increases and retention is not effective any more (Olde Venterink et al. 2002).

#### 2.4.2 Calculating nutrient loads

Changes in concentrations and loads were tracked along the five stations considered. Therefore, altogether 1170  $NO_3-N$  and 1150  $TP$  concentrations and their corresponding discharges were applied to calculate loads on a daily basis for the available concentrations and discharges for the years 1996 to 2002 for at least three subsequent monitoring stations where sampling took place on the same day. 256 concentration-discharge pairs were considered for Wittenberg, 221 for Aken, 229 for Tangermünde and 226 for Wittenberge for both nutrients and 217 for  $TP$  and 241 for  $NO_3-N$  at Magdeburg.

#### 2.4.3 Calculating average inundated floodplain extent

Calculating an average inundated floodplain extent based on current hydrological conditions in consideration of frequent floods is crucial for this study. Therefore, a methodology has been developed to generalize the information derived from the software FLYS for individual river sections under defined hydrologic conditions (statistical long-term observations). It has to be ascertained, how often these intermediate floods occur in the study period. Figure 4.2 illustrates these discharge frequencies at Wittenberg and Tangermünde in 2002 in comparison with their statistical long-term mean. We also calculated the mean from the years 1990 to 2005 which almost equals the statistical long-term mean, resulting in three almost congruent lines. This allows us to apply the statistical values provided by the software for our chosen period and to develop an empirical approach based on these discharges to calculate inundated floodplain extent.

For calculating an average inundated floodplain extent all discharges above MQ

	Wittenberg- Aken	Aken- Barby	Barby- Magdeb.	Magdeb.- Tangerm.	Tangerm.- Wittenb.
Section length [km]	110.9	37.9	49.2	101.5	95.0
Theoretical flood- plain widths at respective flooding events [km]	D270	0.01	0.01	0.01	0.01
	D300	0.02	0.02	0.02	0.04
	D320	0.04	0.03	0.22	0.42
	D330	0.05	0.03	0.24	0.50
	D340	0.08	0.08	0.48	0.69
	D350	0.26	0.13	0.57	0.97
	D360	1.53	1.00	0.84	1.20

**Table 4.2:** Comparison of calculation results by FLYS 2.1.3; the theoretical floodplain width for seven floodplain events for different sections along the river Elbe is shown; Magdeb. = Magdeburg, Tangerm. = Tangermünde, Wittenb. = Wittenberge

of one year are averaged and applied in the empirical equation to calculate an average inundated floodplain extent depending on hydrologic conditions of the respective year.

### 3. Results

#### 3.1 Flood and floodplain characteristics

The connectivity of floodplains plays a major role for nutrient retention (Tockner et al. 1999). On a landscape scale two parameters - the theoretical floodplain width and the inundation extent at small floods - are found to describe the connectivity levels.

##### 3.1.1 Theoretical floodplain width

Table 4.2 gives an overview of the theoretical floodplain width of the river stretch considered divided into six river sections. Although  $L_r$  of the considered river sections differs markedly, this parameter allows a comparison because by dividing the  $A_{fl}$  by  $L_r$ , the ratio is unified. The theoretical floodplain width is different for river stretches upstream and downstream from Magdeburg. Whereas, these widths do not differ at small floods, differences can be found starting at  $D320$ . Floodplain widths of less than 0.3 km can be found upstream from Magdeburg, whereas downstream from Magdeburg values are higher. The difference between these two sections disappears between  $D350$  and  $D360$  events: then floods are high enough to inundate vast areas upstream from Magdeburg, resulting in theoretically wider floodplains than downstream from Magdeburg. On a landscape scale, the parameter theoretical floodplain

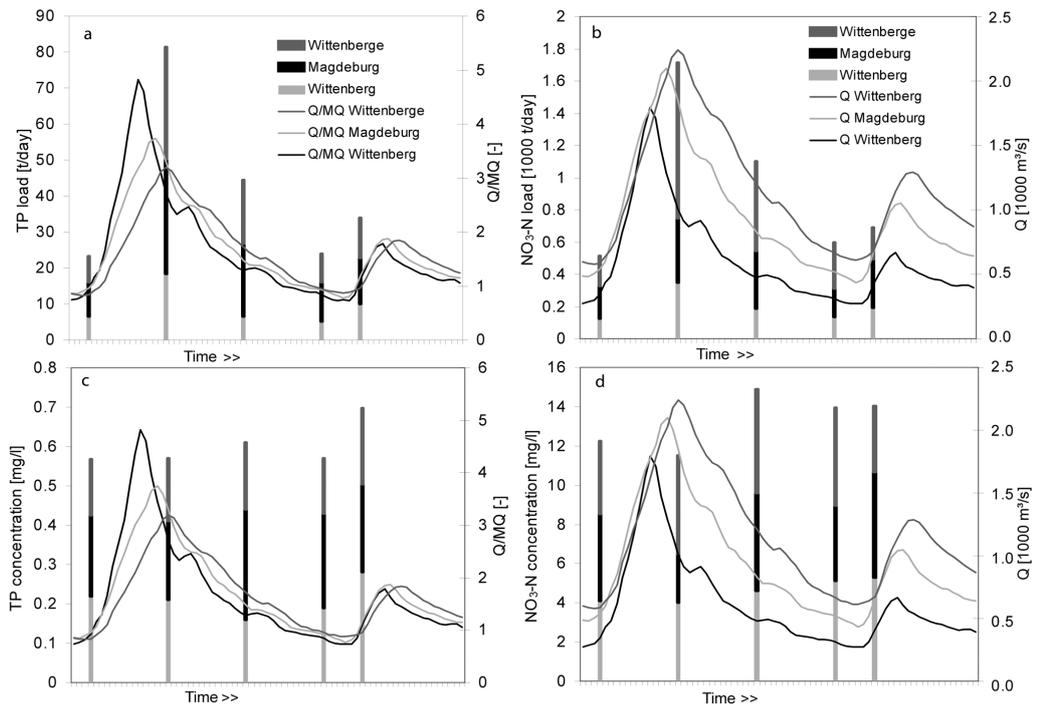
width describes the difference between these two sections at intermediate floods very well.

### 3.1.2 Actual hydrologic conditions

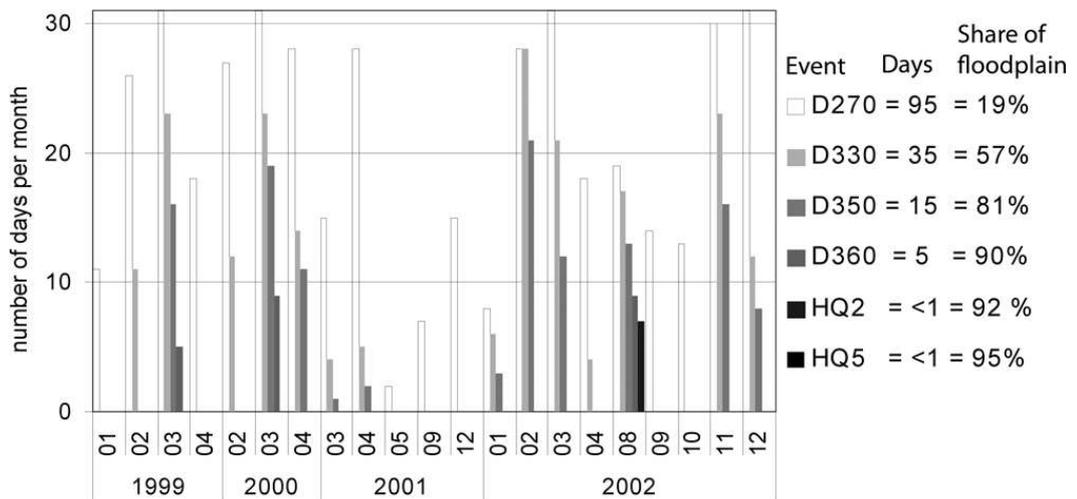
Figure 4.2 considers flooding frequencies and the size of inundated areas at certain flooding frequencies together. It can be seen, that with a decreasing probability of occurrence the inundated area increases. Again the two river sections upstream and downstream from Magdeburg can be distinguished, represented by Wittenberg (upstream) and Tangermünde (downstream). In 2002, a hundred year flood occurred, which resulted not only in high discharges but also in long-lasting high discharges. Consequently, the flooding frequencies of this year are significantly above the statistical long-term means. Higher floods occurred more often and more pronounced in Wittenberg than in Tangermünde. Wittenberg represents the upstream section, where smaller floods last longer but the share of inundated floodplains of the potential active floodplain is smaller than at Tangermünde, which is typical of the downstream section where flood peaks flatten because of higher storage capacities along the river and the influence of tributaries (see Figure 4.1, (Poff et al. 1997)). Nevertheless, Tangermünde's floodplains are hydrologically better connected and were flooded more often. Statistically inundation occurs on 95 days per year. In 2002 50 % of Tangermünde's floodplain was inundated on up to 100 days.

### 3.1.3 Observation of nutrient concentrations and loads

Figure 4.3 exemplarily shows the comparison of nutrient loads and nutrient concentrations relative to the corresponding discharges respectively  $Q/MQ$  ratios during a flood wave along the river Elbe, represented by three monitoring stations. Whereas, water quality sampling took place fortnightly, daily information on discharges is shown. It can be seen, that water quality sampling in Wittenberge took place almost on the peak of the flood in November 1998, whereas the peak was missed in Wittenberg for a few days.  $TP$  and  $NO_3-N$  loads in Wittenberg tend to be lower than in Wittenberge because of lower discharges (Figure 4.3a and b). Concentrations, represented as stapled on the other hand tend to be higher in the upstream section than in the downstream section (Figure 4.3c and d).



**Figure 4.3:** Comparison of the development of a typical flood event at selected gauges with *TP* loads (a) and *TP* concentrations (c), expressed as dimensionless  $Q/MQ$  ratio and with  $NO_3-N$  loads (b) and  $NO_3-N$  concentration (d) versus  $Q$  in  $m^3/s$  from October 25<sup>th</sup> 1998 to January 1<sup>st</sup> 1999. Loads and concentrations are shown cumulatively, taken at the same day



**Figure 4.4:** Frequency of certain statistical discharge events in days per month at the gauging station Tangermünde between 1999 and 2002; months January (1) to December (12) only are included, if events occurred; each event equals the inundation of a certain share of the potential floodplain

### 3.2 Inundated floodplain extent

The temporal distribution of flooding events during the year also shows variation. In general floods occur in the winter half of the year as shown in Figure 4.4 resulting in inundated floodplain extent being bigger than in summer time, expressed as percent of the potential floodplain. In 2002 high floods also occurred in summer. Here the potential active floodplain (without the river itself at MQ conditions) is taken as hundred percent. The dependency of inundated floodplain extent from discharge and flood frequency is described for the example of Tangermünde in the legend of Figure 4.4.

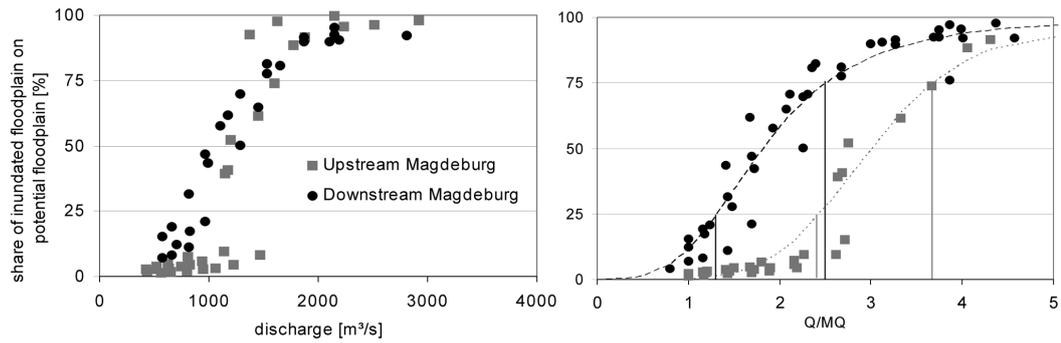
### 3.3 Generalization for application

The dynamic of flooding frequencies in combination with the dynamic of inundated floodplain areas are driven by hydrologic conditions varying from year to year. Both are variables which affect nutrient retention in floodplains remarkably. As a main result an approach is presented to consider the hydrology for calculating average inundated floodplain extent and thus active floodplains relevant for nutrient retention on a yearly basis.

#### 3.3.1 Introduction of the $Q/MQ$ approach

The relation between discharges ( $Q$ ) and the share of inundated floodplain of the potential floodplain is analyzed in Figure 4.5 (left side) for all gauging stations. Therefore, for 11 discharges of the mentioned statistical events (MNQ to  $HQ_5$ ) corresponding inundated floodplain extent was calculated with FLYS 2.1.3 for each of the seven gauges. The values are shown as a scatterplot in Figure 4.5. As such, the two sections do not differ in their behavior. Using the relation  $Q/MQ$  and the share of inundated floodplain of the potential floodplain the difference of the two sections becomes visible (Figure 4.5, right). The advantage of the second approach is that differences in the discharge are compensated by dividing the current discharge through the gauge specific MQ. Thus hydrologic characteristics can be compared, independent of their absolute values. The following equation can be derived for the upstream and the downstream Magdeburg river sections with the respective coefficients a and b (7.7118 and 3.4102 for the downstream section and 380.01 and 5.4 for the upstream section):

$$A_{inundated} = \left( \frac{1}{(1 + a \cdot (\frac{Q}{MQ})^{-1})} \right) \cdot 100 \quad (4.2)$$



**Figure 4.5:** Share of inundated riparian floodplain on potential riparian floodplain versus the discharge ( $Q$ ) (left) and versus the relation of  $Q/MQ$  (right) illustrating two river sections. Two sigmoidal relationships can be found between  $Q/MQ$  and inundated floodplain extent. Three classes were identified regarding the inundation characteristics of the floodplain above  $MQ$  ( $Q/MQ = 1$ ): a) less than 25 %, b) between 25 and 75 % and c) more than 75 % share of inundated floodplain on potential floodplain (see also Table 4.4)

This finally allows us to calculate the share of inundated floodplains on the potential floodplain for continuous discharges, without applying FLYS 2.1.3 for every discharge, which is presented in the following section. Whereas, downstream of Magdeburg the share of inundated floodplain already increases at low  $Q/MQ$  ratios, upstream from Magdeburg the increase only starts at  $Q/MQ$  ratios  $> 2$ , meaning a discharge twice the mean discharge. At  $Q/MQ = 4$  around 95 % of the potential floodplain of both sections is inundated. Consequently, the percentage of inundated floodplain can be taken as the second parameter to describe the similarity of floodplains upstream and downstream from Magdeburg, which was already indicated in Figure 4.2.  $Q/MQ$  ratios  $> 4$  happen more often in the upstream section than in the downstream section. But higher  $Q/MQ$  ratios are also necessary to inundate the floodplain.

### 3.3.2 Nutrient retention in floodplains

Based on the relationships presented in Figure 4.5, mean inundated areas can be calculated. Therefore, for every gauge all  $Q > MQ$  were considered to calculate an average  $Q/MQ$  ratio per year as well as a long-term mean. This ratio was then inserted into Equation 4.2 to calculate an average inundated floodplain (active floodplain) which is visualized in Figure 4.1. As proxy values are available on a yearly basis only, yearly retention is calculated although inter annual variation in flooding frequencies and inundation extent occurs (see section Inundated floodplain extent). The effect of dynamic floodplain sizes on a simple nutrient retention approach by proxy values is examined in Table

		Upstream Magdeburg	Downstream Magdeburg
river km upstream		214.14	326.67
river km downstream		326.67	453.98
Potential floodplain	[ $km^2$ ]	203.47	164.51
Mean Q/MQ ratio 1990-2005	(1999)	1.68 (2.35)	1.65 (2.21)
Mean yearly inundated floodplain	[%]	4.10 (20.83)	41.71 (65.97)
Mean yearly inundated floodplain	[ $km^2$ ]	8.36 (43.38)	68.50 (108.53)
NO <sub>3</sub> -N retention [ $t \cdot yr^{-1}$ ]	min	4.2 (23.1)	42.0 (68.8)
	max	292.5 (1617.3)	2937.0 (4799.4)
	mean	83.6 (462.1)	839.1 (1371.2)
TP retention [ $t \cdot yr^{-1}$ ]	min	0.4 (2.3)	4.2 (6.9)
	max	46.0 (23.1)	461.5 (754.2)
	mean	4.2 (254.1)	42.0 (68.6)

**Table 4.3:** Calculated  $NO_3$ -N and TP retention by proxy values (100 and 5  $kg \cdot ha^{-1} \cdot yr^{-1}$  respectively) for the two distinguished river sections, basing on a mean yearly inundated floodplain calculated from daily discharges, which lead to inundation. Calculations for the year 1999 are shown in brackets

4.3. A long-term mean (1990-2005) of average inundated floodplain extent is compared to the average inundated floodplain extent of a year, in which floods were not extremely high, but inundation occurred very often. Although there is potentially more active floodplain in the upstream area, the average annual inundated floodplain is smaller and retains fewer nutrients under mean conditions. Riparian floodplains in the downstream section contribute higher nutrient retention of the Elbe under mean conditions. But, also flooding frequencies as shown in Figure 4.2 are lower for Wittenberg than for Tangermünde. As can be seen from Figure 4.4 different shares of floodplain are inundated for different lengths and the potential floodplain is barely inundated once in five years. However, under mean conditions a total retention of 923  $t NO_3$ -N  $yr^{-1}$  and 46  $t TP yr^{-1}$  is calculated for the observed section between Wittenberg (with a yearly river load of approx. 60000  $t NO_3$ -N  $yr^{-1}$  respectively approx. 3000  $t TP yr^{-1}$ ) and Wittenberge (with a yearly river load of approx. 70000  $t NO_3$ -N  $yr^{-1}$  respectively 3600  $t TP yr^{-1}$ ).

### 3.3.3 Inundation classes

On the basis of Figure 4.5 (right) three classes were identified regarding the inundation characteristics of the floodplain above the mean discharge ( $Q = MQ$ ) (see Table 4.4). Load differences between monitoring stations could be calculated, when sampling took place on the same day, assuming the ability to compare these loads due to similar conditions. Most of the approx. 370 samples

class	description	Share of inundated floodplain on potential floodplain [%]	Q/MQ upstream Magdeburg	Q/MQ downstream Magdeburg
1	Start of inundation	<25	1-2.5	1-1.2
2	Inundation, low flow velocity	25-75	2.5-3.8	1.2-2.6
3	Inundation, higher flow velocity	>75	>3.8	>2.6

**Table 4.4:** Flooding classes upstream and downstream of Magdeburg under consideration of the share of inundated floodplain on potential floodplain

considered relevant for inundation were taken at class a (low inundation cf. Table 4.4) whereas class b and c were considered in 114 respectively in 30 cases, only. Load differences occurring at  $Q/MQ > 1$  in summer and winter were tested by using the Mann-Whitney-Test (the exceptional summer flood 2002 was excluded due to irregular sampling frequencies). Statistically significantly higher loads could be found for  $NO_3-N$  ( $N = 602$ ;  $P < 0.001$ ) and  $TP$  ( $N = 407$ ;  $P < 0.001$ ) in winter than in summer, which was also reported for other European rivers (Olde Venterink et al. 2002).

## 4. Discussion

### 4.1 Hydrology dependent floodplain extent versus proxy based retention rates

There are many factors influencing sedimentation and denitrification as the most important processes for  $TP$  and  $NO_3-N$  retention in floodplains (Kronvang et al. 1999, Saunders & Kalff 2001, Trepel & Palmeri 2002, Pinay et al. 2007, Verhoeven et al. 2006). Proxy based retention rates based on the experience of wetlands and floodplains studied and reported in literature average middle European conditions (Kronvang et al. 2004, Schulz-Zunkel et al. 2012) such as the dominant occurrence of winter and spring floods. Low water temperatures decrease biological activity (Venohr 2006) and result in the reduction of denitrification rates. Hence, the applied average retention rates of  $100 \text{ kg } NO_3-N \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  which are lower than the retention rates described in Mitsch et al. (2005) represent a conservative estimate. Further site specific floodplain characteristics carbon content, soil moisture or water depths are more variable than water temperatures and cannot be accounted for as

explicitly. These uncertainties have to be considered, which is why minimum and maximum rates are calculated next to mean retention. Applying the same proxy values for morphologically different floodplains has to be interpreted carefully because flooding frequencies increase from upstream Magdeburg to downstream Magdeburg. These affect nutrient retention, but they do not necessarily increase nutrient retention, since erosion and the location relative to the main channel can also decrease nutrient retention (Kronvang et al. 2004, Schulz-Zunkel et al. 2012). In addition, higher concentrations are found in the upstream section (see Figure 4.3) which might have an effect on nutrient retention (Hoffmann et al. 2011). On the other hand, higher loads are observed in the downstream section due to higher discharges and nutrient loads are known to be a good predictor for nutrient retention (Saunders & Kalff 2001). Consequently, as we do not know better for this first analysis, we have calculated with the same proxy value for both river sections. Also flow velocities induced by vegetation roughness (van der Lee et al. 2004) could not be accounted for but play an important role (Tockner et al. 1999). Low flow velocities increase the retention time, allow sediments to settle and an increased exchange between surface water and sediments and consequently favorable conditions for denitrification (Venohr 2006). Both, differences in transported nutrient loads and flow velocities should be considered in the following studies. Consequently, the temporal variability, which is considered in the inundated floodplain extent calculation is neglected for the retention rate. This means that proxy values have to be replaced by hydrology dependent approaches similar to the way the average inundated floodplain extent is calculated.

## 4.2 Limits of fortnightly monitoring

Although the fortnightly sampling frequency is supposed to be sufficient for river monitoring (Kronvang & Bruhn 1996) and for small study areas (Hoffmann et al. 2011) no statistical significance of river load reduction could be found for the class-wise investigation of TP or  $NO_3-N$  river loads. Retention in class b could not be detected clearly and there were far fewer samples taken in class c than in class a. Nonsynchronous tributary inputs (Mulde, Saale and Havel) from different hydrologic and topographic areas not only influence discharge patterns due to storage capacities and channel widths (Poff et al. 1997) but also nutrient concentration and thus load levels, too. Flood peaks at different gauges are monitored with a certain time lag, depending on the discharge and thus flow velocity (see Figure 4.3). Hence, samples from the

same day, as taken along the river Elbe, do not necessarily reflect comparable conditions in contrast to the analysis of Olde Venterink et al. (2002), where the actual flood wave was tracked and hence TP retention could be found in one of the study floodplains. Comparing the yearly nutrient loads calculated for the river sections an average increase of the loads from the first (Wittenberg) to the last considered (Wittenberge) gauge by approx 24000  $t NO_3-N$  and 1083  $t TP$  can be observed. However, subtracting the inputs of the tributaries Mulde, Saale and Havel (average 31000  $t NO_3-N$  and 2391  $t TP$ ) retention in the river system cannot be neglected, as Behrendt & Opitz (2000) found by comparing emissions and measured loads and concluding a net loss in the river system. With their approach instream retention could not be distinguished from floodplain retention. But the lower flow velocities in the floodplain than in the river channel increase the contact between water and surface due to lower flow velocities (Olde Venterink et al. 2002). Another point which underlines the role of floodplains for nutrient retention is that floodplains are inundated under high flow conditions when most of the loads are transported in a short period of time (Tockner et al. 1999). Assuming additional diffuse emissions (according to Behrendt et al. (2003) 3700  $t TN \cdot yr^{-1}$  were calculated with the model MONERIS as a long term mean (1983-2005)) retention in the total river system has to be even higher than the suggested average 100  $kg NO_3-N \cdot ha^{-1} \cdot yr^{-1}$ . However, diffuse emissions and inputs from tributaries also make it difficult to track retention by fortnightly monitoring in the Elbe river, although retention in the river system is present.

## 5. Conclusion

Riparian floodplains are heterogeneous landscapes: They change over time, due to flooding frequency and ecosystem age which might have an influence on retention efficiency, and in their spatial extent, due to varying inundation extent. Additionally, it is important to consider, that after flooding, parts of riparian floodplains remain inundated although water levels have dropped in the river. This is due to the fact that the water cannot retreat from the floodplain immediately, but stays in flats and oxbows. Hence, conditions for sedimentation as well as for denitrification are favored by inundation, even after river water has withdrawn, because of groundwater interactions. Using FLYS 2.1.3 it is possible to describe the extent of inundated riparian floodplains for 330 km of the river Elbe from Wittenberg to Wittenberge at various discharges, especially for small floods occurring frequently during the year. We could

derive a simple empirical model which allows the calculation of a yearly average active floodplain based on daily discharges. This is important to estimate nutrient retention, which depends on the flooding frequency and the extent of inundated floodplains of frequently occurring floods. Consequently, when Federal States work on the fulfillment of the Flood Risk Assessment Directive the chance should be taken to consider and identify the extent of smaller floods as multicriterial benefits in contrast to risks of bigger floods. Based on these results the role of active floodplains can be evaluated more in detail. Floods occur generally in winter and spring time, and the highest flows appear in March or April. Water temperature is very low during winter floods and may slow down denitrification. The effect can be captured when the presented spatial approach is coupled with a temporal dynamic approach. Ongoing research is dealing with this fact.

## **6. Acknowledgments**

The authors greatly thank the FLYS team J. Graf, M. Hammer, M. Hatz, N. Busch and D. Meißner from the BfG who provided the software FLYS 2.1.3 and always found time to help if questions occurred.

## 5 Nutrient retention in riparian floodplains on landscape scale, the necessity for a monthly retention approach

S. Natho and M. Venohr 2012 Nutrient retention in riparian floodplains on landscape scale, the necessity for a monthly retention approach. *Water Science and Technology* **66**(12), 2800-2807.

Keywords: modelling; nutrient retention; riparian wetlands

### Abstract

This study analyses the computed nitrogen retention, the distribution and the extent of riparian floodplains of three German rivers, since input data and application of retention model has not been carried out on landscape scale so far. The Software FLYS 2.1.3 was used for the calculation of the floodplain extent and depth at certain discharges. Thus a first empirical approach is suggested to quantify the share of load that enters the floodplain (incoming load) and the extent of floodplain as variables depending on discharge ratios. Measured loads have subsequently been applied to the presented approach to calculate incoming loads on a monthly and yearly basis for the years 1999 and 2002. Finally, linear and exponential yearly retention models were applied, obtained from the literature.

Large variations in the retention results were found between the years and the models and between monthly and yearly calculations. In hydrologically average years, calculated retention rates are in the range of reported values ( $440$  to  $670 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ ), whereas for wet years retention values account for  $1400 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ . Consequently, this approach needs to be improved to reduce overestimation by considering more complex characteristics of the floodplain, but generally its application is possible on the landscape scale.

### 1. Introduction

In recent times German politics have recognised the effect of riparian floodplains on nutrient (nitrogen ( $N$ ) and phosphorus ( $P$ )) retention (BMU & BfN

2009). As a cost-effective measure to reach the goals of the EU-Water Framework Directive (WFD) by 2015, dyke back-shifting projects have been and will be initiated to increase the area of floodplains for inundation. The reason for this is the assumption, that hydrologic connectivity affects nutrient retention (Rücker & Schrautzer 2010): the lower the flow velocity the more load can enter the wide floodplain which subsequently underlies nutrient retention by denitrification and settlement of fine particles. But, the effect of these potential floodplains cannot be quantified so far, as monitoring programs, if initiated at all, have just started. Information is published in regional papers but mostly not reviewed (IKSR 2006, Jährling 2009). In most cases floodplains were re-connected to control floods. Although nutrient retention is recognised as an important function of floodplains, flood control has always been the main focus of dyke back-shifting. This is because the processes of nutrient retention, mentioned above and their relative contributions are not fully understood, such as the influence of retention time which turns floodplains from nutrient sources to nutrient sinks (Arheimer & Wittgren 2002). So far various results exist on the nutrient retention capacity of wetlands or wetland types. Studies suggest retention rates from less than  $1 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  to more than  $400 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ , depending on wetland type, monitoring period, vegetation, soil type (Cooper 1990, Leonardson et al. 1994, Mitsch et al. 2005, Hefting et al. 2006, Rücker & Schrautzer 2010) and status of the wetland, e.g. rewetted or natural (Hoffmann et al. 2011). There is also only minimal knowledge on the distribution and degree of functionality of riparian floodplains in Germany on landscape scale. Only recently, such a first inventory of the recent floodplain as the floodplain which is inundated at least once in 100 years was carried out, indicating that this area is not necessarily active for retention processes (BMU & BfN 2009, Brunotte et al. 2009).

Several approaches are described in literature for calculating nutrient retention in surface flow wetlands, especially for nitrate ( $\text{NO}_3$ ). Very often these models are applied for small river systems and, thus, small wetland areas. Trepel & Palmeri (2002) compared three nutrient retention approaches for surface flow wetlands as an evaluation tool for the highest retention rates. It is stated that all models neglect seasonal variations and thus overestimate the effect of high floods. Applying monthly loads is a trade-off between input data necessity and result accuracy.

The objective of this study is to bring together both aspects mentioned above: (i) firstly the distribution, extent and frequency of flooded riparian floodplains for three German rivers (Elbe, Main and Rhine). Thereby the numerical sim-

ulation is done by the aid of the Software FLYS 2.1.3, which was developed by the Federal Institute of Hydrology (BfG 2009). It is hypothesised that taking into consideration water depths and inundated floodplain areas, which can be calculated with FLYS 2.1.3, a first potential approach can be developed to calculate the share of a riverine load which enters the floodplain at certain discharges for each river system.

(ii) Secondly, based on the results of (i), load comparisons for various river sections were performed to determine load changes during the river course on a monthly and a yearly basis. It is further hypothesised that the variation of loads and discharges can be seen only when considering monthly load calculations, because means calculated on a yearly base average over individual peaks.

As a last step, data from the river Elbe, calculated under (i) and (ii) are implemented in the above mentioned models. Results will be compared with (ii).

## 2. Methods

The basic assumption for the present study is, that although not every floodplain is a wetland, retention processes (e.g. denitrification) in floodplains can be compared to retention processes in surface flow wetlands, as long as inundation occurs by river water. This is why the inundated areas are taken into account to model nutrient retention in floodplains. Therefore, the distribution, extent and frequency of flooded riparian floodplains were modelled by the River Hydrology Software FLYS 2.1.3. (BfG 2009), a water level information and analysis tool for German Federal Waterways. FLYS is not a hydraulic flow model but processes model results (1D) as well as basic and special geographical data to calculate flooded riparian floodplains of the German parts of the rivers Elbe, Main and Rhine at arbitrary discharges. These three rivers differ strongly in their characteristics, ranging from semi-natural morphometrics (Elbe), heavily modified (Rhine) to heavily modified with several dams (Main). The software calculates the water level depending on discharges for official gauging stations along their validated length in 100 m sections. Thereby, various digital cartographical maps as dams or the morphological river valley are considered. In combination with digital terrain models (DTM) the extent of the inundated area on the riparian floodplains can be modelled for various discharges as well as the water heights.

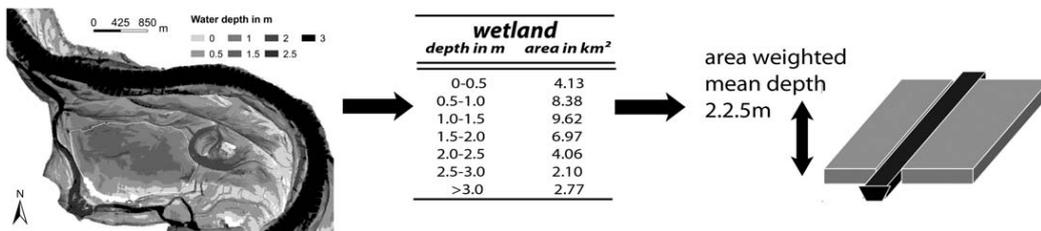
Along the river Elbe seven gauging stations are considered, as well as ten by

the river Main and six for the river Rhine. Thus, for the Elbe app. 290 km, for the Main app. 290 km and for the Rhine app. 250 km flow lengths are taken into consideration by applying FLYS at various discharges (ranging from low flow to high flow events that statistically occur once in five years). These discharges reflect events based on the gauging station's long term calculations. The theoretical width of a floodplain was introduced as a parameter to improve the comparability of floodplains between the rivers.

$$w_{floodplain} = \frac{A_{floodplain}}{l_{riversection}} \quad (5.1)$$

### (i) Analysis of inundated areas, water depths and volumes

The results from the FLYS 2.1.3 calculations are provided in GIS compatible file format, and have been further processed with ArcGIS. Detailed flooding maps for the above mentioned discharges were produced and inundated areas could be derived. Furthermore, detailed maps considering the water depth for river stretches were analysed: For events  $D320$ ,  $D330$ ,  $D340$ ,  $D350$ ,  $D360$ ,  $HQ_1$  or  $HQ_2$  and  $HQ_5$  inundation heights up to 3 metres were calculated in 0.5 metre steps, deeper sections were considered as deeper than 3 metres. For each gauge and each discharge area weighted mean water depths were calculated. Therefore, the average of the ranges (0-0.5 = 0.25, ..., 2.5-3.0 = 2.75) were multiplied with the corresponding areas to obtain an area weighted mean depth (see Fig. 5.1). The river area (area of the  $MQ$ ) and its depths were accounted for separately. With the knowledge of the extent of inundated areas



**Figure 5.1:** Illustration of the applied method starting from left to right: FLYS 2.1.3 result with polygons of the same depth for a detailed river section; calculation table; resulting mean depth for a schematic floodplain; the river (dark colour) is not included.

and the mean depths of the floodplain the volume of the floodplain was calculated (Thew et al. 2010) for each calculated flooding event. At flooding events the water volume entering the floodplain is unknown. Thus, for simplification, we assumed the same flow velocities in the river and in the floodplain, although in reality flow velocities decrease in the floodplain because of increased roughness. Due to lack of data different flow velocities cannot be estimated as yet and the incoming water volume will be overestimated. Nevertheless, this

assumption is applicable for our study since the considered temporal and spatial resolution is insensitive to this, as will be shown in the results. However, because of this time independent volume it can be assumed, that for a certain flooding event the calculated floodplain volume is filled with water ( $V_Q$ ), which equals a defined share of the total discharge ( $Q_{share}$ ) as well as the share of total load ( $L_{in}$ ).

$$V_Q = Q_{share} = L_{in} \quad (5.2)$$

This can be explained by the fact, that dissolved chemicals are distributed evenly in the river (considering the spatial resolution of this study). Hence, the discharge entering the floodplain is assumed to occur at the same concentration as the discharge in the river.

## (ii) Comparison of calculated loads

For the calculation of nutrient loads, the relatively natural river Elbe (BMU & BfN 2009, Brunotte et al. 2009) was chosen as a case study area, since the floodplains extend further than for the other rivers. The following gauging stations were considered for the years 1999-2002: Wittenberg, Aken, Magdeburg, Tangermünde and Wittenberge.

Since not all gauges are equipped with water quality stations, for Aken and Wittenberge monitoring stations in the vicinity (Rosslau and Cumlosen) were selected. The OSPAR (2008) method, applied in most European countries with continuous discharge measurements and at least twelve water samples per year, were applied to calculate annual and monthly loads.

$$Load_{annual} = Q_r \cdot c_r = Q_r \cdot \frac{\sum_{i=1}^n (Q_i \cdot c_i)}{\sum_{i=1}^n Q_i} \quad (5.3)$$

Where the mean discharge ( $Q_r$  in  $m^3 \cdot s^{-1}$ ) during the sampling period is multiplied with  $c_r$ , (the discharge weighted concentration with:  $c_i$  = measured concentration in  $mg \cdot l^{-1}$  in sample  $i$ ,  $Q_i$  = discharge in  $m^3 \cdot s^{-1}$  in sample  $i$  and  $n$ = number of samples taken in the observed period).

type	author	model
linear	Mander & Mairing (1994)	$N_{ret} = 0.005 + 0.61 \cdot W_L$
linear	Jansson et al. (1998)	$N_{ret} = W_L \cdot 0.6154$
linear	Saunders & Kalff (2001)	$N_{ret} = 0.42 + 0.64 \cdot W_L$
exponential	Byström (1998)	$N_{ret} = 7.56 \cdot W_L^{0.49} \cdot W_A^{0.51}$
hydro exponential	Dortch & Gerald (1995)	$N_{ret} = W_L \cdot (1 - e^{-k_{TN} \cdot \tau})$

**Table 5.1:** Comparison of applied nitrogen retention models from the literature, where  $W_L$  = nitrogen load, that enters the floodplain.  $W_A$  = wetland area.  $k_{TN}$  = first order removal rate for nitrogen and  $\tau$  = hydraulic residence time

### (iii) Application of different retention models

Different nitrate retention approaches from the literature were applied to calculate nutrient retention in inundated riparian floodplains along the river Elbe (see Tab. 5.1). Only surface flow retention models were considered, since inundation of floodplains leads to comparable conditions for denitrification as in surface flow wetlands.

Whereas the linear approaches only consider the wetland load as input parameter (Mander & Mairing 1994, Jansson et al. 1998, Saunders & Kalff 2001), the exponential approaches also account for wetland area ( $W_A$ ) (Byström 1998), a first order removal rate (ratio of  $TN$  and  $NO_3-N$  concentrations and a specific denitrification rate, which is taken as 0.12 following Trepel & Palmeri (2002)) and the hydraulic residence time ( $\tau$ ) which depends on wetland volume, incoming discharge, ratio of wetland length to wetland width and upstream area.

Retention was calculated for the years 1999 to 2002. To obtain the necessary information in incoming loads,  $MQ/Q$  ratios were calculated on a daily basis. Thus, 365  $MQ/Q$  ratios were calculated per year and applied on the presented approach to calculate the share of incoming loads on the total transported load. These ratios were then averaged on a monthly and yearly basis respectively. For the calculation of inundated areas  $Q/MQ$  ratios were processed according to Natho & Venohr (n.d.).

## 3. Results & Discussion

### (i) Analysis of inundated areas, water depths and volumes

To draw a comparison Table 5.2 summarises the most important characteristics of the rivers and their floodplain. The Rhine is the river with the highest

	Elbe	Rhine	Main
$MQ$ in $m^3 \cdot s^{-1}$ at start of section	Wittenberg: 372	Maxau: 1250	Trunstadt: 106
$MQ$ in $m^3 \cdot s^{-1}$ at end of section	Wittenberge: 701	Andernach: 1250	Obernau: 165
observed river length in $km$	287	252	286
potential floodplain in $km^2$	399.0	192.2	202.0
inundated floodplain in $km^2$ at $HQ_5$	323.8	172.5	63.7
inundated floodplain in $km^2$ at $D360$	274.8	96.0	12.3
theoretical width of potential floodplain in $km$	1.4	0.8	0.7
theoretical width of floodplain in $km$ at $HQ_5$	1.1	0.7	0.2
theoretical width of floodplain in $km$ at $D360$	1.0	0.4	0.0
% of floodplain inundated at $HQ_5$	81.1	89.9	31.5
% of floodplain inundated at $D360$	68.9	50.0	6.

**Table 5.2:** Comparison of river and floodplain characteristics of the rivers Elbe, Rhine and Main along specified sections.  $HQ_5$  and  $D360$  values based on long term discharges, provided by BfG.

discharge ( $2040 m^3 \cdot s^{-1}$  at Andernach); but it is not the river with the largest total riparian floodplain. Only 50 % of the potential floodplain is inundated 5 days per year, which equals  $96 km^2$ . The Elbe, with a  $MQ$  of  $701 m^3 \cdot s^{-1}$  at Wittenberge, possesses  $399 km^2$  of potential floodplain area, of which 81 % are inundated once in five years. 69 % are still inundated for five days per year. In contrast, the river Main only discharges between 100 and  $165 m^3 \cdot s^{-1}$ . Floodplains are separated from the river by dykes. The potential floodplain amounts to  $202 km^2$ , but only 32 % is statistically flooded five times a year. The widest potential floodplain can be found for the river Elbe with  $1.4 km$ ; this mean value does not reflect, that at certain sections widths can reach up to  $3 km$  (around Magdeburg). The theoretical width of the potential riparian floodplain of the river Rhine follows with  $0.8 km$  and the river Main with  $0.7 km$  (see Tab. 5.2).

As can be seen from the results (see Fig. 5.1), floodplains rarely fill evenly but via preferential pathways such as oxbows. Thus, the theoretical floodplain width helps as a tool to compare the floodplains, but it does not help to explain a functional aspect of floodplains.

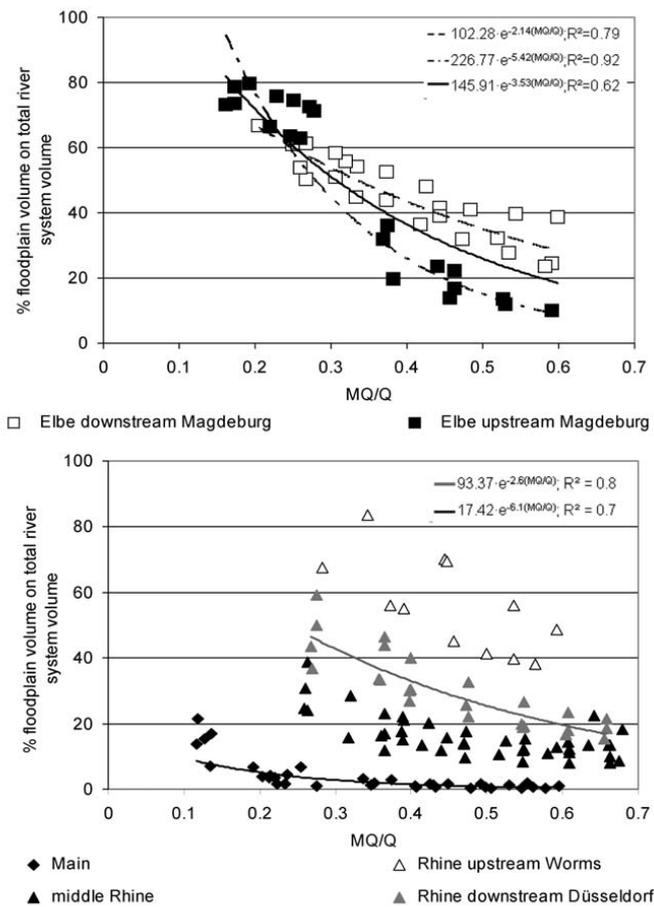
Volumes of riparian floodplains for given discharges were calculated for all three river systems. Fig. 5.2 shows the  $MQ/Q$  ratio against the calculated discharge, which enters the floodplain. Whereas all sections of the river Main could be summarized with one algorithm, different algorithms are necessary to describe the floodplain size for the Rhine sections. Three groups can be distinguished depending on the natural and anthropogenically influenced morphology of the valleys. The Elbe could be separated into upstream and downstream sections, which can also be described with

one equation as a first approach (black line). This finding is crucial for further work, as normally it is not known, how much water and, thus, load enters a riparian wetland at certain discharges.

As an example, the exponential model is given, derived for the total Elbe stretch on the basis of Fig. 5.2 and Eq. 5.2.

$$V_Q = 145.91 \cdot e^{(-3.53 \cdot \frac{MQ}{Q})} \quad (5.4)$$

where  $MQ$  = long term mean discharge and  $Q$  = current discharge, it is possible to calculate the share of the load which enters in the riparian wetland. The overestimation of incoming loads as mentioned in the method section, is insignificant for incoming load calculation on a yearly basis, since very high floods resulting in 80 % of the incoming load (Fig. 5.2, river Elbe) occur sta-



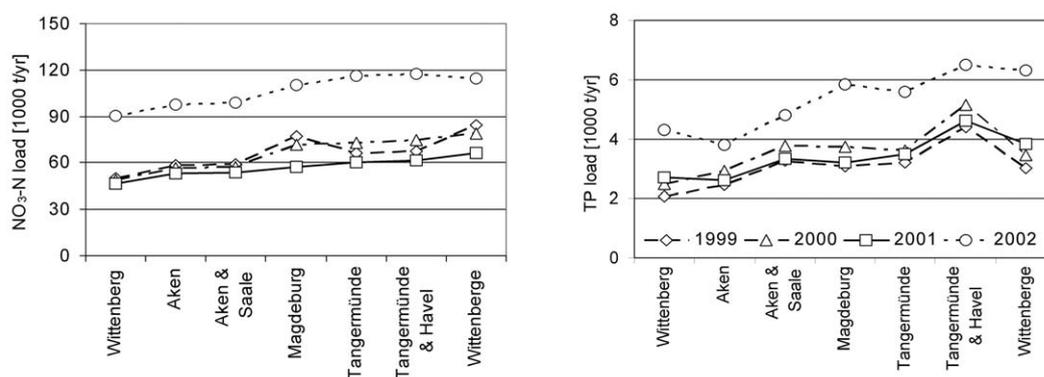
**Figure 5.2:** Illustration of the relationship between % floodplain volume on the total river system volume and the  $MQ/Q$  ratio for the Elbe (upper figure) and Main and Rhine (lower figure).

tistically once in five years.

## (ii) Comparison of calculated loads

The *TP* load calculations show the influence of the tributaries on the loads in the river Elbe. This is why additionally the incoming load of the tributaries Saale and Havel were calculated and added to the load at the previous gauge (see Fig. 5.3). Results for  $NO_3-N$  loads on a yearly basis can be seen in Fig. 5.3.

2002 was the year with the hundred year flood, reconnecting huge shares of



**Figure 5.3:** Comparison of observed  $NO_3-N$  loads (left) and *TP* loads (right) at various gauges along the river Elbe on a yearly basis, calculated according to OSPAR (2008). At Aken and at Tangermünde the influence of tributaries is accounted for by adding the load from the Saale and the Havel respectively. Scales vary according to differences in loads.

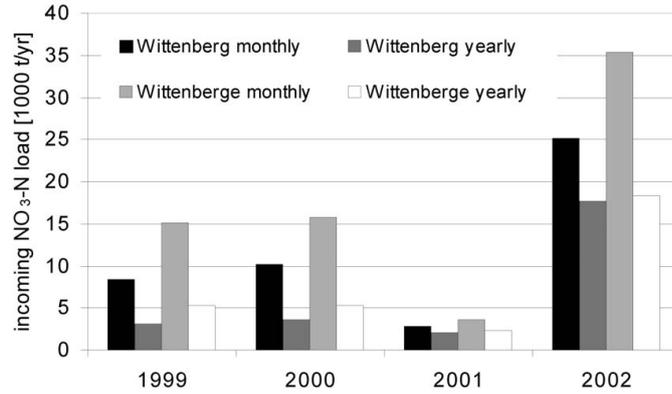
floodplains to the river at all sections. 1999 and 2000 are very similar regarding the loads. Interestingly, the  $NO_3-N$  load is higher in Wittenberge than at all previous stations, except in the year 2002. This might give a hint on retention effects in the floodplains at high floods – for this section only, whereas no decline of loads can be found for other sections. Generally, on a yearly basis it is not possible to extract any influence of riparian floodplains on  $NO_3-N$  loads from the in-stream retention, which occurs as well (Venohr 2006). In contrast, the decline of *TP* loads between Tangermünde & Havel and Wittenberge is more pronounced (Fig. 5.3, right) and also remained during the high floods in 2002.

On a monthly basis (not shown) the temporal distribution of high flow events varies significantly and, thus, also loads. Floods occur during the winter months, especially from January to April and transport more than 69% of the yearly load in these months, which is typical for middle European rivers.

### (iii) Application of different retention models

Monthly and yearly calculations were carried out (Fig. 5.4). Both approaches reflect higher loads in 2002. But the variation of  $NO_3-N$  loads between 1999, 2000 and 2001 is shown clearer by the monthly calculation.

For the application of the retention models, the floodplain area had to be allocated to the corresponding gauge. Thus, it is assumed that the load, which passes between Tangermünde and Wittenberge, equals the load measured at Tangermünde (Tab. 5.3). The



**Figure 5.4:** Comparison of a yearly and a monthly approach to calculate the  $NO_3-N$  retention in wetlands for the first and the last gauge of the analysed river section of the Elbe.

comparison of the nutrient retention models showed large differences in the calculated  $NO_3-N$  retention. Based on load reductions in percent, linear approaches show constant removal rates of more than 60% (see Tab. 5.1). According to Dortch & Gerald (1995) several parameters, which vary depending on the mean yearly discharge, led to removal rates of between 2.5 and 20.4% on a yearly and 3.8 and 27.7% on a monthly basis. Byström's approach (1998) produced lower removal rates between 4.5 and 16.8% on a monthly basis, which lie in the range of values reported by Rucker & Schrautzer (2010). If the loads are calculated on an area basis  $kg \cdot ha^{-1} \cdot yr^{-1}$ , the linear approaches result in values for the high flow year 2002 up to  $14,500 kg \cdot ha^{-1} \cdot yr^{-1}$ , which is higher than values for constructed wetlands reported in literature (e.g. Bachand & Horne (2000)). This underlines Trepel & Palmeri's (2002) findings that linear approaches tend to overestimate retention at high discharges.

gauge & quality station	downstream floodplain	floodplain in $km^2$
Wittenberg	between Wittenberg and Aken	112.1
Aken & Rosslau	between Aken and Magdeburg	145
Magdeburg	between Magdeburg and Tangermünde	114.7
Tangermünde	between Tangermünde and Wittenberge	97.8

**Table 5.3:** Result of transferred floodplain sections from FLYS 2.1.3 refers to sections between gauges and their potential size.

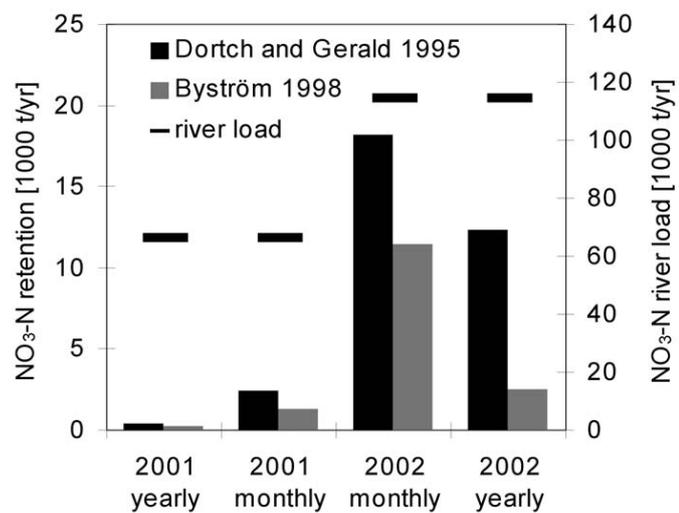
Instead, the approach by Dortch & Gerald (1995) leads to results between 440 and 660  $kg N \cdot ha^{-1} \cdot yr^{-1}$  on a yearly basis and 330 to 930  $kg \cdot ha^{-1} \cdot yr^{-1}$  and 130 to 450  $kg N \cdot ha^{-1} \cdot yr^{-1}$  according to Byström's approach on yearly basis. Values between 390 and 600  $kg N \cdot ha^{-1} \cdot yr^{-1}$  are also found in literature (Cooper 1990, Leonardson et al. 1994, Mitsch et al. 2005, Rucker & Schrautzer 2010). For the year 2002 even retention rates of up to 1400  $kg N \cdot ha^{-1} \cdot yr^{-1}$  were calculated, which lies above reported values. This might be a result of the overestimation of incoming loads (due to a high frequency of high floods in 2002) reaching up to 12,500  $kg N \cdot ha^{-1} \cdot yr^{-1}$ . Similar values are reported in agriculturally intensive catchments (Mitsch et al. 2005).

Under consideration of the total river stretch, up to 18,000 t  $NO_3-N$  can be retained per year, depending on temporal resolution, approach and hydrologic conditions (see Fig. 5.5). In comparison to the total river load, measured at the last gauge of the study area, this equals less than 12%. In dry years, as in 2001, retention is calculated to be 5% maximum. Keeping

in mind that the approach introduced in this study probably overestimates the incoming load, these maximum values also overestimate the real retention, but they are still in the range of realistic retention values reported in studies presented above.

#### 4. Conclusion

This study was able to model nutrient retention on landscape scale for a 280 km long section of the river Elbe. On the basis of the results of FLYS 2.1.3 several previous data gaps for nutrient retention approaches, concerning the distribution and the extent and the flooding frequency of riparian floodplains along the river Rhine, Main and Elbe, were filled on a landscape scale. Therefore, empirical approaches could be deduced to estimate the incoming load and



**Figure 5.5:** Comparison of total  $NO_3-N$  retention in  $t/yr$  calculated with two different approaches for the total study area along the river Elbe to the  $NO_3-N$  river load at the last gauge of the river section in Wittenberge.

the floodplain size, depending on the discharge, the river load and the potential floodplain size respectively. The floodplains' depth and volume were averaged to simplify the complex characteristics, assuming an average discharge through the whole floodplain. This oversimplification does not necessarily reflect real conditions, but it allows a first application of existing retention models on landscape scale.

The applied nutrient retention models are based on a yearly approach to calculate  $NO_3-N$  retention in wetlands, and application on a monthly basis gave slightly higher retention values, still ranging in the order of reported retention values. Applying the monthly approach allows the consideration of hydrologically induced variation in load transport, which is usually highest in wintertime and cannot be considered by yearly calculations. Nevertheless, a temperature which accounts for slower denitrification rates could improve the retention approaches. Calculating on a monthly basis is possible at landscape scale, since water quality sampling takes place fortnightly.

The present work can be understood as a preliminary study to introduce a new approach to calculate the incoming load in floodplains depending on daily discharges. Parameters were identified that will be crucial to consider in the next step, in which the approach will be improved by using more precise data on floodplain characteristics and validation by gauges.

## 5. Acknowledgments

The authors warmly thank the FLYS team J. Graf, M. Hammer, M. Hatz, N. Busch and D. Meißner from the BfG who provided the software FLYS 2.1.3 and always found time to help if questions occurred. We also thank Angela Kämpfer for correcting our English as well as three nameless reviewers for their constructive improvements.

## 6 Modelling spatial and temporal dynamics in floodplains: extent, nutrient loads and retention

S. Natho and M. Venohr 2012 Modelling spatial and temporal dynamics in floodplains: extent, nutrient loads and retention. in Sorial, G. and Hong, J. (Eds.) *Environmental science and technology* Volume 2 American Science Press, Houston, USA, PP1-632, 2012. ISBN: 9780976885344

### Abstract

This study extends and improves the recently introduced approach of Natho & Venohr (2012a) to calculate the extent of flooded riparian wetlands and share of nutrient load entering the floodplain as discharge dependent variables. The new approach does not only take the results of the Software FLYS 2.1.3 into account, as the former approach, but also flow velocities. Since the new approach was successfully validated by means of reference discharges provided by the gauges along the rivers (Elbe, Rhine and Main) this model can be used as an appropriate tool for predicting incoming nutrient loads depending on actual discharge and river characteristics.

The new database allows the application of yearly and monthly nutrient retention models from literature for phosphorus and nitrogen in comparison to the riverine retention for the years 1997-2004.

Maximum cumulative nitrate retention of 14 % of the river nitrate load and 13 % of the total phosphorus load could be calculated for the floodplains of the considered river stretch of the Elbe during August floods in 2002, whereas riverine retention contributed only 5.6 % and 6 % respectively. With this approach it is possible to calculate nutrient retention depending on the dynamics of flooded riparian area and incoming nutrient load.

### 1. Introduction

The role of riparian floodplains for nutrient retention (e.g. nitrogen and phosphorus) is widely accepted (Mitsch & Gosselink 2000, Verhoeven et al. 2006). As main processes denitrification and sedimentation are identified on yearly

basis for nitrogen retention (Saunders & Kalff 2001, Venohr 2006) and phosphorus retention respectively (Behrendt & Opitz 2000). On a monthly basis also aquatic plant uptake has to be considered (Venohr et al. 2011). There are several case studies (Trepel & Palmeri 2002) concerning measurement and modeling of nutrient retention in constructed floodplains (Mitsch et al. 2000). However, from what we know, there is no broad approach available for nutrient retention on landscape scale, since appropriate input data are hardly available. The reason for this are spatial and temporal dynamics, which result from changing hydrologic conditions on daily or even hourly basis. Thus total floodplains are inundated only seldom, but parts more often. Although the extent and the frequency of inundation are currently not known, the potentially active floodplain has decreased regarding the total floodplain. This was found out by a German wide inventory on recent floodplains, carried out for large rivers (Brunotte et al. 2009). Therefore Natho & Venohr (2012a) applied the Software FLYS 2.1.3. Based on statistical values the authors empirically derived a first approach that enables the calculation of river loads entering the floodplain (incoming loads) as well as floodplain extents depending on actual discharges. This for the first time available dataset was subsequently applied on nitrate retention models taken from the literature. But Natho & Venohr (2012a) considered too high incoming loads, due to a high degree of simplification of morphometrics and due to a disregard of flow velocity differences in river and floodplain. Furthermore yearly calculations did not reflect seasonal changes which are necessary to estimate the effect of floodplains in nutrient retention properly.

Hence the present study is addressed to improve this recently introduced approach which enables a more reliable prediction of incoming nutrient loads. The improved approach is capable to also be applied to phosphorus and nitrate retention models on a monthly basis.

## 2. Material and Methods

For the present study, some hundred kilometer of main river sections were considered for each of the rivers Elbe, Main and Rhine, respectively (for details see Natho & Venohr 2012a). Whereas in the recently developed approach of Natho & Venohr (2012a), time independent volumes were considered in river and floodplain, flow velocities were now taken into account. Detailed land-use information was obtained from digital maps in 10m resolution (of the federal states Saxony, Saxony-Anhalt, North Rhine Westphalia and Rhineland Palati-

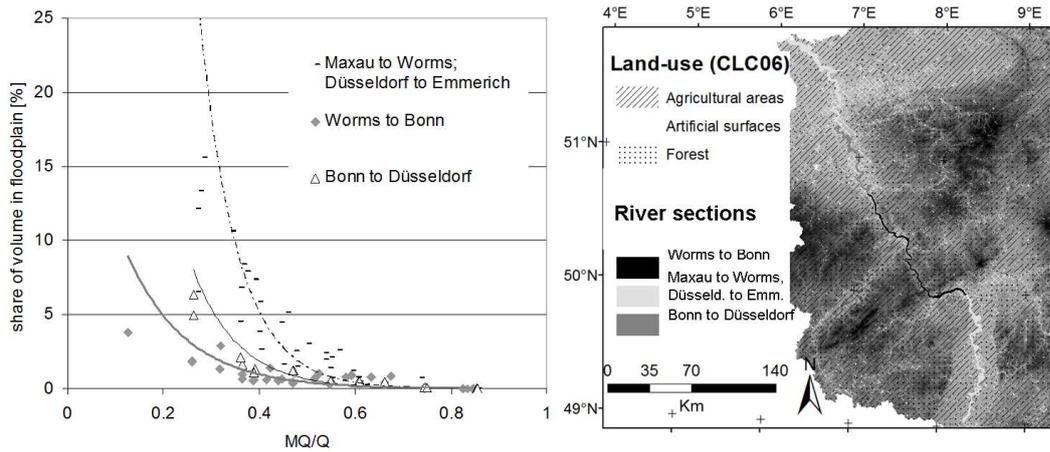
nate) and intersected with FLYS 2.1.3 model results on inundated floodplains at certain discharges (for details see Natho & Venohr 2012a). Additional land-use data were processed from the cooperation with the Helmholtz Centre of Environmental Research (for details see Natho et al. 2013). On these intersected areas land-use induced roughness ( $k_{st}$ ) was estimated according to Schneider (2010). The hydraulic radius ( $r_{hy}$ ) describes the ratio of water surface area to sediment-water-surface which is crucial for the empirical Gauckler-Manning-Strickler equation (Eq. 6.1) to estimate flow velocities.

$$v = k_{st} \cdot r_{hy}^{\frac{2}{3}} \cdot \sqrt{I_{So}} \quad (6.1)$$

To calculate rhy information on water depths is needed. The Software FLYS 2.1.3 calculates inundated floodplain extents ( $A$ ) and water depths ( $d_{water}$ ) for given discharges. The linear difference of two gauging heights relative to N.N. was considered to estimate mean slopes ( $I_{So}$ ) between two gauges. Following general hydrologic equations, this flow velocity was multiplied with the mean cross section area ( $A_{crosssection}$ ) to obtain the discharge ( $Q$ ), whereby the mean cross section results from multiplication of water depth and surface area and the division by the length of river stretch (Eq. 6.2).

$$Q = v \cdot A_{crosssection} = v \cdot \frac{A \cdot d_{water}}{l_{riversection}} \quad (6.2)$$

For the river Elbe and the river Main one equation was sufficient to describe the relationship between the ratio of long-term mean discharge and daily discharge as a function of the incoming load expressed as share of volume in floodplain. Instead for the river Rhine three different sections could be identified with three different equations for each of them (see Figure 6.1). These characteristically differences can also be found considering land-use and elevation. It is assumed, that nutrients are evenly mixed transported in the discharge, so that the share of volume equals the share of load that enters the floodplain. Daily discharges were applied for calculating daily incoming loads according to the relation between long term discharge and daily discharge (Figure 6.1). Then, the daily incoming loads were averaged on a monthly basis and on yearly basis. Similarly, inundated areas were derived on a monthly and on a yearly basis, respectively. Based on these input data, different retention models taken from the literature were applied for phosphorus and nitrogen retention calculation for the years 1997 to 2004 (see Table 6.1).



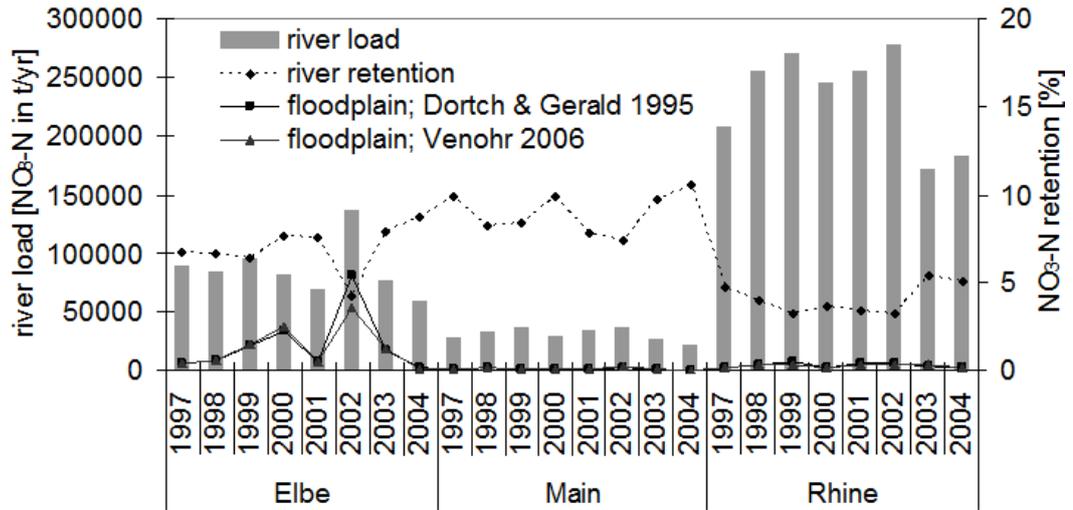
**Figure 6.1:** Relations of volume to discharge, characterizing different sections of the river Rhine (left); illustrated by a land-use map (Federal Environment Agency, DLR-DFD 2006) underlain with a SRTM 90m (US Geological Survey 2000) as well as floodplains provided by FLYS 2.1.3 (right).

	temporal resolution	considered nutrient	considered process	main parameter
Venohr (2006)	yearly	nitrogen	denitrification	HL, T
Dortch & Gerald (1995)	yearly	nitrogen	denitrification	$HRT$ , $c_{NO_3-N}$ / $c_{TN}$
Venohr et al. (2011)	monthly	nitrogen	denitrification and uptake by aquatic plants	HL, T, R
Behrendt & Opitz (2000)	yearly monthly	phosphorus phosphorus	sedimentation sedimentation	HL HL

**Table 6.1:** Overview of applied retention models. Beside the necessary incoming nutrient load, following parameters are considered:  $HL$  = hydraulic load (discharge/area),  $T$  = temperature,  $R$  = global radiation,  $HRT$  = hydrologic retention time (area, discharge and shape dependent),  $c$  = concentration.

### 3. Results

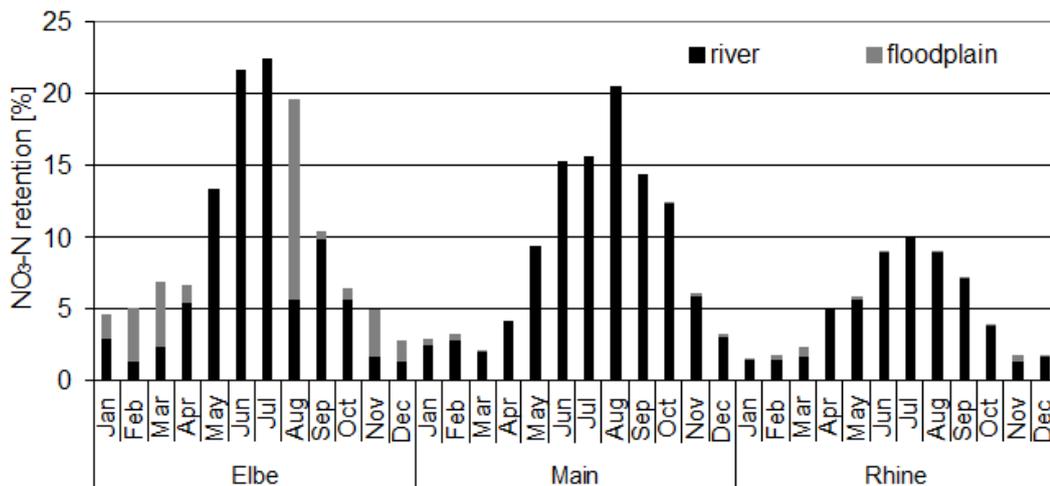
In the first part of the present study the former approach of calculating incoming loads could be reduced: whereas the former approach calculated up to 80 % of the load entering the floodplain, this value is reduced to only maximum 35 % according to the new approach. These values are found along the river Elbe, where floodplains are relatively natural. Smaller values (15 %) are found for the river Main, which has small floodplains. For smaller floods, also for the river Elbe, less than 20 % of the river load enters the floodplain and underlies retention. Considering nitrate retention on yearly basis, the results of the two retention models are similar (Figure 6.2). River retention decreases when river loads increase due to floods. However, deviation between the models can be



**Figure 6.2:** Comparison of yearly  $NO_3-N$  retention calculations (in floodplains and rivers); yearly river loads are also shown

found along the Elbe for the year 2002.

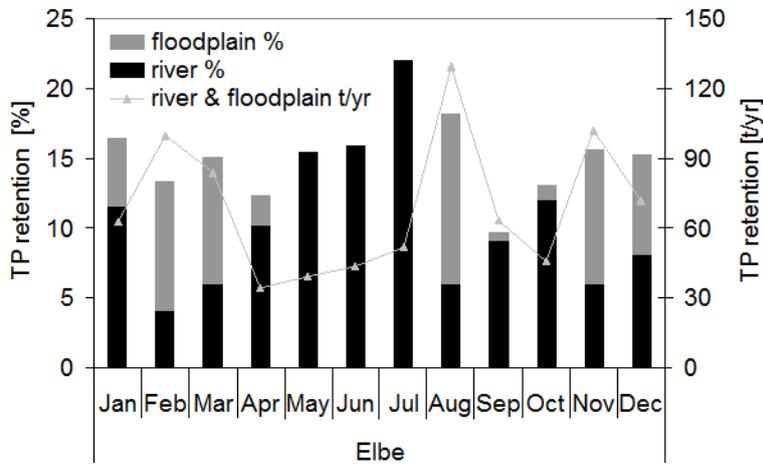
On a monthly basis the approach proposed by Venohr et al. (2011) reveals the influence of water temperature: floods in August lead to extremely high retention rates in the floodplain, exceeding the cumulative nitrate retention in the river by a factor of 2.5. Generally nutrient retention is higher for the river Elbe than for the river Rhine or for the river Main. Total phosphorus retention is only shown for the river Elbe in Figure 6.3, where floodplain retention is highest in August 2002. As sedimentation is not water temperature dependent, floodplain retention in August does not exceed river retention as pronounced as for nitrate. Nevertheless, the contribution of floodplain retention on phosphorus retention in the whole river can be demonstrated.



**Figure 6.3:** Comparison of monthly nitrogen retention results in 2002, calculated according to Venohr et al. (2011)

After this general observation, area specific retention rates can be derived. On

a yearly basis the calculated nitrogen and phosphorus retention rates range between 50 and 930  $kg\ NO_3-N \cdot ha^{-1} \cdot yr^{-1}$  and 2 and 70  $kg\ TP \cdot ha^{-1} \cdot yr^{-1}$ , depending on hydrologic condition and river.



**Figure 6.4:** Cumulative TP retention in 2002; calculated according to Behrendt & Opitz (2000)

values of 186 and 18  $kg \cdot ha^{-1} \cdot yr^{-1}$ ), whereas for the river Rhine floodplains between 310 and 64  $kg \cdot ha^{-1} \cdot yr^{-1}$  are calculated respectively.

Again highest values can be found for the river Elbe, with average retention rates of 455  $kg\ NO_3-N \cdot ha^{-1} \cdot yr^{-1}$  and 44  $kg\ TP \cdot ha^{-1} \cdot yr^{-1}$  for the years 1997 to 2004. Along the river Main the lowest retention is calculated (with mean

#### 4. Discussion

Flow velocities are crucial for the amount of discharge and thus load entering the floodplain. Compared to the former approach, with the new approach the incoming load could be reasonably reduced.

On a yearly basis the calculated nitrogen and phosphorus retention rates are within the range of reported values (Mitsch et al. 2000). Nutrient retention is higher for rivers with relative well connected floodplains like the river Elbe than for rivers without intact floodplains (Mitsch & Gosselink 2000). Although parts of the river Rhine possess large floodplains, their contribution to nutrient retention is relatively low, because retention is only accounted for flooded floodplains. In the considered years, most of the floodplains were not inundated and thus not active. Reconnection und hence more frequent inundation of floodplains can contribute to nutrient retention, if connection is similar to the connection of the floodplains of the river Elbe.

Inter annual variation of the retention is high due to variation in hydrology and due to potential floodplain extent. With respect to the modelling, this leads to a variation of the inundated floodplain extent in the current year. Usually floods occur in early spring, leading to inundation of floodplains and thus retention in all rivers. The model of Venohr et al. (2011) captures the

effect of summer floods, since water temperature increases which in turn leads to higher denitrification rates. The consideration of temperature based effects explains the difference in nitrate retention calculation between the model given by Dortch & Gerald (1995) and Venohr (2006) for the year 2002. Nevertheless on a monthly basis nitrogen retention might still be overestimated, since the model was developed for riverine retention. It is assumed that aquatic plant uptake occurs in summer time only. Terrestrial plants, as existent on floodplains, might have a slightly different effect on nitrogen transformation and thus nutrient retention processes. The additive nutrient retention effect of floodplains is very important, since floodplain and river retention behave conversely: river retention is high, when discharge is low, whereas floodplain retention is high, when flood conditions are low. The latter occurs, when the biggest share of nutrient loads is transported as was shown in Figure 6.4 (Johnes 2007, Oeurng et al. 2010). Hence, under flooded conditions retention in floodplains is higher than in rivers (Saunders & Kalff 2001).

## 5. Conclusion

This study presents an improved approach for calculating incoming nutrient loads for riparian floodplains of three German rivers, depending on flow velocities in river and floodplain. According to the naturalness of the floodplains, up to 35 % of the river load for very high flood events and under normal conditions less than 20 % of the river load enters the floodplain. This approach is applicable for creating a reliable database for monthly and yearly retention models, since variation in hydrology and thus floodplain extent can be modelled. Using different retention models the significant contribution of floodplains to nitrogen and phosphorus retention could be shown on landscape scale, which even exceeds river retention under wet hydrologic conditions, leading to several flooding events: In floodplains, nitrate retention of up to 14 % of the transported load could be found for the river Elbe, a relative natural river. This indicates the retention potential of existing floodplains when reconnection is possible.

## 6. Acknowledgments

The authors thank the Helmholtz Centre of Environmental Research for additional data processing.

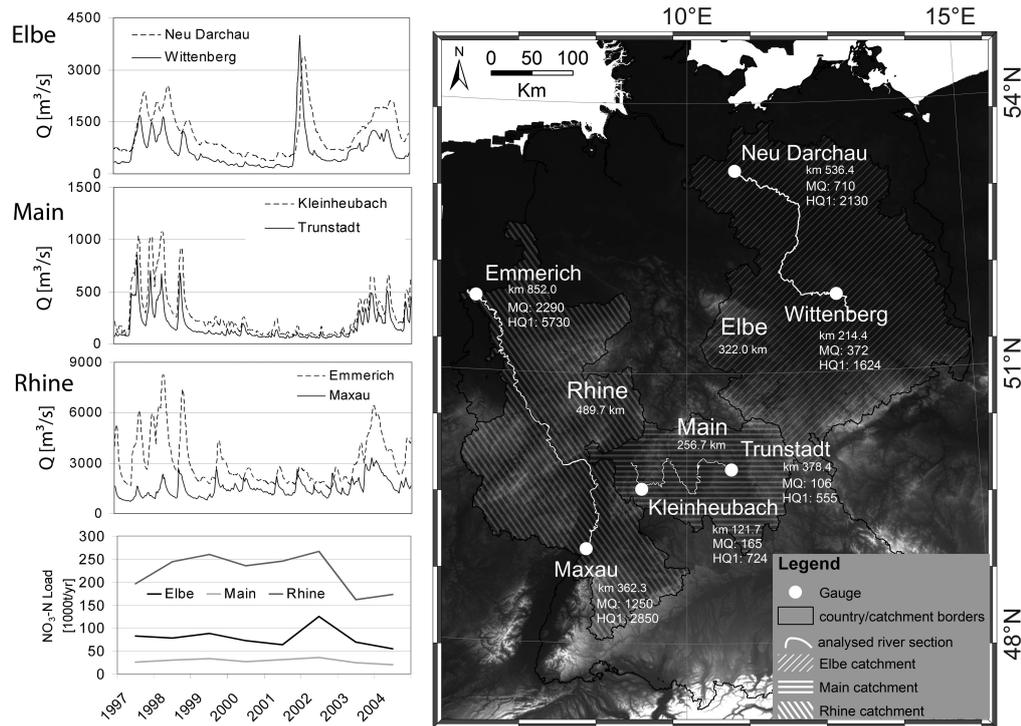
## 7 Modelling nitrogen retention in differently degraded floodplains of three large rivers in Germany

Natho, S. Venohr, M., Henle, K. and C. Schulz-Zunkel 2013 Modelling nitrogen retention in differently degraded floodplains of three large rivers in Germany. *Journal of Environmental Management* **122**, 47-55. <http://dx.doi.org/10.1016/j.jenvman.2013.02.049>

Keywords: connectivity, inundation, flood event, land use, ecosystem functioning, nutrient retention

### 1. Abstract

Floodplains perform a variety of ecosystem functions and services - more than many other ecosystems. One of these ecosystem services is the reduction in nitrogen (N) loads and a subsequent improvement to the water quality. Since diffuse and also point nitrogen sources continue to cause a variety of problems in rivers and floodplains, inundated floodplains could act as net sinks for N and are therefore of great importance throughout Germany and Europe. This study analyses the effects of riparian floodplains on N-retention on the landscape scale for three large river systems with different degrees of degradation. Two approaches, differing in terms of the complexity of their respective input data and methods, were applied under wet and dry conditions. Whereas the proxy-based approach considers proxy values for N-retention, the model-based approach accounts for event-driven dynamic input data such as the extent of the inundated floodplain and incoming loads. Comparing the results of the two approaches it can be observed that floodplains of the near-natural river can retain up to 4 % of the river load under wet conditions. During such conditions N-retention in floodplains is similar to that of rivers. For the two other floodplains, the results of the two approaches were quite different, showing lower N-retention capacities. However, for these floodplains as well, both approaches are suitable for calculating measurable N-retention rates, which is an important result because it also suggests that even degraded floodplains still preserve this particular ecosystem function and therefore still contribute to improving the quality of river water.



**Figure 7.1:** Studied catchments of the rivers Elbe, Main and Rhine in Germany, under consideration of a digital elevation map (SRTM). Discharge patterns are shown for the year 1999. The map shows mean discharge (MQ) and discharge occurring once a year ( $HQ_1$ ) for the start and end gauges of the analysed river sections.

## 1. Introduction

Floodplains provide several ecosystem services such as floodwater retention, the most recognised, carbon storage, maintenance of biodiversity etc. (Constanza et al. 1997, Maltby et al. 2009). Recently, awareness has grown that floodplains can also improve water quality because of their natural capacity to retain nutrients. In the context of the EU Water Framework Directive (WFD) aimed at achieving a 'good ecological status' of surface water and groundwater by 2015, this service is relevant, seen as the desired status can hardly be reached by applying conservative measures alone. This is due to the fact, that nitrogen (N) inputs from agricultural areas are still high, leading to excessive N-loads and ultimately river loads (Behrendt et al. 2002, Deutsch et al. 2006) that get into floodplains when inundation occurs. Consequently, N-levels are high and it is very likely that a combination of all available management options will be necessary to reach the goal of the WFD.

Since most of the N transported in the river is available as nitrate (Deutsch et al. 2006), denitrification is the main process of N-retention in floodplains (Byström 1998, Kronvang et al. 2004, Pinay et al. 2007, Saunders & Kalff 2001,

Verhoeven et al. 2006) and, as such the process of permanent removal of N from the river system. During this process N is converted via  $N_2O$  to atmospheric  $N_2$  (Trepel & Palmeri 2002). Water temperature, water content, duration of inundation, and carbon content are the main driving forces behind denitrification as described in several studies on floodplains also at the local level (Arheimer & Wittgren 1994, 2002, Kronvang et al. 1999, Hernandez & Mitsch 2007, Pinay et al. 2007, van der Lee et al. 2004, Olde Venterink et al. 2003, 2006, Venohr 2006). Generally denitrification rates vary greatly depending on different wetland characteristics and climate conditions (Mitsch et al. 2000, Pinay et al. 2007). Seasonally-changing water tables (groundwater or river water) influence the characteristics and processes of floodplains. Mineral and organic soil patches develop which favour denitrification differently because of water storage capacity and organic carbon content (Cooper 1990). Such patches can be defined as biogeochemical hot spots because they show disproportionately high reaction rates relative to the surrounding matrix. Rises in water levels depending on the season may also lead to hot moments, which are defined as short periods of time that exhibit disproportionately high reaction rates relative to longer intervening time periods (McClain et al. 2003).

Consequently, spatial as well as seasonal heterogeneity are likely to play an important role in terms of N-retention in floodplains. Another very important characteristic of river-floodplain systems is the level of connectivity between rivers and their floodplains (Amoros & Roux 1988). Here the degree of connectivity is strongly determined by the dynamics of discharge, the exchange of matter and the processing of organic matter and nutrients across river-floodplain gradients (Junk et al. 1989, Tockner et al. 2000). However, little is still known about the actual extent to which floodplains can contribute to improving water quality in large river systems. This is due to a lack of complete datasets at the landscape level, where and to which extent floodplains exist and to which level they are connected to the river or not.

The floodplain inventory for Germany (Brunotte et al. 2009) has for the first time ever made information available on the spatial extent of active and inactive floodplains. We used this data to develop two different approaches, 'proxy-based' and 'model-based', for assessing and quantifying N-retention in large floodplains at the landscape level. With the proxy-based approach we were able to assess and quantify the N-retention rates of large rivers nationwide and provide comparisons between several floodplains (Schulz-Zunkel et al. 2012). However, on this scale, the temporal variations that depend on the seasonal-flooding dynamics within active floodplains are still not fully known, therefore

we also developed a model-based approach, which tackles these questions by including the days of inundation as well as the spatial distribution of floodwater during inundation events. Three of the different empirical model approaches described in the literature were applied (see Tab. 7.1).

Using three river systems as examples we wanted to demonstrate that quantifying N-retention at the landscape level is possible and that hot spots and hot moments of N-retention within floodplains can be identified. Further, we were able to distinguish between the different degradation levels of river-floodplain systems, which we assume is revealed by different N-retention capacities. Finally, we quantified the contribution of floodplains to N-retention compared to in situ river retention depending on their degree of degradation.

## 2. Methods

### 2.1 Study site

We investigated the floodplains of the rivers Elbe, Main and Rhine (Fig. 7.1). The lengths as well as the discharges studied differed markedly from each other. Only slight variations could be observed for the flow regime, as only the stretches in the lowlands and low mountain ranges were considered. All of the three rivers usually experience winter and/or early spring floods; summer floods usually only occur under special circumstances, such as those in 2002 when due to heavy rainfalls an extreme flooding event occurred along the river Elbe. Overall, the study sites show clear differences in the remnants of active floodplains. Floodplain losses range from 50 to 90%. The active Elbe floodplains are the largest covering about 54,000 ha, while the Rhine floodplains account for approx. 30,000 ha and the Main floodplains for approx. 11,000 ha. In terms of features of the natural environment, both the river and the floodplains of the Elbe can be regarded as near-natural. Within the Rhine floodplains, the degree of floodplain degradation ranges from greatly-modified to almost intact. Contrarily, the floodplains of the river Main have been heavily modified due to waterway constructions and resulting hydraulic installations as well as a loss of morphodynamics (see Brunotte et al. 2009).

### 2.2 Methodology

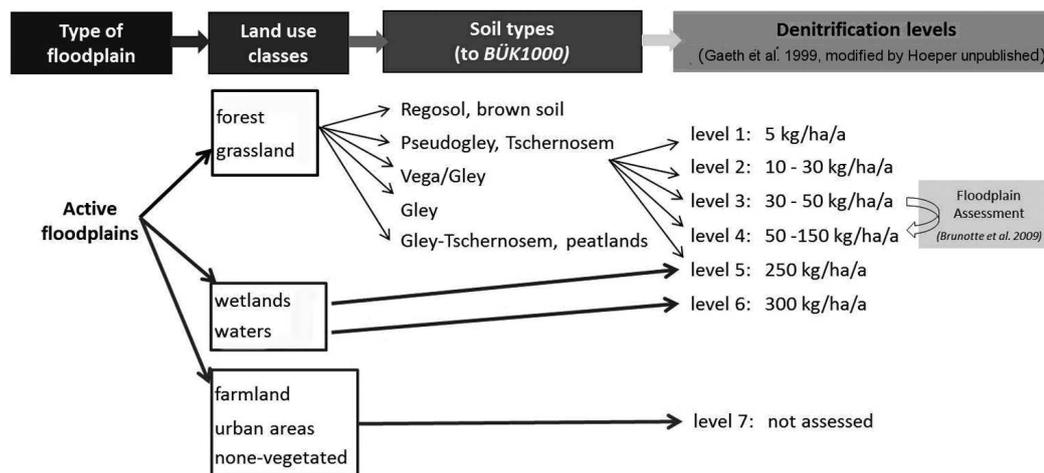
For both approaches, we considered a) dissolved nitrogen in the river water, b)  $NO_3-N$  retention (hereafter referred to as N-retention), and c) denitrification

as the main process of N-retention, because we wanted to focus on the contribution of floodplains to improving river water quality through N-retention.

### 2.2.1 Proxy-based approach

Figure 7.2 shows the decision cascade of the proxy-based approach. It was designed to carry out a nationwide assessment of active floodplains in Germany with a catchment area greater than  $1,000 \text{ km}^2$ . This classification is built on the knowledge that, depending on their redox characteristics, different soil types have different capacities to convert  $\text{NO}_3\text{-N}$  into  $\text{N}_2$ . The characterized soil types were derived from the German soil map 1:50,000 (BÜK 50).

However, for the German wide assessment the BÜK50 does not provide a comprehensive database which is why we used the BÜK1000, which maps information on soil types from the German soil map 1:1,000,000, instead. As we are aware of a greater generalization within BÜK1000 compared to BÜK50 we had to slightly modify the existing methodology and classified six denitrification levels (DNL) ranging from 1 (very low) to 6 (very high) as opposed to the original five. Beyond that, we distinguished between the soil types ‘Vega’ and ‘Gley’ which are pooled in the BÜK 1000 as ‘Vega/Gley’, but display significantly different abilities for denitrification (DNL2 for ‘Vega’ and DNL 4 for ‘Gley’) in order to find a more appropriate DNL. The methodology enables modification to the DNLs when the investigation sites are known to be water-logged. In our case we assume that when the soil type ‘Vega/Gley’ is present within active floodplains, then at least temporal water-logging can be expected and therefore we assigned DNL3 to the soil type ‘Vega/Gley’. Subsequently, we combined the soil data with German-wide data sets that had been collected within the scope of previous projects (Brunotte et al. 2009). This data provided detailed information on the extent of floodplains, the differentiation between active and inactive floodplains - including area-specific land-use data (7 classes summarized from a digital land-use map 1:25,000). Since the land-use data are more detailed than the soil data of BÜK1000 we were able to assess scattered land-use classes for ‘wetland’ and ‘water’ that are widely known as exceptionally important sites for denitrification in floodplains (Olde Venterink et al. 2006, Verhoeven et al. 2006). To assess both ‘wetland’ and ‘water’, DNL5 was re-classified for ‘wetland’ and a new DNL6 was introduced for ‘water’ according to published data (e.g. see Kronvang et al. 1999, Pina-Ochoa & Alvarez-Cobelas 2006). Furthermore, we included the ascertained status of rivers and floodplains in Germany that described the



**Figure 7.2:** Decision cascade of the proxy-based approach for assessing nitrogen retention in floodplains

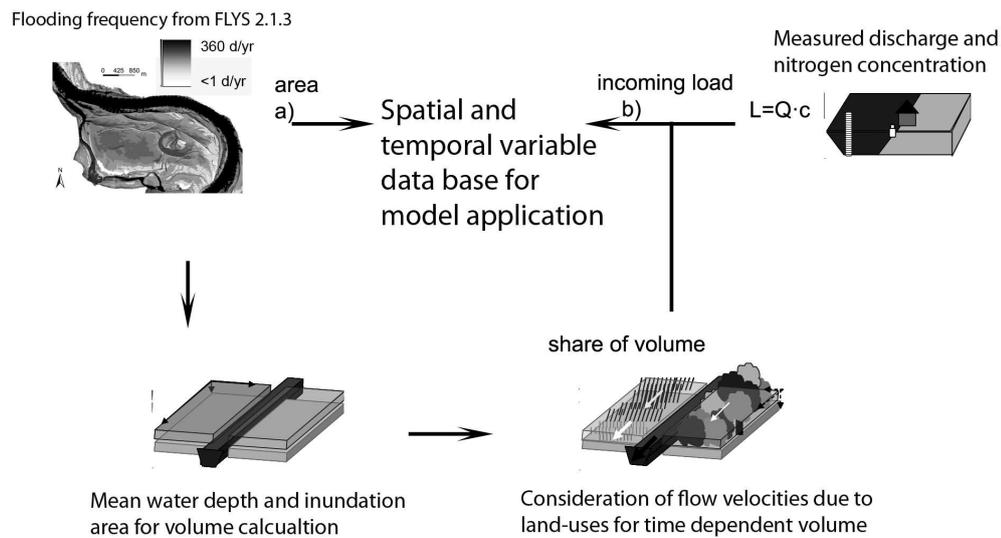
extent of the floodplains, their loss of area that could potentially be flooded and their degradation in five classes from ‘slightly modified’ (1) to ‘greatly modified’ (5) (Brunotte et al. 2009). Here we assumed that an overall good condition of floodplains (classes 1-3) indicates a generally good connection of floodplains with river dynamics and thus also floodplain functions with a good performance. For example, if soils lead to DNL3 in an overall well classified floodplain, we manually upgraded DNL3 to DNL4. We excluded the land-use classes ‘arable land’, ‘urban areas’ and ‘areas without vegetation’ regardless of their soil type from the analysis. This was due to uncertainties that are related to these classes such as an artificial increase in nitrogen input e.g. from fertilizers or sealed areas, which cannot be denitrified. Furthermore, we assume that the inundation of these areas is an extremely rare event. Therefore, by not incorporating these land-use types we indirectly exclude those areas that are expected to have very little connection with river dynamics. By considering the overall floodplain conditions and the differences within the given land-use classes in addition to the existing method, we account, at least indirectly, for important hydrological parameters such as the duration of inundation and the size of flooded areas.

### 2.2.2 Model-based approach

Various N-retention models are described in the literature (see Table 1). When incoming loads are high, then exponential models can be said to reflect retention values more realistically than linear models (Trepel & Palmeri 2002, Natho & Venohr 2012a). For this reason we only considered exponential (Byström

author	system, the model was developed for	temporal resolution	a)Complexity b)number of variables (V) and constants (C)
Arheimer & Wittgren (1994)	Lakes and wetlands treated as ponds	Day	a)Linear & 2V; 1C b) $W_A$
<b>Dortch &amp; Gerald (1995)</b>	Surface flow wetlands, either fully mixed batch reactors or plug flow	Year/long term average flow	a) hydro-exponential b) $W_L$ , $W_A$ and $>2V$ & 2C
Mander & Mauring (1994), Jansson et al. (1998), Saunders & Kalff (2001)	Fens and bogs	Year	a)linear b) $W_L$ & 1C/2C
<b>Byström (1998)</b>	unspecific wetland	Year	a) exponential b) $W_L$ , $W_A$ & 2C
Arheimer & Wittgren (2002)	Surface flow wetlands, treated as fully mixed batch reactors	Day	a)exponential b) $W_A$ and $>2V$ & 1C
Kronvang et al. (2004)	Riparian wetland	Year	a) linear b) $W_A$
<b>Venohr (2006) improvement of the approach provided by Behrendt &amp; Opitz (2000)</b>	Rivers and inundated floodplains	Year	a)hydro-exponential b) $W_A$ , $W_L$ and 2V & 2C
<b>Venohr et al. (2011)</b>	Rivers and inundated floodplains	Month	a)hydro-exponential b) $W_A$ , $W_L$ and $>2V$ & $>2C$

**Table 7.1:** Overview of empirical nitrogen retention models which are applicable on landscape scale. If considered in the model, the variables wetland load ( $W_L$ ) and wetland area ( $W_A$ ) are mentioned explicitly, other variables are counted only; bold models are compared in the model based approach.



**Figure 7.3:** Methodology of the model-based approach to derive information on inundated floodplain size (a) and incoming load (b)

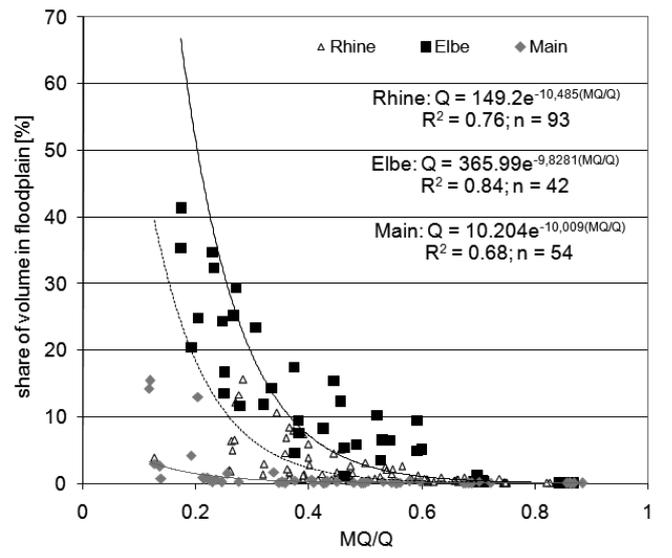
1998) and hydro-exponential models (Dortch & Gerald 1995, Venohr 2006, Venohr et al. 2011). The application of these models is restricted at the landscape scale, due to a lack of necessary input data regarding the incoming load and the size of the inundated floodplain. Thus it was deduced empirically that the size of the inundated floodplain and the incoming load depend on the ratio of daily discharge and on the long-term mean discharge averaged on a yearly basis (Natho & Venohr 2012a) based on the results of the extent and the depth of inundated floodplains for given discharges using the software FLYS 2.1.3. This software was developed by the Federal Institute of Hydrology (BfG) and derives data from 1D hydrological models. Calculations using FLYS are regularly made for the maintenance of the German Federal Waterways, which is why the results can be regarded as reliable (BfG 2009). With this dynamic approach it was possible to calculate a) the extent of the inundated floodplain and b) incoming loads for any discharge and any river section (Fig. 7.3). It is assumed that the flow velocity is the same in the river and the floodplain, although flow velocities in the river are actually higher than in the floodplain (Natho & Venohr 2012a). As a result, this assumption leads to high amounts of incoming loads compared to the N-loads in the river itself. We were able to successfully improve the incoming load approach in this study by taking into account different flow velocities for individual floodplains and rivers as well as more detailed information on floodplain geometries (Natho & Venohr 2012b). Flow velocities ( $v$ ) were calculated for different discharges by trans-

ferring roughness values ( $k_{st}$  values) of the vegetation types Schneider (2010) to the land-uses found in the floodplain (arable land =  $18m^{1/3} \cdot s$ , wetlands =  $8m^{1/3} \cdot s$ , water surfaces =  $30m^{1/3} \cdot s$ , grassland =  $20m^{1/3} \cdot s$ , urban settlements =  $30m^{1/3} \cdot s$ , open area = 30 and forest =  $12m^{1/3} \cdot s$ ) and  $35m^{1/3} \cdot s$  for the river. The Gauckler-Manning-Strickler algorithm was then applied to validate the discharges that had been calculated ( $Q_{calculated}$ ) with observed discharges at the corresponding gauge ( $Q_{gauge}$ ) (six gauges respectively for the Elbe and the Main and twelve gauges for the Rhine were considered):

$$w_{floodplain} = \frac{A_{floodplain}}{l_{riversection}} \quad (7.1)$$

The mean slope ( $I_{So}$ ) was derived from linear height interpolation of the gauges at the inlet and outlet of the floodplain. The hydraulic radius ( $r_{hy}$ ) was calculated by accounting for the water surface area and for simplified cross section geometry ( $A_{floodplain}$ ).

Figure 7.4 shows the relationship between the amount of volume in the floodplain and discharge for the three rivers for calculating the proportion of the incoming load depending on the ratio of the long-term mean and the current discharge. Whereas all analysed river sections of the Elbe and the Main are similar, the river Rhine can be divided into three classes (Natho & Venohr 2012b). For the



**Figure 7.4:** Relationship between the incoming load expressed as share of volume in floodplain and the ratio of long-term mean discharge and current discharge for the three rivers Elbe, Rhine and Main.

model application, the respective equations were applied for daily discharges from gauges of each river section. Finally, the mean share of the incoming load was applied to calculate the mean incoming load for each year. Corresponding steps were taken to calculate averaged inundated areas. With this new information on area and incoming load, three N-retention approaches were

applied for the years 2002 and 2004, representing wet and dry conditions from a hydrological perspective.

### 3. Results

#### 3.1 Quantifying nutrient retention

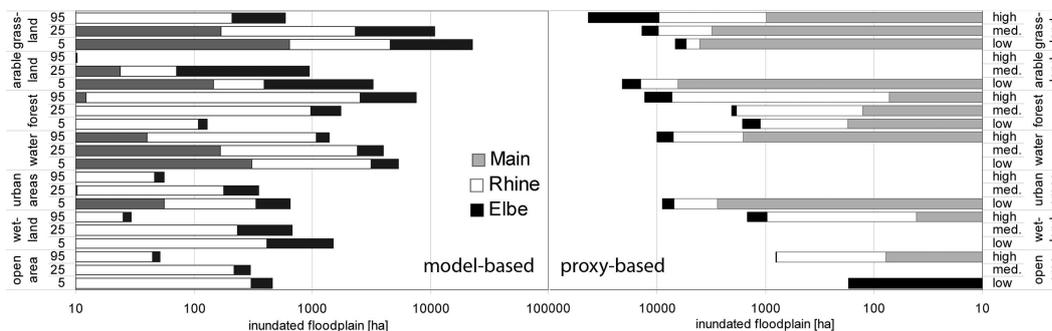
Generally speaking, the results show that quantifying N-retention at the landscape level can be described by proxy-based and model-based approaches, although the calculated retention rates differ according to changing hydrological conditions. Table 7.2 shows the calculated N-retention capacities for a dry (2004) and a wet (2002) year also expressed by minimum and maximum values. Both approaches calculate lower retention rates in the dry rather than in the wet year for all floodplains. It is also shown that the Elbe floodplains have significantly higher retention rates (3.9% the transported river load according to Venohr (2006) and 5.8% according to Dortch & Gerald (1995) for 2002) compared to the Rhine and the Main floodplains. Furthermore, the proxy-based approach follows this trend and provides percentage retention rates from 2.8 – 3.8% for the Elbe floodplains. Table 7.2 also shows that the importance of N-retention in the floodplain increases with high flood events. Whereas for 2004 N-retention in the Elbe floodplains is calculated to be significantly less than in the river, for 2002 the approaches of Dortch & Gerald (1995) and Venohr (2006), proxy-based approach calculate N-retention rates similar to those in the river Elbe itself. For the river itself, absolute N-retention rates increase with increasing discharges, whereas relative retention rates decrease. Contrarily, for floodplains both relative and absolute N-retention rates increase with discharge.

The results of the model-based approach also identify hot spots of N-retention within the inundated floodplains, which occur mainly in ‘wetlands’ and ‘water’ that are inundated at least 95 days per year (Fig. 7.5). These areas however are underrepresented within the floodplains and together only account for 7% of the Elbe floodplains, 8.5% of the Main floodplains and 14% of the Rhine floodplains. The Elbe floodplains have approx. 450 ha of ‘wetland’ areas which are probably inundated for at least 100 days of the year. Although the Rhine floodplains have a similar extent of ‘wetland’ areas, inundation here only lasts for approx. 60 days per year and only on around 230 ha of these areas. Moreover, the proxy-based approach is able to identify such hot spots by combining land-use, soil type and floodplain characteristics and thus to classify denitrifi-

		$t \cdot 100 \text{ km}^{-1} \cdot \text{yr}^{-1}$			% of river load		
		Elbe	Main	Rhine	Elbe	Main	Rhine
proxy based	min	705	118	442	2.3	0.9	0.8
	max	1628	128	725	3.8	1.1	1.3
Dortch & Gerald (1995)	2004	297	11	144	0.1	<0.1	0.2
	2002	2520	28	233	5.8	0.2	0.4
Byström (1998)	2004	86	10	26	<0.1	<0.1	<0.1
	2002	439	17	60	1.1	0.1	0.1
Venohr (2006)	2004	316	11	12	0.1	<0.1	0.2
	2002	1636	32	199	3.9	0.2	0.4
in situ river retention Venohr (2006)	2004	1728	2001	1174	9.6	11.8	5.4
	2002	2072	2327	1365	4.9	8.0	3.4

**Table 7.2:** Comparison of retention calculations with the proxy-based approach and the model-based approach in  $t \cdot 100 \text{ km}^{-1} \cdot \text{yr}^{-1}$  and in % of river load.

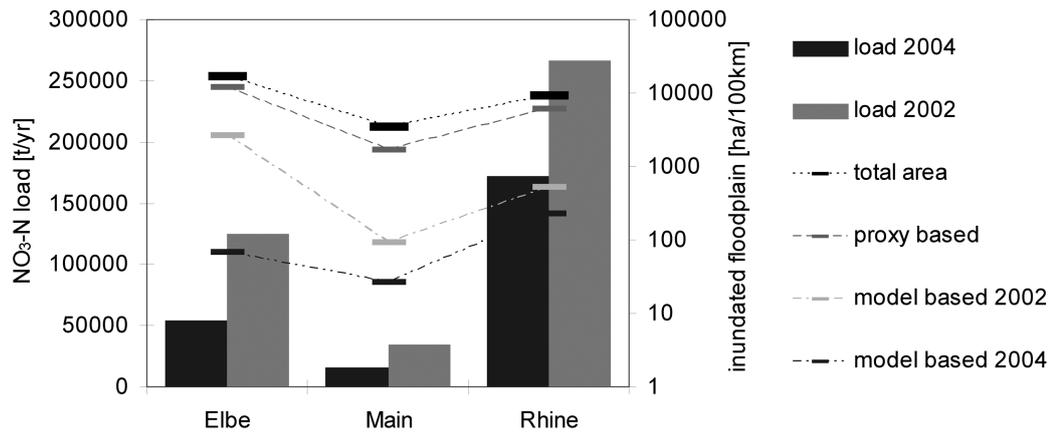
cation levels (DNL). More than 50 % of ‘grassland’ as well as 10 % of ‘forests’ can be classified as having high DNLs. After comparing these DNLs with statistical inundation periods derived from FLYS combined with land-use types it becomes clear that grassland is the dominant and most effective land use in inundated floodplains (Fig. 7.5). Within the Rhine floodplains land-use



**Figure 7.5:** Land-use types and assessed denitrification levels (DNL) for the floodplains of Elbe, Main and Rhine (on right) in comparison to the floodplains statistically inundated on 95, 25 and 5 days per year respectively. Inundation data is derived from FLYS 2.1.3 results.

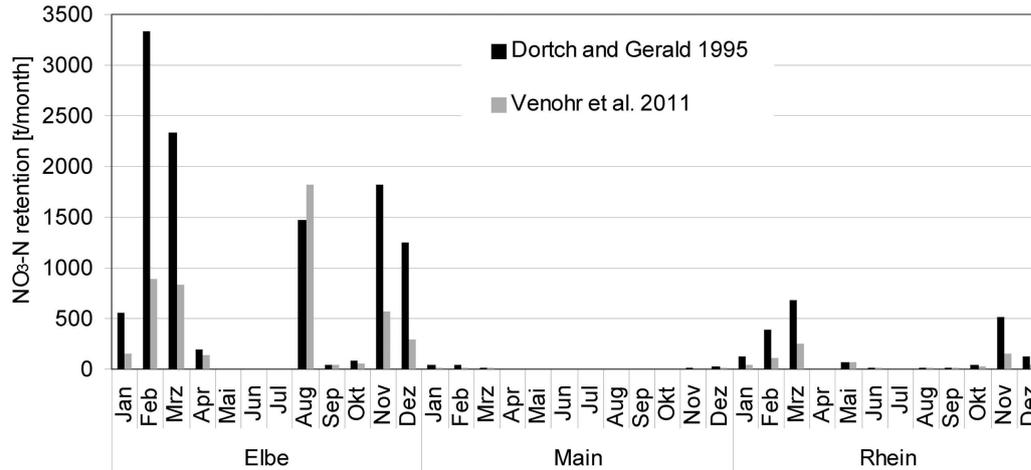
classes and DNLs are equally distributed. More than 50 % show medium to high DNLs for ‘forests’ and ‘grasslands’. In contrast, the natural environments of the Main floodplains, which are mainly dominated by ‘grassland’, only have low and medium DNLs (25 %).

The three study sites also differ in their degree of hydrological connectivity as expressed by the excluded land-use classes (‘arable land’, ‘urban areas’ and ‘areas without vegetation’). These classes amount to 15 % for the Elbe floodplains, 28 % for the Rhine floodplains and 48 % for the Main floodplains. We also looked at site-specific N-retention values for each floodplain



**Figure 7.6:** Load differences between the rivers and comparison of inundated floodplains (in  $ha \cdot 100 km^{-1}$ ) between the rivers and the approaches applied as well as between the total floodplain.

and observed differences between the study sites and between the different approaches. Whereas the proxy-based approach calculates N-retention rates of between 30 and  $131 kg N \cdot ha^{-1} \cdot yr^{-1}$  the model-based approach calculates between 58 and up to a maximum of  $928 kg N \cdot ha^{-1} \cdot yr^{-1}$  by an average N-retention of around  $400 kg N \cdot ha^{-1} \cdot yr^{-1}$ , depending on the model applied. Differences between the floodplains taken into account on the three study sites are more obvious, when one looks at the floodplain that is assumed to be inundated during flood events at every 100 km of the river course (Fig. 7.6). Further, we were able to confirm that the extent of the active floodplain is the crucial factor for retention at the landscape level. Due to the fact that the proxy-based approach can only assess the whole area of active floodplains, by excluding parts that are assumed to be less frequently flooded the resulting N-retention potential is rather estimated and the overall area assumed to have a potential for flooding is much higher than the actual inundated area calculated by the model-based approach. On the contrary, the results of the model-based approach can reveal that hydrological characteristics have a dominant influence on the extent of the inundated area. During 2002 approx. 3,000 ha per 100 km were flooded within the Elbe floodplains, which is ca. thirty times more than within the Main floodplains and ca. five times more than in the Rhine floodplains (Fig. 7.6). During 2004, the inundated area within the Main floodplains was even lower than in 2002 but within the Rhine floodplains the inundated area was more than ca. four times greater than that of the Elbe floodplain.



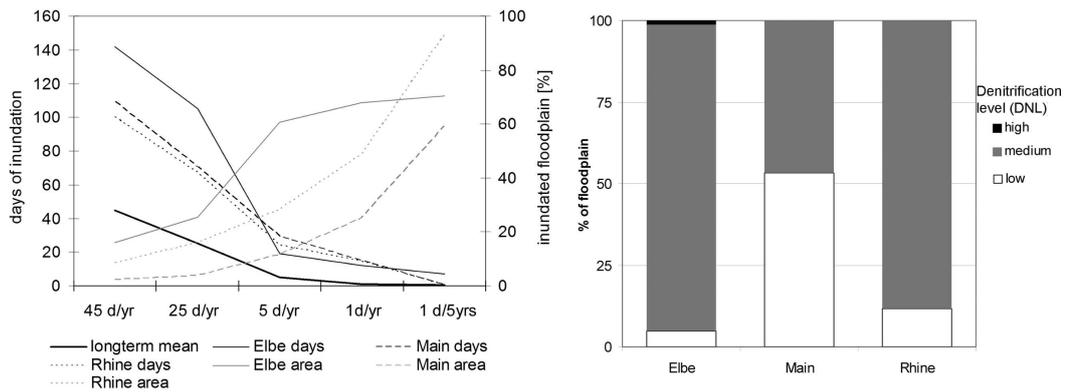
**Figure 7.7:** Comparison of two  $NO_3$ -N-retention approaches on a monthly basis for the Rhine, Main and Elbe floodplains for the year 2002.

### 3.2 Hot moments

It can be expected that seasonally-dependent hot moments of N-retention occur. Such hot moments can be expected during regularly occurring flood events in early spring. By using approaches that consider temperature as input data Venohr (2006), Venohr et al. (2011) such seasonal hot moments of N-retention can be identified, compared to the other hydro-exponential approach (Dortch & Gerald 1995). Due to the fact that increased water temperature promotes denitrification processes, summer floods and the resulting higher water temperatures can be accounted for. Consequently, in August 2002 higher N-retention rates could be calculated using the approach by Venohr et al. (2011) although the incoming N-load was lower in August than during usual spring floods (Fig. 7.7). Here too, N-retention rates seem to be generally lower in the other floodplains, confirming the above results.

### 3.3 Inundation and connectivity

Since the extent of active floodplains and, in particular, the extent of the seasonally-flooded areas vary greatly between study sites, we introduced the so-called theoretical floodplain width, as a ratio of floodplain and river length. In general, the mean floodplain widths increase from the Main (0.4 km) to Rhine (0.6 km) to Elbe (1.7 km) due to the extent of the associated floodplain area. Under high flood conditions (e.g. statistically occurring 1 day/year) some river sections in the upper as well as in the lower Rhine valley are 1.6 km wide which is comparable to the widest floodplains along the river Elbe. Consequently, the theoretical floodplain width is a good tool to compare these study sites of



**Figure 7.8:** a: Comparison of days of inundation along the Elbe, Main and Rhine for the year 2002 in comparison to the statistical long-term mean. Flooding probabilities are shown as statistical flooding frequencies on a daily basis. Inundated areas are presented as floodplain extent in percent of the total active floodplain. b: Valuation classes for denitrification as carried out by the proxy-based approach for the floodplains of Elbe, Main and Rhine, expressed as percent of the total active floodplain.

different sizes. However, to better understand the comparison between both approaches further knowledge of floodplain characteristics is necessary. Figure 7.8a shows the relationship between the days of inundation and the inundated area within the active floodplains during different flood events; the higher a flooding event, the lower its statistical probability of occurrence (graph 'long-term mean'). Considering the effect of wet years compared to their statistical occurrence it visualises that in wet years the inundation period is prolonged, especially for smaller floods. The Elbe floodplains (graph 'Elbe area') are flooded most frequently. Even at small flood events such as one occurring statistically on 45 days per year, the inundated Elbe floodplain is still twice as big as the floodplains of the Main and the Rhine. However, the Rhine floodplains still have some potential for flood retention during higher flood events (e.g. 1 day/year or 5 days/year), since wider areas of the existing floodplains are inundated than during regularly occurring flood events. This is also expressed by the proxy-based approach (Fig. 7.8b). The distribution of the DNL classes for the Elbe and the Rhine floodplains are only marginally different from each other. Lower flooding frequencies along the river Main are expressed by an amount of the DNL = 'low' in approx. 50 % of its floodplains.

#### 4. Discussion

The proxy-based and model-based approaches were applied to calculate N-retention in floodplains on the landscape scale. At first glance, both delivered

conceivable results but similar results could only be assessed for the floodplains of the river Elbe during wet years. Overall we obtained different N-retention rates which were lowest for the Main floodplains under dry and wet conditions but differed by a factor of around four to ten between the two approaches. These factorial differences can be explained by the dissimilar consideration of the floodplain area and its connectivity respectively. While the proxy-based approach could only assume the active floodplain to be represented by all land-use classes except for ‘arable land’, ‘urban areas’ and ‘areas without vegetation’, the model-based approach could clearly consider the dynamically modelled floodplain during inundation events, which is very low along the river Main during all considered events. Thus the calculated N-retention expressed as a percentage of the river load is very low since these floodplains are degraded and their remnants are not connected to the river very well. By contrast, the relatively large remnants of the Elbe floodplains are well connected and both approaches calculate higher N-retention rates. On the other hand, floodplain losses of the Rhine are comparable to those of the Elbe, but connectivity and thus inundation is less. In spite of a high river load only small amounts enter the Rhine floodplains and consequently N-retention is low. Overall these values should be interpreted with caution and related to the different approaches. The proxy-based approach uses averaged proxy values derived from literature reviews on a yearly basis assumed to be valid for different river systems and thus not specifically related to real flood events and not taking into account the different characteristics of the different river systems, such as incoming load or the actual inundated area, etc. The model-based approach assumes that, depending on the discharge, only a certain area of the floodplain is inundated and thus only a certain amount of load enters the floodplain. The different approaches assume that in terms of N-retention, inundated floodplains may behave as wetlands (Dortch & Gerald 1995) or as rivers (Venohr 2006). However, as the results demonstrate, whether floodplains are treated as a wetland or a river makes no difference in the calculation of the expected N-retention capacity. The comparatively higher site-specific N-retention rates of the model-based approach might provide us with some insight into hot spots, where high retention takes place due to flooding characteristics specific to river systems such as flooding frequency and incoming load. However, by combining the proxy-based approach with this specific information for the river system, it is possible to refine the proxy values to minimise possible misjudgements. Therefore, the hydrological characteristics of different river-floodplain systems have to be identified and compared to the connectivity levels of our study sites. On

a monthly basis, as for August 2002 when the flood peak occurred, the effect of N-retention in floodplains is even more pronounced due to high water temperature (Hernandez & Mitsch 2007, Pinay et al. 2007, Boulêtreau et al. 2012) and low flow velocities. Floodplain retention exceeds the in situ river retention by a factor of four. Awareness of such changes in potentially temporarily shifting hot spots and hot moments of N-retention is extremely important, because such overlay patterns increase retention rates dramatically. However, the model-based approach rests on the assumption that inundation occurs when water levels are high enough to enter floodplains and yet inundation does not withdraw as fast as water levels drop. This can very often lead to temporary ponds and higher groundwater tables within floodplains at times of decreasing water levels in rivers. This process is taken into account by the proxy-based approach, applying higher values for ‘water’ and ‘wetland’ within floodplains and also for areas that are assumed to be connected to river water dynamics. Connectivity between rivers and floodplains are of crucial importance for fulfilling floodplain functions. Here we identified three different river systems that differ regarding N-retention capacities due to different connectivity levels between the rivers and their floodplains. The highest site-specific N-retention values are found in the Elbe floodplains, while the lowest values are found in the floodplains of the Main. We can attribute these differences to floodplain degradation levels with low connectivity since it is assumed that load and retention correlate. By showing differences between the inundation area under consideration using the two approaches and the existing active floodplain, the highest deviations were found within the Main floodplains. By identifying land-use characteristics for all floodplains we can reflect several degrees of loss of connectivity and inundation and provide (mostly from historic knowledge) information about connectivity between rivers and their floodplains. In intensively -used areas like the Main floodplain, inundation rarely occurs during the year. The Elbe and Rhine floodplains are quite similar in terms of land-use classes but the river Rhine has experienced a long history of river regulation resulting in severe soil erosion (Cioc 2002). This in turn has led to increased river depths and reduced floodplain connectivity. In contrast, only less regulation work was carried out in the Elbe stretch under consideration and consisted mainly of the construction of groyne fields which still allow river water to regularly reach the floodplains. The proxy-based approach was not able to project inundation and connectivity levels in detail due to a more general data base. The FLYS model was able to identify areas within floodplains that actually flooded during flood events and thus show different levels of connectivity in

more detail. The introduced indicator for floodplain width, which allows a comparison of river sections irrespective of their lengths, can be used to express different levels of inundation and connectivity for the proxy-based as well as for the model-based approach. It also incorporates hydrological variability and thus floodplain extent (Natho & Venohr 2012a). However, the valuation classes assigned with the proxy-based approach only show significant differences for the floodplains of the river Main whereas the other two seem quite similar, even when we assessed significantly different N-retention rates. Finally, we are able to state that degradation, expressed as inundation and connectivity and thus flooding frequency, can be reflected by our approaches. The results also allow a discussion about possible management options for floodplains that may be derived from this study. We identified connectivity between rivers and floodplains as being crucial for the N-retention capacity of floodplains. Short-term flooding as well as small-scale inundation events improves this ability. Consequently, small-scale restoration measures such as clearing stones from riversides or re-connecting oxbow lakes can further improve the N-retention potential in floodplains. Additionally, an increase in active floodplain areas e.g. through dyke relocations will probably always lead to an improvement of N-retention potential. To improve the proxy-based approach for regions where data availability is poor, long-term monitoring measures would improve the quality of proxy values e.g. for ‘water’ and ‘wetland’ and could then be transferred to other river-floodplain systems. This kind of monitoring could also support hydrological models applied to river systems to implement the Flood Risk Directive (European Community 2007). Furthermore, one should seize the opportunity to map the extent of more frequently inundated floodplains to provide a finer and more precise nationwide floodplain inventory regarding hydrological characteristics. This in turn will make it possible to estimate the effects of flooding on N-retention as well as on biodiversity more precisely than at present.

## 5. Conclusion

In this study two different approaches dealing with information on floodplain areas were compared to calculate N-retention. However, the two approaches differ in their basic assumptions and the detailed results have to be compared and interpreted with caution. This is due to input data with different detail, seen as the approaches were developed to answer different questions. The proxy-based approach is based on existing data and is well-suited to compare

N-retention in the floodplains of different river system estimates on a nationwide basis. For a more detailed analysis, such as for hot spots of N-retention as well as for identifying different inundation and connectivity levels of river-floodplain ecosystems, the model-based approach is required as it includes event-driven hydrology as a major driving force which varies both yearly and seasonally. The limitation here is the availability of data. However, by combining both approaches it may be possible to refine some assumptions of the proxy-based approach. But still, for a broader application and even for an extrapolation to the landscape level, both approaches need to be validated in more case studies as well as in different river-floodplain systems. Therefore, a dense monitoring network, regarding time and space, is necessary for N-balances in floodplains, since hydrological and land-use gradients influence N-retention significantly. However, in situ river retention decreases under high flow conditions, whereas retention in the floodplain increases. Thus the effect of floodplains on water quality is of crucial importance.

## 6. Acknowledgments

The proxy-based approach was a result of the study “Ecosystem Functions of Floodplains”, funded by the Federal Agency for Nature Conservation (BfN), Germany. The authors would like to thank Thomas Ehlert (BfN) for fruitful discussions and his constructive input during the development of the proxy-based approach. Mathias Scholz and Hans Dieter Kasperius are also warmly acknowledged for their support. The FLYS team at the Federal Institute of Hydrology (BfG), namely Jörg Graf, Matthias Hammer, Marcus Hatz, Norbert Busch and Dennis Meißner not only provided the software but were also of great help during the calculations.

## 8 Modelling event related nutrient retention in natural floodplains, examples of three large rivers in Germany

Natho, S., Venohr, M.

Keywords: event related nutrient retention, inundated floodplain, connectivity, nitrogen, phosphorus

### Abstract

Floodplains are considered as important ecosystems to reduce nutrient loads which originate from agriculturally used catchments. Modelling the inundated floodplain extent ( $W_A$ ) as well as the load, which enters the floodplain ( $W_L$ ) are crucial factors to determine nutrient retention on a yearly and monthly basis. So far,  $W_A$  is considered as a constant, although it depends on hydrology which changes over the time. This paper presents a new theoretical concept to obtain average  $W_A$  and  $W_L$  for the application of empirical models to calculate nutrient retention (nitrate and phosphorus) in inundated floodplains on a landscape scale, using the examples of three large German rivers. Gauges provide the discharge necessary to calculate  $W_A$  and  $W_L$ . Recently found exponential and Sigmoid relationships between discharge and  $W_A$  for several river sections along Rhine, Main and Elbe were unified resulting in Sigmoid curves for all rivers. However, recently developed approaches to calculate the  $W_A$  and  $W_L$  as yearly or monthly averages from daily discharges led to high loading rates and removal rates relative to values reported in literature. For this reason this study proposes to calculate average yearly respectively monthly  $W_A$  and  $W_L$  by considering event related discharges of high flow conditions leading to inundation only. This in turn necessitates a new methodology to calculate daily nutrient loads, based on fortnightly water quality monitoring data. The validation of this methodology could be successfully carried out. Calculated retention rates lie between 100 and 400  $kg\ NO_3-N\ ha^{-1} \cdot yr^{-1}$  and <1 and 28  $kg\ TP\ ha^{-1} \cdot yr^{-1}$ . The significance of floodplains for nutrient retention can be shown on a monthly basis for the Elbe and Rhine during winter and spring floods. Maximum retention rates

are calculated during a summer flood along the Elbe with 11 % of the transported  $NO_3-N$  load and 9 % of the TP load.

## 1. Introduction

Since nutrient pollution is still a major concern in river basin management several management options have been carried out to reduce diffuse emissions the agriculturally used catchments typical of European rivers. Nevertheless, the potential of relatively cost effective measures is depleting. River basin managers have to think of alternatives which include the management of floodplains (Opperman et al. 2009). According to the American Geological Institute floodplains are defined as “the surface or strip of relatively smooth land adjacent to a river channel, constructed by the present river in its existing regime and covered with water when the river overflows its banks” (in Hamilton 2009). Intact and thus regularly inundated, floodplains are known to offer multi-criterial benefits, namely water and nutrient retention, carbon storage among others (Constanza et al. 1997) but there are only few evaluations carried out (Schulz-Zunkel et al. 2012). Additionally most floodplains are modified, degraded and separated from their rivers by dykes (Brunotte et al. 2009). Dyke relocations are possible options to increase connectivity between rivers and their adjacent floodplains. The idea is to use the naturally given purification function of floodplains (Verhoeven et al. 2006) to act as a nutrient sink when inundated by river water during bank overflow. Therefore, the knowledge about inundated floodplain extent ( $W_A$ ) and incoming nutrient load ( $W_L$ ), as well as on the main retention processes is crucial. Information on  $W_A$  and  $W_L$  is insufficient on a landscape scale, and there are approaches to empirically derive information from available datasets (Natho & Venohr 2012a,b, Natho et al. 2013) since national floodplain inventories only provide information on floodplain with statistical inundation frequencies of at least once in 100 years (Brunotte et al. 2009). If nutrient retention is quantified in natural riparian floodplains inundated area (water surface) dynamics have to be considered which increases complexity. In contrast, water surfaces in most constructed wetlands and thus areas relevant for nutrient retention are constant over the year (e.g. Mitsch et al. 2005). Relevance for nutrient retention can be defined as the ability of a spatial unit to either trap sediments (mainly for TP) or to denitrify (for  $NO_3-N$ ). Denitrification is accounted for nitrate ( $NO_3-N$ ) (Byström 1998, Pinay et al. 2007, Saunders & Kalff 2001, Verhoeven et al. 2006), and sedimentation is most important during surface

flow for phosphorus (as total phosphorus TP) (Hoffmann et al. 2008) which is transported mostly attached to particles (SedNet 2005). Although the main retention mechanisms are identified, processes are complex and not fully understood.

Generally, there are two strategies to quantify nutrient retention in floodplains on landscape scale: the application of a) proxy values or b) empirical models. Since in general information on floodplain characteristics (e.g. dynamics in inundated areas) is low, proxy values (obtained from studied wetlands and floodplains) are applied on the extent the active floodplain, neglecting hydrological dynamics (Kronvang et al. 2004, Schulz-Zunkel et al. 2012). As the load which enters the floodplain ( $W_L$ ) is expected to be a good predictor for retention rates (Saunders & Kalff 2001), most applied proxy values are not appropriate since they do not consider different loading rates of rivers. On the other hand, the total river load can only be taken as an indirect parameter as high river loads do not necessarily lead to high  $W_L$  or retention rates (Natho et al. 2013). Firstly, the amount of load entering the floodplain also depends on  $W_A$ , inundation depth, and the land-use induced flow velocity (Natho & Venohr 2012b). Secondly, the flow velocity or residence time have a direct effect on sedimentation or denitrification, which can decrease under too high loading rates (van der Lee et al. 2004). Recently, Natho & Venohr (2012a) presented a methodology to estimate  $W_A$  and  $W_L$  depending on the ratio of long-term mean discharge (MQ) and current daily discharge (Q) and vice versa from generally available data of the three large German rivers. Combining the empirically derived  $W_L$  and  $W_A$  retention models from literature can be applied to calculate nutrient removal rates in floodplains on landscape scale (Natho & Venohr 2012a,b, Natho et al. 2013).

Although promising, the approach still calculates too high retention rates compared to other studies due to a simplified consideration of flooding frequencies. The aim of this study is to extend this approach by incorporating the concept of event related retention rates for calculating  $W_L$  and  $W_A$ . This concept describes hydrologic characteristics and their effect on retention in a more realistic way. Therefore, a new method is presented to calculate daily nutrient loads from general available fortnightly water quality monitoring data. Additionally, a unified methodology is developed to refine the so far existing relation between Q/MQ ratios and  $W_A$ . The aim is to transfer this methodology to other river systems to quantify the role of nutrient retention in floodplains. Exemplarily, three differently degraded river systems are chosen and reten-

tion results of different empirical models are compared to results of previous studies.

## 2. Methods

### 2.1 Study area

The study area is described in detail Natho et al. (2013). The rivers Elbe, Main and Rhine are located in Germany, varying in their degree of naturalness regarding flow regime and state of floodplains (Brunotte et al. 2009). Altogether around 1100 km of river length are accounted for diverted into 24 river sections with 950 km<sup>2</sup> of active floodplain. 50 % of the floodplains belong to the Elbe river system. According to calculations carried out with FLYS 2.1.3 river sections show great variation in inundation frequencies of their adjacent floodplains: 1 % to 69 % of the active floodplain is inundated at least 25 days per year. Long-term mean discharges (MQ) of the last gauge considered in this study are 710 m<sup>3</sup> · s<sup>-1</sup> (Neudarchau at the Elbe), 160 m<sup>3</sup> · s<sup>-1</sup> (Kleinheubach at the Main) and 2290 m<sup>3</sup> · s<sup>-1</sup> (Emmerich at the Rhine). Nutrient loads vary respectively with NO<sub>3</sub>-N as the main nitrogen compound. For retention calculations river sections were aggregated, so that one gauge and monitoring station pair can be attributed to every section providing information on the river load and finally wetland load.

### 2.2 Refinement of $W_A$

Natho & Venohr (2012a) compared the active and the average inundated floodplain extent and showed that for most parts of the active floodplains no inundation takes place most of the year. Inundated floodplain extents are driven by the flow regime and show great variation during the year. On a yearly basis, an average  $W_A$  underestimates the maximum extent of inundation. Since the flow regime in middle European rivers has prominent flow peaks in certain spring, winter or summer months, calculating on a monthly basis reflects the variation of maximum inundation extent (Natho & Venohr 2012a). Daily MQ/Q ratios were applied to obtain the percentage of total floodplain, inundated at a specific discharge. The average percentage of total floodplain, calculated from all available data, was then taken for calculating the average inundated floodplain extent.

### 2.2.1 Average inundated floodplain extent

The former approach (Natho & Venohr 2012a,b, Natho et al. 2013) considers all daily discharges, leading to several days with no inundation (0 % of share of floodplain inundated) which of course, decreases the mean average inundated floodplain. In contrast we now introduce a new methodology, where only these days are considered for calculating average floodplain extents, when inundation occurs. This will result in higher average inundated floodplain extent, since all the "0"-days without inundation would be eliminated. Therefore, it is assumed, that all sites within the floodplain-river-system which are not inundated at MQ, belong to the floodplain. Hence, every discharge  $> MQ$  leads to an inundation of the floodplain and will be regarded as relevant for the calculation of the average inundated floodplain. Here the average inundated floodplain is regarded as the average in case of bank overflow. To oppose overestimation the calculation of the average  $W_L$  is adapted to consider river load only on days of inundation (see Fig. 8.1). The methodology is described in section 2.3.

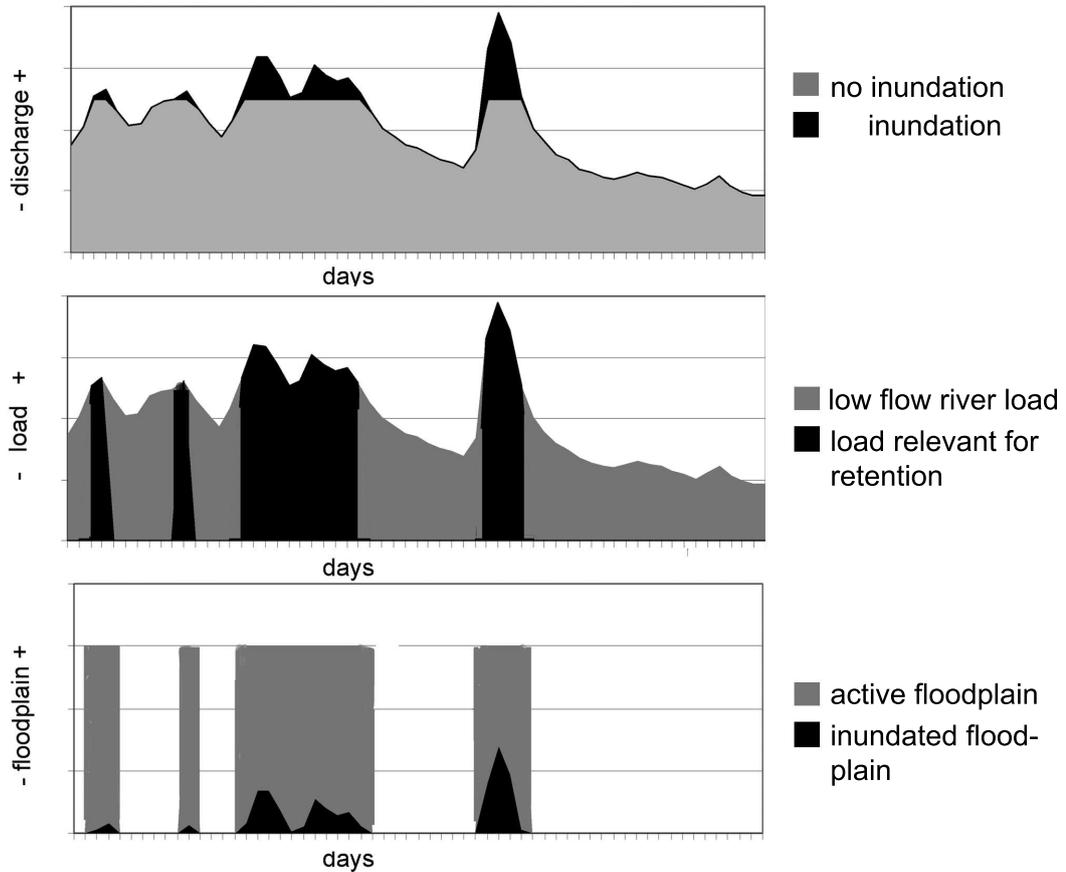
### 2.2.2 Sigmoid relationships

Natho & Venohr (n.d.) presented Sigmoid relations between discharge and  $W_A$  for the river Elbe. For the rivers Rhine and Main so far exponential curves are used to describe the relation between discharge and  $W_A$  since this relation was the most obvious for the available data. The inundated area does not increase exponentially, but flattens at a certain discharge, since natural obstacles such as shores or human-made dykes prevent further increase of flooding extent. Water depth increases instead. Mathematically this can be described best by Sigmoid functions. The floodplains of Rhine, Main and Elbe were analysed to find a universal function that describes the relation of discharge and the share of inundated floodplain best. The discharge is expressed as the ratio of current discharge ( $Q$ ) and long term mean discharge ( $MQ$ ) because the applied ratio allows comparing differences in absolute discharges which can be found between the rivers as well as between river sections.

### 2.3 Refinement of $W_L$

Most water quality monitoring programs assume that nutrients, such as nitrate, are completely mixed within the water column, so that one sample provides information on the state of water quality. Consequently, transferring this assumption on the floodplain, if the share of discharge which enters the floodplain is known, the nutrient load entering the floodplain is also known. This share

is described by the relationship between  $W_L$  and  $MQ/Q$  by Natho & Venohr



**Figure 8.1:** Concept of average  $W_A$  and  $W_L$  calculation basing on discharge. In case the discharge leads to inundation, transported load and inundation extent are considered for average  $W_A$  and  $W_L$  calculations.

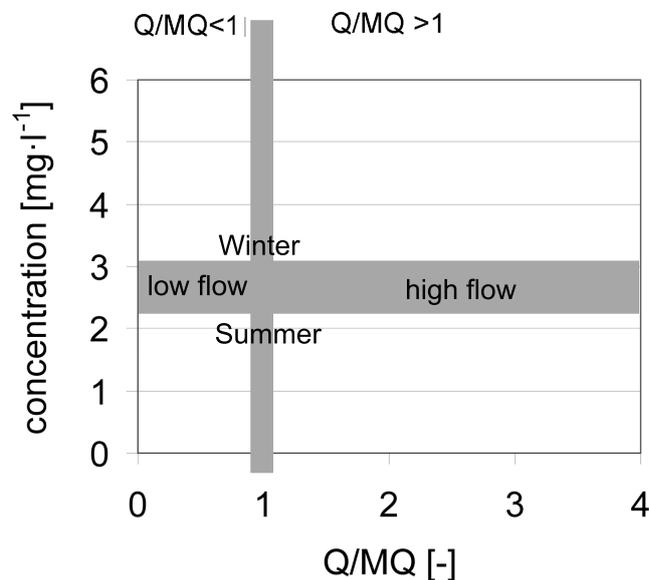
(2012a). Daily  $MQ/Q$  ratios were applied for each river section. The calculated daily percentages of the nutrient load entering the floodplain were then averaged on a yearly or a monthly basis. The river load was calculated according to the method provided by OSPAR (2008), based on fortnightly water quality samplings and daily discharges. The calculated percentage was then applied to model  $W_L$ . Following the suggested methodology in this paper, only that nutrient load is considered to calculate  $W_L$  which is transported in the river during periods of floodplain inundation (see Fig. 8.1). Consequently, loads have to be considered on a daily basis. The problem here is that there are no daily water quality measurements to calculate daily loads. Hence we present a methodology to calculate daily nutrient concentrations. For validation the sum of all daily loads, calculated according to the methodology described in the following, was compared to the load calculation carried out following the methodology of OSPAR (2008).

### 2.3.1 Methodology to calculate daily nutrient loads

We looked at the relationship of discharge and concentration for the available dates of each gauge and monitoring station representing generally the time period between 1990 and 2005. Average concentrations of each year were analysed to exclude general water quality improvements from the analysis. First we analysed the relationship between discharge and concentration for every single gauge and monitoring station with regard to whether  $NO_3-N$  or TP concentrations decrease or increase with increasing discharge. Then we separated concentration and discharge pairs belonging to groups with discharges ( $Q$ )  $>$   $MQ$  and  $<$   $MQ$ . Afterwards concentration and discharge pairs were divided into summer and winter sampling.

Finally, we looked at concentrations during winter and summer in combination with high flow and low flow conditions together (see Fig. 8.1). Average concentrations were then applied to calculate daily nutrient loads. Only the daily loads which occurred at high flow conditions were then summed up to represent the river

load at days of inundation.  $W_L$  is then calculated as the share of river load with the percentage derived according to the methodology described above.



**Figure 8.2:** Analysis of concentration and discharge pairs, assumptions of 4 classes to be found, belonging into different discharge classes ( $Q/MQ <$  or  $>$  1) and different seasons (summer or winter)

### 2.4 Calculating loading rates and retention rates

The newly gained information on  $W_L$ ,  $W_A$ ,  $Q$ , river load and consequently residence time respectively hydraulic load was processed. All serve as input data for two hydro-exponential models on a yearly and a monthly basis for  $NO_3-N$  (Dortch & Gerald 1995, Venohr 2006, Venohr et al. 2011) which showed the best results in recent modelling (Natho et al. 2013). Both models calculate residence time respectively, hydraulic load, as a crucial parameter to affect

retention. For TP the empirical approach presented in Venohr et al. (2011) was applied, both for yearly and monthly retention. River retention was also calculated following the methodology presented in Venohr et al. (2011).

With this information analysis were carried out regarding retention rates as well as loading rates in the floodplains of Elbe, Rhine and Main for the years 1997 to 2004.

### 3. Theory

This study presents concepts to calculate nutrient retention in inundated floodplains basing on  $W_A$  and  $W_L$  as empirically derived input parameter. Assumptions derived from studies dealing with retention in wetlands and floodplains are considered. To identify differences and similarities this section delivers the justification by presenting more detailed background information. Additionally the introduction of the new concept of the event related retention rate is explained in more detail.

#### 3.1 Flooding extent on natural floodplains

In 2009, Brunotte et al. published the first national floodplain inventory of rivers with catchments  $> 1000 \text{ km}^2$ , providing fundamental insights into the distribution and losses of floodplains in Germany. Here, an inactive floodplain, which is physically not connected to the river channel and with this to the flow regime anymore, is distinguished from the active floodplain. The active floodplain is formed by the existing flow regime and it inundated at least once in 100 years (relating to the currently carried out Flood Risk mapping according to EC 2007). This is not detailed enough for quantifying retention in floodplains since hydrological dynamics are neglected. Therefore different models are available to calculate the extent of water levels in the adjacent floodplain of Federal Waterways (FLYS, MIKE11, SOBEK; see Vanderkimpen et al. (2009) for details), processing 1D hydrologic model results. FLYS is freely available for research and was developed by the Federal Institute of Hydrology in Germany (BfG 2009) and applied by (Natho & Venohr 2012a,b) for the three rivers studied Elbe, Rhine and Main. With this Software detailed information on the inundated area can be calculated for given discharges on a daily basis since information on discharges is available on a daily basis. Each river is divided into validation sections between 20 and 100km length, for which calculations are carried out for every discharge. Recently, Natho & Venohr (2012a) developed a methodology to estimate the inundated floodplain

extent ( $W_A$ ) depending on the ratio of long-term mean discharge (MQ) and current daily discharge (Q). Simple exponential and sigmoid relationships were derived to calculate ( $W_A$ ) as percentage of the total active floodplain, which are quick to apply and valid for river sections with similar geomorphologies.

### 3.2 Conditions favouring retention in floodplains

During high flow conditions inundated floodplains are connected with the river. Water, nutrients as well as other properties can be exchanged and retained. Whereas, sedimentation takes place when flow velocities are low enough for particles to settle, denitrification is more complex, combining, physical, chemical and biological factors and is mostly measured indirectly (Groffman et al. 2006). Boyer et al. (2006) define four critical parameters generally found in wetlands: availability of nitrate, denitrifying bacteria and an energy source as well as the absence of oxygen. During inundation the input of nitrate is given. Studies on denitrifying bacteria suggest that there is a high diversity and number of denitrifying bacteria in the soils. Since most of them are facultative, they do not necessarily depend on permanent inundation to survive, but they are able to change their metabolism to denitrifying bacteria if environmental conditions have changed (see Groffman et al. (2006) for an overview). Their activity increases with increasing water temperature (Pinay et al. 2007), but it is still measurable at low water temperatures (Ambus 1993). Organic carbon provides energy for denitrifying bacteria and can be found, where water logging prohibits complete mineralization of organic particles. Thus, peat forming soils provide so called hot spots of denitrification, where denitrification rates are higher than in the surrounding matrix, which was also found by Cooper (1990) in floodplains. Considering these factors relevant for retention processes, inundated floodplains can be assumed to act as wetlands.

### 3.3 Dealing with uncertainties and the need of event related nutrient retention rates

To compare the ability of different floodplains to retain nutrients, very often the retention rate is expressed as a time and space dependent unit:  $kg \cdot ha^{-1} \cdot yr^{-1}$  (Hoffmann et al. 2008, 2011, Kieckbusch & Schautzer 2007, Leonardson et al. 1994). Other similar units such as  $g \cdot m^{-2} \cdot yr^{-1}$  (Mitsch et al. 2005, Noe & Hupp 2005),  $g \cdot m^{-2} \cdot d^{-1}$  (Hefting et al. 2006, Olde Venterink et al. 2002) or  $(mg, \mu g \text{ or } g) \cdot m^{-2} \cdot h^{-1}$  (Cooper 1990, Hernandez & Mitsch 2007) are also published. Phosphorus rates in  $g \cdot m^{-2}$  or  $kg \cdot m^{-2}$  are also related to the flooding duration

(event related) (Baborowski et al. 2007, Kronvang et al. 1999, 2007, Schulz-Zunkel et al. 2012, van der Lee et al. 2004) and to the sampling time (Hoffmann et al. 2008) depending on the method carried out. Although these units seem to be easily comparable and transferable into each other, they are not because most methods deal with point samplings of small sized patches analysed over a defined period of time. It is not known whether the analysed soil patches with their given characteristics are representative of the wetland soil respectively morphology of the floodplain. When retention rates are temporarily and spatially upscaled an overestimation of denitrification hot spots (for example patches of organic soils as reported by Cooper (1990)) respectively effective sediment traps could then lead to an overestimation of retention rates. Consequently, reported retention rates vary and the comparison of retention rates from one floodplain to the other bears uncertainties. Apart from soil characteristics external effects also influence retention such as loading rates (Saunders & Kalff 2001) or floodplain morphology for sedimentation (Olde Venterink et al. 2006). Another source of uncertainties for expressing retention rates is the method applied. Sedimentation rates can be measured by comparing the elevation on floodplains, by calculating load balances or by applying sediment traps or tracers, depending on the temporal and spatial scale of the analysis to be carried out (Krüger et al. 2006). Sediment traps are reported to be applied in most studies, varying in the duration of being laid out in the floodplain between 17 days and one year (e.g. Kronvang et al. 2007, Noe & Hupp 2005). Groffman et al. (2006) provide an extensive overview of the methods applied for measuring denitrification indirectly on different scales, showing that even the most common acetylene inhibition method bears uncertainties. Other methods, e.g. N isotopes are used less frequently and might lead to different results in comparison to the acetylene inhibition method (Watts & Seitzinger 2000). Even if mass balances are carried out (inflow loads versus outflow loads) for larger study sites (Cooper 1990, Kieckbusch & Schautzer 2007, Leonardson et al. 1994, Trepel & Kluge 2002), the exact area of one ha during the year is rarely reached, which necessitates up or downscaling of measured rates.

## 4. Results

### 4.1 Event related $W_A$

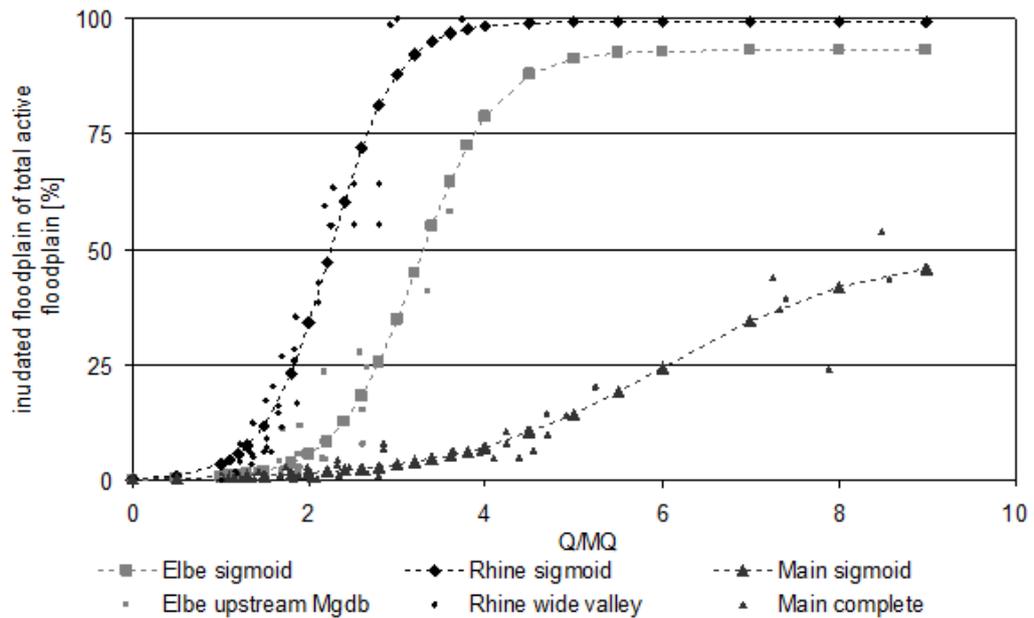
Three parametric Sigmoid relationships describe the relationship between discharge (expressed as Q/MQ ratio) and the share of inundated floodplain of

the active floodplain for morphological similar river sections of the river Elbe, Main and Rhine. It is assumed that inundation starts as soon as  $Q$  exceeds  $MQ$ . Figure 8.3 presents examples of Sigmoid curves, representing three types of Sigmoid relations: All Main river sections behave similarly, resulting in one graph to be sufficient to describe the very slow increase of inundated floodplain with increasing discharge. This is due to the reservoirs, which are situated in the analyzed river section between Trunstadt and Kleinheubach. The discharge is managed, leading to minor changes in the reservoirs until  $Q$  is fourfold higher than  $MQ$ . Rhine and Elbe sections are differentiated in three respectively two groups, in respect to the way inundation occurs. Wide river valleys with floodplains being inundated easily occur at both rivers and are characterized by an early start of inundation, which increases strongly and reaches 50% of the floodplain to be inundated by  $Q$  being around twice the mean discharge (see Figure 8.2; presented by "Rhine wide valley", which can be found between Maxau and Worms as well as downstream Düsseldorf, see also Natho & Venohr (2012b)). The Elbe river section upstream of Magdeburg is an example of slower inundation, with only 7% of floodplain being inundated at  $Q/MQ = 2$ . Whereas, along the Elbe natural shore lines are higher, forming a natural barrier for floods before entering the wide floodplains, floodplains along the Rhine are smaller and flooding barriers are also anthropogenic due to more densely populated areas. The third Rhine group is characterized by a 45km long narrow and rocky valley. At  $Q/MQ$  1.1 a threshold is reached where suddenly inundation starts, resulting in 25% of the only 4  $km^2$  floodplain being inundated at  $Q/MQ = 1.5$ . At  $Q/MQ = 2$  the gradient decreases and the slope is similar to the "wide valley" graph.

#### 4.2 Event related $W_L$

According to nutrient concentration levels, in the 90's of the last century, water quality improved significantly for the Rhine, Main and Elbe.  $NO_3-N$  and TP concentration levels of the Elbe and the Main changed similarly, whereas levels of the Rhine are lower (see Tab. 8.1). Concentrations also vary with the course of the rivers, decreasing for the Elbe but increasing for the Rhine (not shown).

However, due to the strong concentration changes before 1997, only the years 1997 to 2004 are used to calculate average nutrient concentrations and thus are analysed within the application of empirical models. Nitrate concentrations showed strong seasonality with higher concentrations in winter than in summer time for all three study rivers (compare Fig. 8.2 and Fig. 8.4). Flow

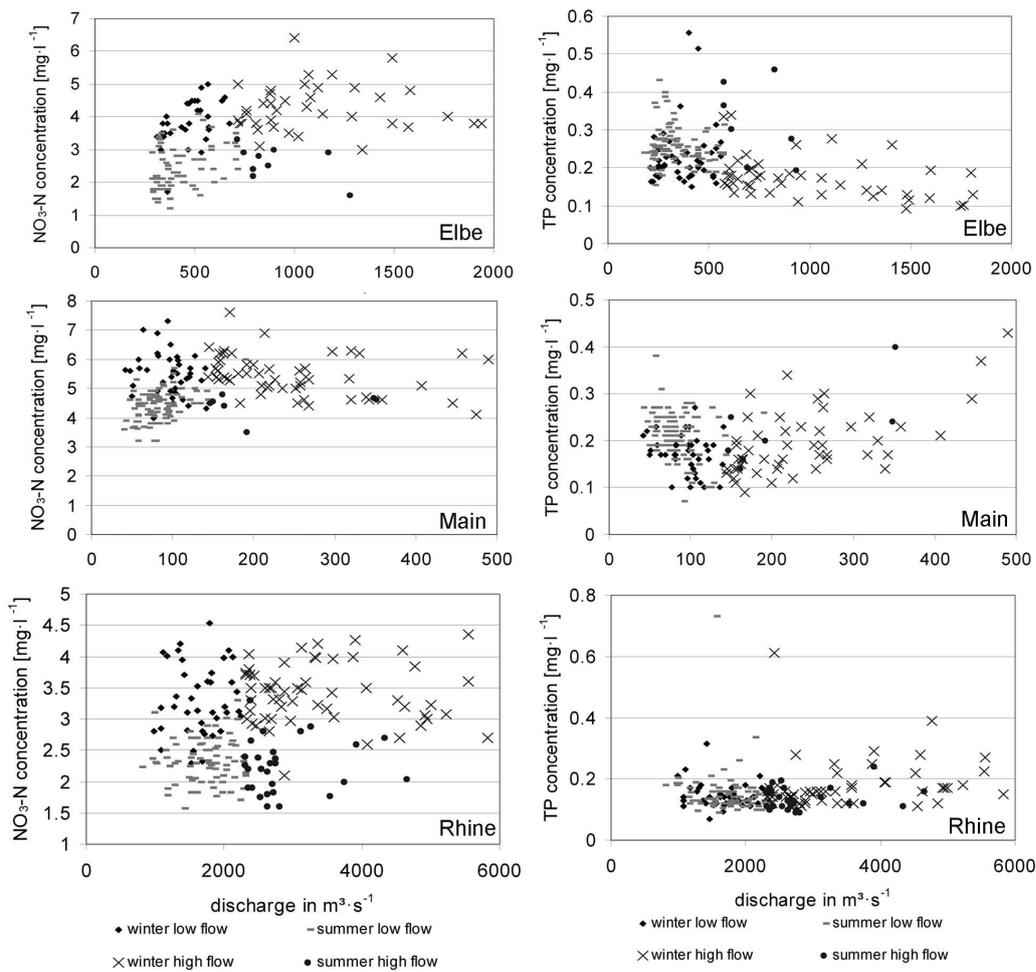


**Figure 8.3:** Relationship between discharge and percent inundated floodplain of the active floodplain, FLYS results (miniatures) and deduced Sigmoid relationships (signs with dotted lines)

	average $NO_3-N$ concentration [ $mg \cdot l^{-1}$ ]				average TP concentration [ $mg \cdot l^{-1}$ ]			
	1992	1997	1998	2004	1992	1997	1998	2004
Elbe	5.4	4.3	3.9	3.4	0.38	0.25	0.25	0.17
Rhine	3.1	2.6	2.6	2.3	0.16	0.12	0.14	0.11
Main	5.4	4.0	4.0	3.6	0.32	0.22	0.23	0.20

**Table 8.1:** Comparison of decrease of  $NO_3-N$  and TP concentration as averages for the rivers Elbe, Rhine and Main between 1992 and 2004.

conditions instead do not influence concentration levels significantly (Fig. 8.4, left side) in contrast to the findings of Frick & Sigleo (2007). The seasonality of phosphorus concentrations is not as pronounced and least relevant for the Rhine. In contrast to nitrate, TP concentrations tend to be higher in summer time for the Elbe and the Main, though not statistically significant. Average winter respectively summer concentrations were then applied to calculate daily nutrient loads based on daily discharges for both nutrients, to ascertain the same methodology for  $NO_3-N$  and TP. The sum of daily loads (=yearly load) were compared to the respective yearly load calculated according to OSPAR (2008) method, being the most frequently applied methodology in Europe to calculate nutrient loads (Zessner et al. 2008). For 95% of the  $NO_3-N$  loads from Elbe, Rhine and Main variation lies between +10% respectively -10%. For 93% of the TP loads from Elbe, Rhine and Main variation lies between +15% respectively -15%. On a monthly basis for 87% of the  $NO_3-N$  and for



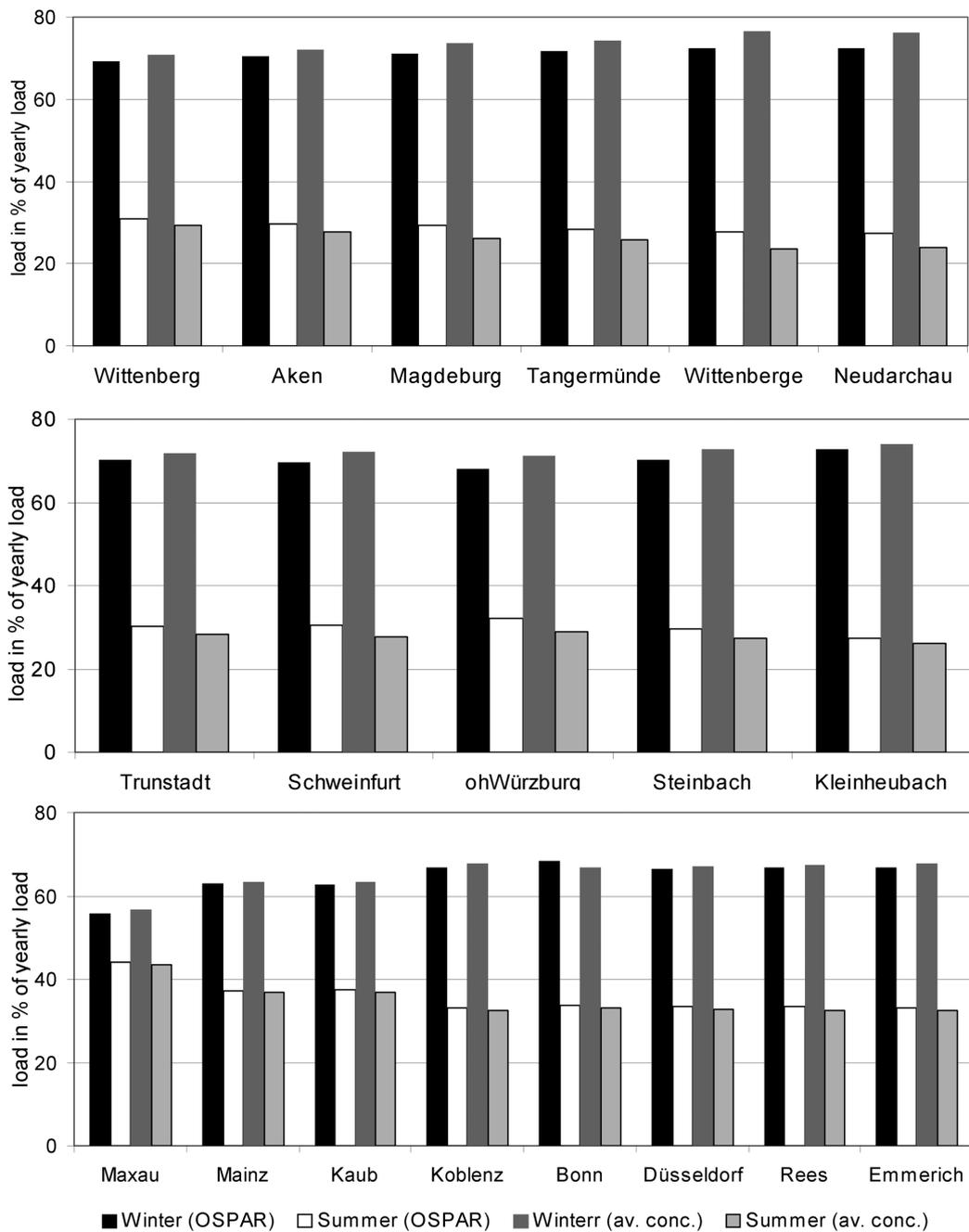
**Figure 8.4:** Nitrate (left) and TP concentration (right) versus discharge for the years 1997 to 2004, shown by the example of Rhine (top), Elbe (middle) and Main (bottom).

73% of the TP load's variation lies between +15% respectively -15%. Nutrient loads in the Elbe calculated with the average concentration approach tend to be lower in 1997 than according to the OSPAR method, because the applied average concentration is lower than the average concentration in 1997 (compare Tab. 8.1).

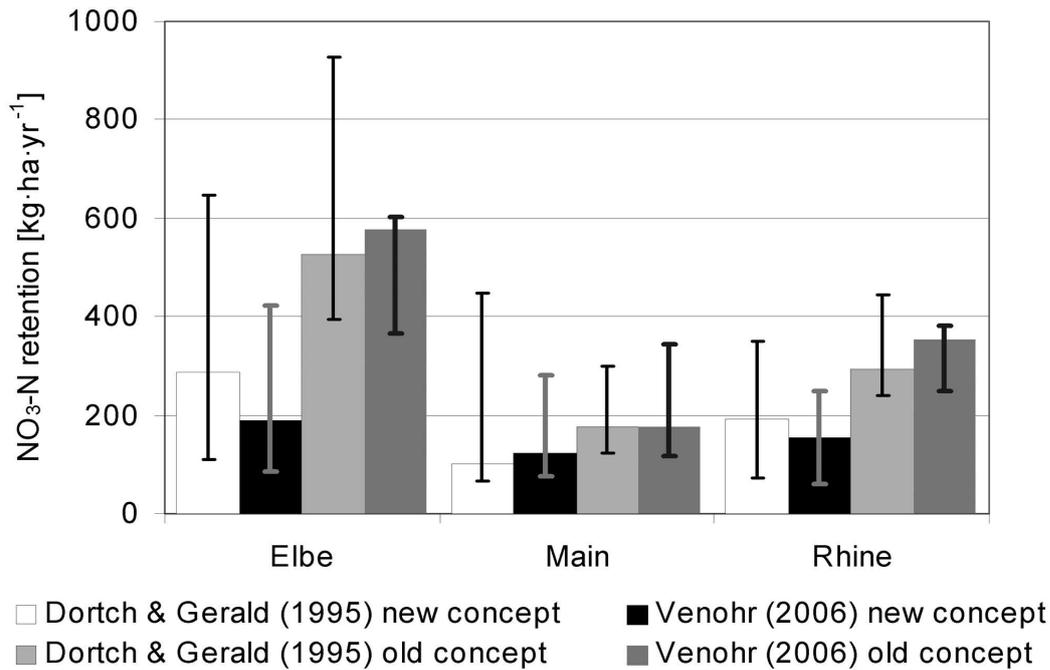
The comparison of seasonal load calculations from 1997 to 2004 according to the OSPAR method and the average calculation method is shown by the example of the Elbe in Figure 8.6. Rhine and Main are equal and show the accordance of both methods. Based on these promising results, average nutrient concentrations are applied for calculating daily nutrient loads.

### 4.3 Event related loading rates and retention rates

Having provided input data on  $W_L$ ,  $W_A$ ,  $Q$  and  $NO_3-N$  and TP river load, loading rates as well as retention rates, using two hydro-exponential models,



**Figure 8.5:** Comparison of seasonal load calculations according to the OSPAR method and the average concentration method for the combination of season and discharge class, shown for  $NO_3-N$  along the river Elbe (top), Main (middle) and Rhine (bottom).



**Figure 8.6:** Calculated nitrate retention rates in the floodplains of the analysed rivers Elbe, Main and Rhine for dry, wet and mean hydrologic years (represented by the years 2004=lower whisker, 2002=upper whisker respectively 2000 for  $NO_3-N$  and 1999 for TP= column). The new methodology of  $W_L$  and  $W_A$  calculations is applied to two hydro-exponential models in comparison to the formerly applied methodology described in Natho & Venohr (2012a).

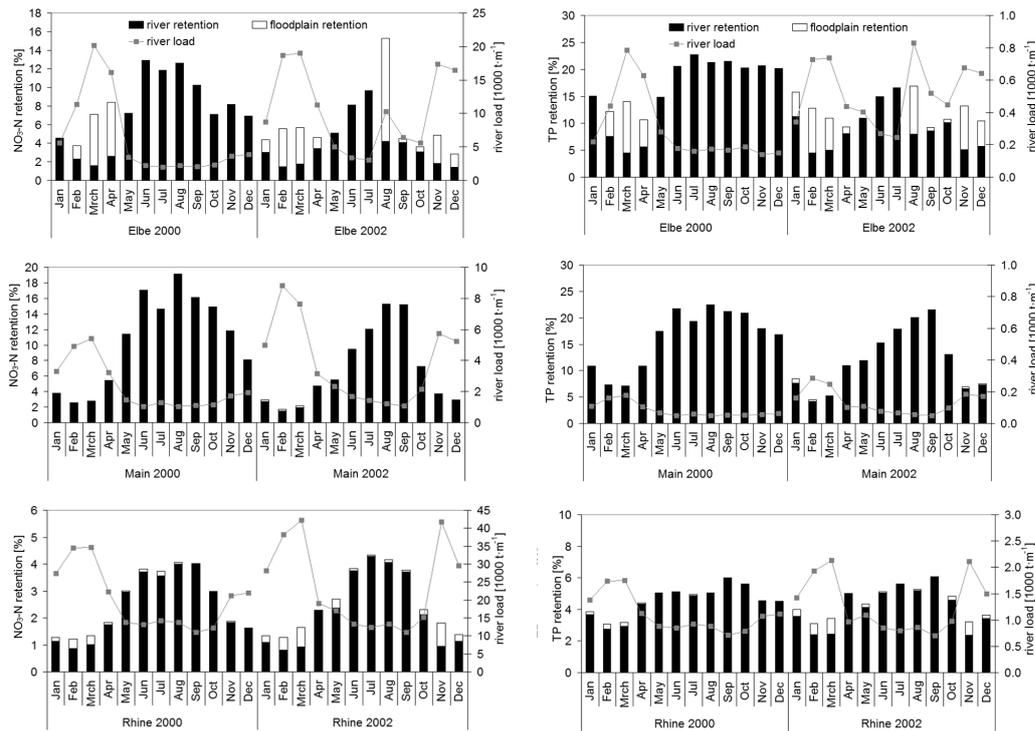
were calculated on a monthly and a yearly basis for the years 1997 to 2004. On a yearly basis loading rates vary from river to river and from year to year, as well as from river section to river section. Under dry conditions loading rates for the Elbe and Rhine floodplains lie around  $430 \text{ kg } NO_3-N \text{ ha}^{-1} \cdot \text{yr}^{-1}$  and around  $270 \text{ kg } NO_3-N \text{ ha}^{-1} \cdot \text{yr}^{-1}$  for the Main. Maximum loading rates lie between  $1100 \text{ kg } NO_3-N \text{ ha}^{-1} \cdot \text{yr}^{-1}$  for the Main and  $2100 \text{ kg } NO_3-N \text{ ha}^{-1} \cdot \text{yr}^{-1}$  for the Rhine. For the Elbe a year with a hundred year flood was analysed, resulting in loading rates of  $4000 \text{ kg } NO_3-N \text{ ha}^{-1} \cdot \text{yr}^{-1}$ . Loading rates of up to  $175 \text{ kg TP ha}^{-1} \cdot \text{yr}^{-1}$  are calculated for the Elbe floodplains, with minimum and mean rates of about 25 respectively  $50 \text{ kg TP ha}^{-1} \cdot \text{yr}^{-1}$ . Lower loading rates are calculated for the Rhine and the Main with maximum rates of 70 respectively  $6 \text{ kg TP ha}^{-1} \cdot \text{yr}^{-1}$ . On a monthly basis inter-annual variation is high. Discharges with  $Q > MQ$  are typical to occur along the Rhine, whereas summer floods occur less often along the Elbe and the Main.

Figure 8.6 shows the resulting  $NO_3-N$  retention rates on a yearly basis in comparison to former calculations reported in Natho et al. (2013). Both hydro-exponential models calculate highest retention rate for the Elbe in 2002, where the highest floods occurred. Generally, the Elbe shows the highest retention

potential in contrast to the Main, where retention is very low. The new concept results in retention rates ranging between 100 and 200  $\text{kg } NO_3\text{-N } ha^{-1} \cdot yr^{-1}$ , whereas former calculations were also above 400  $\text{kg } NO_3\text{-N } ha^{-1} \cdot yr^{-1}$ . For TP mean retention rates around 12  $\text{kg } TP ha^{-1} \cdot yr^{-1}$  are calculated for Elbe and Rhine. Under wet and dry conditions rates are higher for the Elbe than for the Rhine (28 and 14 respectively 7 and 4  $\text{kg } TP ha^{-1} \cdot yr^{-1}$ ). Retention rates of the Main floodplains range between  $<1$  and 4  $\text{kg } TP ha^{-1} \cdot yr^{-1}$ .

Regarding retention in the floodplain and in the river as percent of the total river load, Figure 8.7 visualizes the role of floodplain retention along the Elbe and along the Rhine on a monthly basis. Floodplain  $NO_3\text{-N}$  retention as presented in Figure 8.7 is calculated according to the approach by Venohr et al. (2011) because this approach considers water temperature as an important factor influencing denitrification. The consideration of temperature leads to lower retention in winter time and higher retention in summer time compared to Dortch & Gerald (1995). However, applying the approach of Venohr et al. (2011) allows the differentiation of summer and winter floods. This is why the presented results focus on the monthly retention calculation. Instream retention decreases at high flow conditions, but the sum of river and floodplain retention can exceed the river retention at normal flow conditions. Additionally, under high flow conditions loads are highest and consequently the same retention expressed in percent of the river load as under normal low conditions results in higher absolute retention. For the Main the effect of floodplain retention is minimal. Instead river retention plays an important role, since the river is regulated by several weirs, leading to very small floodplains but large water surfaces in the river itself with high residence times. As a result retention in the river is highest in the Main.

Although 2002 was a wet year for all of the three rivers, significant summer floods occurred along the Elbe only. In August floodplain retention exceeded 10% of the transported river  $NO_3\text{-N}$  load and is 8% of the transported river TP load whereas river retention decreased from 10% in July to around 4% (for  $NO_3\text{-N}$ ) respectively from 14% to 7% for TP (Fig. 8.7). Along the Rhine floodplain retention contributes to total retention but with generally less than 1% floodplain retention for both nutrients is not as significant as along the Elbe. Under average conditions floodplain retention occurs mainly in winter time between November and April and exceeds or equals river retention along the Elbe. Generally, the contribution of river retention is higher for TP than for  $NO_3\text{-N}$ , especially during summer low flow conditions, which is also described by Kronvang et al. (1999).



**Figure 8.7:** Comparison of in situ river retention and floodplain retention ( $NO_3-N$  left, TP right) for the Elbe, Main and Rhine for the mean year 2000 and for the wet year 2002.

The effect of riparian floodplains on nutrient retention can also be shown by calculating in-situ river retention with and without considering the discharge which is entering the floodplain. This is due to the fact, that the floodplain relieves the river from discharge, reducing flow velocity and increases retention. In case there was no floodplain along the Elbe, during the August flood in 2002 river retention would contribute only 2.8 % of the  $NO_3-N$  and 6.1 % of the TP retention instead of 4.2 respectively 7.7 %.

## 5. Discussion

### 5.1 The concept of event related retention rates

This study showed the successful application of the new concept to calculate nutrient retention in riparian floodplains, using the example of three morphologically different rivers. When considering the flooding events for  $W_A$  and  $W_L$  calculations only, retention rates are significantly lower than retention rates calculated with the previous approach (Natho et al. 2013). Retention rates lie between 100 and 400  $kg NO_3-N ha^{-1} \cdot yr^{-1}$  and  $<1$  and 28  $kg TP ha^{-1} \cdot yr^{-1}$  which are in accordance with measured data (Hoffmann et al. 2011, Kieckbusch

& Schautzer 2007, Kronvang et al. 2007, Mitsch et al. 2005, Noe & Hupp 2005). Nevertheless, variation is still great, which is also in accordance with literature (e.g. Pinay et al. 2007). Variation can be explained by considering the different characteristics of 1) the rivers and their nutrient concentration 2) the difference of hydrological years and 3) the connectivity of floodplains. 1) Although results are generally summarized for one river, calculations were carried out for river sections, demonstrating large differences within a river. The increasing nutrient concentrations along the river Rhine lead to higher retention rates in the downstream river sections, although or because wide floodplain exists already in the upstream section. Consequently, loading rates are low, because a lower load enters a wide area. 2) Hydrologically different years were covered by the analysed time period. Very wet years with long floods increased the already higher retention rates of the Elbe to  $430 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$  and  $28 \text{ kg TP ha}^{-1} \cdot \text{yr}^{-1}$ . As the developed concept includes days of inundation only the presented retention rate  $\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  should be used carefully, since it is related to the days of inundation (event related), following the applied retention rate of Baborowski et al. (2007), Kronvang et al. (1999, 2007), Schulz-Zunkel et al. (2012), van der Lee et al. (2004). This study shows that not only for sedimentation but also for denitrification the flooding duration is relevant. 3) Noe & Hupp (2005) found the hydrological connectivity of floodplains to be crucial for retention processes. We absolutely agree and found very low retention rates for the Main, where hardly any retention occurs because floodplains are not well connected.

## 5.2 Uncertainties of the applied methods

Since daily river nutrient loads are missing on a landscape scale, we developed a method to derive daily loads out of fortnightly water quality data, based on average summer and winter nutrient concentration for a time period, where water quality changes were small. The average concentration methodology provided very good accordance for  $\text{NO}_3\text{-N}$  load calculations in comparison with OSPAR (2008), on a yearly and a monthly basis. For TP yearly variation was slightly higher than for  $\text{NO}_3\text{-N}$ , but on a monthly basis, variation increased for more than 25 % of the loads. Consequently, daily TP loads might not reflect reality. Consequently, for TP the trend of dry, wet and average years can be followed but the comparability of certain years should be considered with caution. Calculating TP loads is known to be more difficult than  $\text{NO}_3\text{-N}$  load, because variation of nutrients bound to particles is more dynamic under

changing hydrology. However, this methodology is not suggested as general methodology to calculate daily, monthly or yearly nutrient loads, before more precise data evaluation has been carried out. As could be shown, especially along the Elbe, 1997 still had higher nutrient concentrations than the following years. But the good accordance justifies the application for this study to generate a database for the empirical models.

Uncertainties dealing with the area relevant for sedimentation and denitrification are shown in Figure 8.1. It is assumed that denitrification relies on water logging conditions of the soil and sedimentation depends on low flow velocities. Consequently, inundation creates areas to be relevant for retention. When flood peaks have passed and river water levels drop, inundation is still possible, since water withdraws only slowly from oxbows and other flats. Although there is still area available relevant for nutrient retention (time between two flood peaks for example in Figure 8.1), the model only considers an inundated floodplain in the moment when bank overflow occurs and new nutrient loads are available.

### 5.3 Relevance of floodplains for nutrient retention of a river system

Nutrient retention in floodplains is regarded as one of many ecosystem services (Constanza et al. 1997, Kronvang et al. 1999), although temporarily floodplains are also reported to act as nutrient sources (Cooper 1990), especially after floodplain restoration (Davidsson et al. 2002, Kieckbusch & Schautzer 2007). The empirical approaches applied in this study calculate net retention, including erosion or resuspension. However, generally retention is assumed to exceed nutrient release.

When quantifying nutrient retention in floodplains the relative contribution to nutrient retention in the whole river system can be compared to the retention in the river itself. Therefore, the total river load at the last gauge is considered in comparison to the cumulative retention up to this point. Since in middle European rivers water flow is permanent, retention takes place during the whole year. Flow velocity is crucial for both retention processes and is considered as hydraulic load in the applied retention model for both TP and  $NO_3-N$  (Venohr et al. 2011). Consequently, the higher the hydraulic load, the lower the retention in percent of the transported load (Venohr 2006): On a yearly basis  $NO_3-N$  retention in floodplains contributes only marginally to total nutrient retention; in very wet years around 3% are calculated for the Elbe with even lower values for TP. These values have to be discussed care-

fully. Considering the uncertainties of load calculations according to the applied methodology, but also according to the OSPAR (2008) method, for which around 12 % variation are reported (Zessner et al. 2008) 3 % is below the load calculation variation. On a monthly basis floodplain retention is calculated to be around 10 % for both nutrients, which indicates the high probability of retention to be significant. Nevertheless, the river sections analysed in this study only consider short sections of the main rivers of Elbe, Main and Rhine. Cumulative retention of longer stretches under consideration of tributaries and their floodplains could increase the retention significantly, both, on a monthly and yearly basis. Retention expressed as percent of river load of this study, basing on the new concept of  $W_A$  and  $W_L$  calculation, are in accordance with results from Natho & Venohr (2012b) and similar to rates calculated in van der Lee et al. (2004) for TP, whereas differences occur for  $NO_3-N$ .

Two hydro-exponential models were applied to calculate  $NO_3-N$  retention in floodplains. Dortch & Gerald (1995) calculate the crucial retention time as a function of the shape of the floodplain (length, width, depth) as well as dependent on the ratio of  $NO_3-N$  and TN concentration. It is known that denitrification is temperature dependent (Venohr 2006, Pinay et al. 2007), but still takes place at temperatures of  $0^\circ C$  (Ambus 1993). Thus the lower retention rates calculated according to Venohr et al. (2011) are a result of considering temperature. Without direct measurements in the floodplains, the evaluation of the two results is not possible.

#### 5.4 Transfer of results

The inundation extent of a floodplain at a certain flood event depends on the hydrologic connectivity as well as the load relevant for retention (Noe & Hupp 2005). Although first studies have now published the extent of the active floodplain of 79 rivers in Germany (Brunotte et al. 2009) this study shows clearly that the average inundated floodplain is significantly below this extent. At maximum 50 % of the active on a yearly basis and up to 83 % of the active floodplain on a monthly basis are inundated, but average values are much lower. Consequently, the role of floodplains is overestimated when considering the active floodplain for nutrient retention. Knowledge on the frequency of small flooding events is crucial to determine the actual retention capacity of floodplains. The event related retention rates obtained from this study can only be transferred to other floodplains, if hydrologic conditions as well floodplain connectivity is considered. Natho & Venohr (n.d.) showed that

inundation frequencies of floodplains can roughly be estimated from landuse characteristics. Further detailed studies are necessary to allow a careful transfer of the obtained retention rates and information on flooding characteristics on the floodplain inventory provided by Brunotte et al. (2009).

## 6. Conclusion

This study presents a new theoretical concept which deals with the calculation of average yearly and monthly nutrient loads and inundated floodplain extent on a landscape scale for the rivers Elbe, Main and Rhine. Event related retention rates were calculated based on an average inundated floodplain and an average incoming nutrient load which were derived by considering days of inundation only. Generally available data forms the database which allows to transfer the methods and concepts to other rivers. Thereby, the inundated floodplain is calculated by an empirical approach considering morphologically similar floodplains, deduced from FLYS results. On a monthly basis nutrient retention for TP and  $NO_3-N$  is significant for the Elbe and the Rhine. Retention rates are comparable to values reported in literature and depend on river characteristics, nutrient levels in the rivers, floodplain connectivity as well as on hydrology.

## 7. Acknowledgments

The authors greatly thank the BfG to provide assistance as well as their software FLYS 2.1.3. A. Kämpfer is also acknowledged for improving our English.

## 9 Discussion

### 9.1 Discussion of Methods and Concepts

This research presents a new concept to calculate inundated floodplain extent and incoming nutrient loads relevant for nutrient retention in floodplains. Two main ideas form the basis of the present study. First, floodplains inundated by river water are relevant for nutrient retention comparable to wetlands as reported in literature. Second, if nutrient retention in natural floodplains is considered on a landscape scale, spatial and temporal dynamics in inundation extent which equal dynamic water surface areas have to be considered. This approach is new, since to the author's knowledge all studies considered the water surface area relevant for nutrient retention to be constant in wetlands (Arheimer & Wittgren 1994, 2002, van der Lee et al. 2004). This does not only impact the retention on the floodplain, but also the incoming nutrient loads.

#### 9.1.1 Wetlands and inundated floodplains

Generally, floodplains are considered as hotspots of denitrification (Boyer et al. 2006, McClain et al. 2003) and riparian buffer strips are known to retain P effectively (Kronvang et al. 2005, Mander & Mairing 1994). Since active floodplains are flooded frequently, the whole area could be defined as a wetland according to Ramsar Convention Secretariat (2006). As the results of this study have shown, large parts of the active floodplain are not flooded during any time of the year. Consequently, when considering the floodplain relevant for retention, this varies from year to year depending on the hydrology. However, there are a lot of studies dealing with the effect of floodplains on nutrient retention, but there are far more studies dealing with the effect of riparian wetlands on nutrient retention. The similarities and differences between wetlands and other land-use forms within floodplains have to be considered regarding their effect on the main mechanisms of retention processes. Sedimentation occurs when flow velocity decreases due to morphology or vegetation induced roughness in floodplains. Different roughness values are reported in literature for vegetation types (Schneider 2010, Schulz-Zunkel et al. 2012) which have to be attributed to the different land use types which can be found on floodplains. Biotope

types typical of wetlands (e.g. trees, ponds and wet grassland) are also common for other land uses (grassland, water, forest). Consequently, roughness values in wetlands do not differ from roughness values found on floodplains. In water logged wetland soils conditions for denitrification are given. Since denitrifying bacteria are ubiquitous and facultative (Groffman et al. 2009b) their activity is not bound to wetland soils only. All water logged soils (or expressed as soil moisture according to Boyer et al. (2006), Pinay et al. (2007) which are found periodically on floodplains and wetlands are anoxic during inundation (Seitzinger et al. 2006). Even if floodplains are drained water logging conditions can be found during inundation since river high flow prevents drainage to discharge into the river. In this case denitrifiers react quickly on the loss of oxygen and start denitrifying (Boyer et al. 2006) regardless of land-use type. Consequently, there is no difference between wetlands and other land-use types in floodplains regarding their relevance for nutrient retention during inundation by river water.

One aspect neglected in this study is that additional nutrient input during inundation such as fertilizing of arable land or grassland is not taken into account. Whereas, the Elbe floodplains consist mainly of grassland, arable land is dominant in Main and Rhine floodplains where inundation does not happen very often.

### 9.1.2 Temporal resolution

Although larger middle European rivers are permanent rivers, inter-annual variation of the discharge is high. High floods in winter or spring are typical of pluvial regimes whereas summer floods can also occur under nival regimes (Koenzen 2005). As demonstrated in chapter 8, high discharges do not coincide with dilution of  $NO_3-N$  concentrations over the year and lower TP concentrations in winter time. Generally, higher  $NO_3-N$  concentrations were found in winter time, independent of the discharge. Thus between 60 % and 70 % of the nutrient load is transported during winter time along the rivers Elbe, Main and Rhine. Consequently, the inter-annual timing of floods plays a great role for the nutrient transport in rivers which cannot be assessed by an annual approach.

In chapter 4 the relation between discharge and modelling results of FLYS was analyzed for inundated floodplains. Thereby, for every discharge the inundated floodplain could be expressed as percent of the active floodplain. Similarly, incoming nutrient loads could be expressed as percent of the transported nu-

trient load in the river (chapter 5). When average inundated floodplain extent and incoming nutrient loads were calculated on a yearly basis, the average discharge of the year was not representative for conditions during individual floods. On a monthly basis the influence of floods can be identified very well if enough data is available. To express inundation, daily discharges are applied to calculate average inundated floodplains on a yearly and on a monthly basis. Nevertheless, because of limited data availability the calculation of retention on a daily basis is not possible on a landscape scale but only on a monthly basis. The effect of wet years with high floods in contrast to dry years can be calculated on a yearly basis as well, as shown in chapter 8. On a monthly basis, variation in hydrology and in the resulting share of inundated floodplain area, respectively incoming nutrient load, are lower than on a yearly basis. Like this the effect of high flow conditions as well as low flow conditions on calculating average inundated floodplain extent, respectively incoming nutrient loads, can be identified.

To exclude days of no inundation from the calculation of average inundated floodplains and incoming nutrient loads, an event related concept was introduced. This concept considers only days of inundation and it was applied by several authors for presenting measured P-retention rates depending on defined inundation lengths or frequencies (Baborowski et al. 2007, Kronvang et al. 1999, 2007, van der Lee et al. 2004). As shown in this study, this concept is also valid for  $NO_3-N$  retention, because the inundation of floodplains as well as the incoming nutrient load depends on inundation length and frequency and both happen only over a limited and short period of time during one year or month, which is also when most of the nutrient load is transported. Accordingly, the time is called hot moment because this is the time when most retention occurs during the year (Seitzinger et al. 2006). The concept presented fits very well to the hot spot-hot moment concept (Groffman et al. 2009a, McClain et al. 2003) as only the days of inundation with their incoming nutrient loads are considered, representing hot spots and hot moments. Inundation occurs on certain shares of the floodplain more frequently, which can be called hot spots, because retention is higher than at other places in the floodplain. These hot spots can derive from land-use characteristics such as carbon availability in wetlands relevant for denitrification (chapter 7) or from geomorphologic features such as distance to the main channel which is relevant for TP sedimentation (Schulz-Zunkel et al. 2012). Though the hot spot-hot moment concept is mainly applied for describing biogeochemical reaction rates as in denitrification (Groffman et al. 2009a,b, McClain et al. 2003), in this study

it is also applied for describing the physical process of sedimentation. This is because sedimentation also takes place in floodplains only over a short period of time during the year at high rates at sites with certain characteristics such as low flow velocities. The consideration of these so-called hot spots and hot moments can only be applied best, when event related retention is calculated, which is discussed in the following sections.

### 9.1.3 Calculation of the average inundated floodplain extent

The inundated floodplain extent depends on the discharge and the hydrologic connectivity, but it does not necessarily coincide with the active floodplain extent. Thus, although the active floodplain is large at the river Elbe upstream from Magdeburg, inundation does not occur as frequently as in the river section downstream from Magdeburg (chapter 5). This is due to naturally occurring high river banks which prevent frequent flooding. To obtain detailed information on floodplain extent during low floods, this study is based on FLYS 2.1.3 calculations, an established Software for calculating inundated flooding extents. A relationship between discharge and inundated floodplain in percent of active floodplain was found (chapter 5) which could be generalized for morphologic similar river sections (chapter 7 and 8). The temporal resolution of the analysis (monthly or yearly - chapter 8) and the applied concept are crucial for calculating the average inundated floodplain extent. Hereby, two concepts were iteratively developed in this study: In chapter 5 yearly  $NO_3-N$  retention was calculated for the Elbe floodplains. Therefore, the above mentioned relationship between floodplain inundation and discharge was developed, which can be described by a Sigmoidal relationship for the Elbe floodplains. On the basis of observed daily discharges provided by gauges, daily inundated floodplain extent could be calculated which was then averaged. Low discharges led to no inundation. With this first approach  $NO_3-N$  retention could be calculated and results were promising, but also showed the necessity of a monthly retention approach to better account for the effect of retention on floodplains compared to the in-stream retention during high flow periods.

The second concept was discussed in chapter 8. Only days of inundation were considered for calculating the average inundated floodplain extent and incoming nutrient load. The start and end of floodplain inundation is defined at a discharge exceeding the long-term mean discharge (MQ), because this value is available for all rivers and describes the long-term average water surface area. This average water surface area does not include days, when low parts

of the floodplains are inundated by high groundwater levels if the groundwater cannot discharge into the river in case of high river levels before or after bank overflow (Tockner et al. 2000). This can prolong water logging and might lead to the formation of wetlands with higher retention capacities than other land-use forms on the floodplain (chapter 7) which was not part of this study where only inundation by river water was considered. As a result, the average inundated floodplain is valid for a defined time period and certain discharge conditions.

#### **9.1.4 Calculation of the average incoming nutrient load**

According to the calculation of the average inundated floodplain area, the average incoming load depends on the hydraulic connectivity of the floodplain (Noe & Hupp 2005) as well as on the hydrologic condition of the analysed temporal scale. Whereas, in the first step (chapter 4), the incoming load was replaced by a proxy based retention rate independent of river characteristics and hydrologic conditions, in the second step the decision was made that empirical retention models would be more flexible dealing with the dynamic incoming nutrient load. For this reason the concept of calculating the share of nutrient load of the yearly river load dependent on the hydrology was introduced in 5. The incoming nutrient load was calculated depending on the yearly nutrient load in the river. In the first run, this approach was too simple, overestimating the contribution of floodplain retention. Volumes of river and floodplain were calculated by applying the average depths in the Software FLYS, ignoring that flow velocity is lower in the inundated floodplain than in the river. Consequently, the volume entering the floodplain is assumed to be too high and subsequently also the share of the yearly transported nutrient load. Nevertheless, the results showed that a general application of this concept is possible but improvements are necessary. Especially under the necessity of monthly calculations which consider the effect of flood peaks, retention rates would be overestimated.

In the second step the concept of the floodplain volume was combined with the temporal scale by introducing flow velocities in river and floodplain (see chapter 6), which were derived by applying roughness values for land use and their typical vegetation according to Schneider (2010). Schulz-Zunkel et al. (2012) also applied roughness values for their modelling approach of P-retention in floodplains depending on land-use types.

The extension of the first iteration explicitly accounted for flow velocities and

led to incoming nutrient loads comparable to values reported in literature (chapter 7). In this context, daily discharges were applied for calculating incoming loads, which finally resulted in comparatively higher retention rates than rates reported in literature (see chapter 7). Finally, in the third step, the concept of event related nutrient retention was incorporated in the applied methodology (chapter 8). Consequently, only days were considered for calculating an average incoming nutrient load when inundation occurred. Due to this enhancement only the share of nutrient load could be considered as a basis for calculating the incoming nutrient load which was transported under high flow conditions. Therefore, further methods were adopted regarding the calculation of daily nutrient loads on the basis of fortnightly monitoring (see chapter 8)

### 9.1.5 Selection of retention models

The discussion of spatial and temporal variability of inundated floodplains and incoming nutrient load shows that proxy based modelling is not suitable for incorporation in the hot spot hot moment concept. Instead, the decision has to be made between deterministic and empirical models. The decision is mainly based on data availability. Additionally, it has to be considered whether processes can be simplified without being oversimplified. Boyer et al. (2006) showed that higher complexity does not necessarily lead to more realistic results, since the necessity of more data can propagate mistakes. For denitrification-induced nitrate-removal (Alexander et al. 2009), approximations include the modelling of environmental conditions, which provide a high likelihood for denitrification to occur instead of biological processes leading to denitrification (Boyer et al. 2006). In addition, as the availability of data on floodplain characteristics on a landscape scale is low, empirical models recently presented in literature are selected for this study for which input data could be generated from measured and modelled data. Therefore, different empirical models, varying in their degree of complexity and input data, were compared in chapter 5. There are several linear models (Jansson et al. 1998, Mander & Mairing 1994, Saunders & Kalff 2001) which empirically deduced a relation between incoming  $NO_3-N$  load and retention in percent from the study of wetlands on a yearly basis. For small floods modelled retention rates show a good compatibility with other, more complex models. But for high loading rates these linear models tend to overestimate retention as demonstrated by Trepel & Palmeri (2002) and chapter 5. This is due to oversimplified flooding

characteristics, since high floods lead not only to higher loading rates but also to higher flow velocities and lower residence times which makes retention less effective for both sedimentation and denitrification (van der Lee et al. 2004). Residence time is applied in several empirical models, and it can also be expressed as hydraulic load. HL is the ratio of discharge and water surface area which is widely accepted as a crucial parameter for riverine retention modelling (for an overview see Alexander et al. 2009, Boyer et al. 2006, Venohr 2006). The wetland retention model by Dortch & Gerald (1995), which considers denitrification was also applied in chapter 5. As it is also possible to apply this model on a monthly basis (Dortch, personal communication), the model was selected for further investigation. Although the retention models by Venohr (2006), Venohr et al. (2011) were developed for river retention they can also be applied for floodplain retention. Thereby, net TN-retention is calculated as the sum of denitrification as the main retention process and sedimentation. Since denitrification is the main retention process in floodplains, the established retention model by Venohr (2006), Venohr et al. (2011) was applied for calculating retention in wetlands in comparison to explicit wetland retention models. As discussed above, the difference should be small because denitrification in rivers takes place mainly at the sediment-river-water interface and not in the water column (Böhlke et al. 2009).

There is no guarantee (Fennel et al. 2009) but a high possibility that the transfer of empirical models from their study sites to other sites works well because the most important parameters, which influence removal processes like flow velocity, respectively hydraulic load and water temperature are considered. This, however, has to be evaluated separately.

## 9.2 Discussion of Results

### 9.2.1 Event related retention rates

Within this work the concepts and methods of creating the database concerning average incoming load and average inundated floodplain area, were iteratively improved. For each iteration a database was successfully created to apply empirical retention models to calculate nutrient retention in inundated floodplains. The improvement was shown and assessed by comparing results of the three iterations applied in the model developed by Dortch & Gerald (1995) and by nutrient retention calculations along the Elbe floodplains for the wet year 2002. The first simple approach, which assumed time independent vol-

umes in floodplain and river, calculated a N-retention of up to  $1400 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$  which can be considered as very high and comparable to retention rates in treatment wetlands (Bachand & Horne 2000). The reason for this are extremely high loading rates which were calculated without considering lower flow velocities in the floodplain rather than in the river. The consideration of different flow velocities in floodplain and river, estimated according to vegetation induced-roughness (Schneider 2010), slope and water depth, reduced the incoming nutrient load effectively. But still retention rates of up to  $930 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$  were calculated.

With the last iteration an event related concept was developed, which is related to the inundation frequency of the analysed year. The application of this concept for the calculation of the inundated floodplain and the average incoming nutrient load led to a maximum retention of  $650 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$  for the extreme wet year 2002 along the Elbe. Consideration of mean years 188-288  $\text{kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$  are modelled to be retained along the Elbe, whereas rates are lower for the Rhine ( $156\text{-}193 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$ ) and the Main ( $100\text{-}122 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$ ) (see Figure 8.6). These rates lie very well in the range of applied proxy values ( $100$  and  $300 \text{ kg NO}_3\text{-N ha}^{-1} \cdot \text{yr}^{-1}$ ) derived by measurements from agriculturally used catchments (Gren et al. 1995, Kronvang et al. 2004, Schulz-Zunkel et al. 2012) (see also chapter 8).

Additionally, with the introduction of iteration step two a second hydro-exponential model, taking water temperature into account, was applied (Venohr 2006) which was originally developed for rivers. Retention rates calculated by Venohr (2006) tend to be lower than the retention rates calculated according to Dortch & Gerald (1995). This is due to the distribution of inundation events which mainly occurs during winter time, when temperature is low which slows biological activity and thus denitrification rates (compare chapter 8). Since both models produce results in the range of reported values (see above), no statement can be made regarding the preference for one or the other model.

But, especially on a monthly basis, lower N-retention rates in winter than in summer time as calculated according to Venohr et al. (2011) are realistic, since denitrification is known to positively respond to water temperature. In contrast, Davidsson et al. (2002) measured higher denitrification rates in March (water temperature of less than  $8^\circ\text{C}$ ) than in July, since N was limited. Applying the retention models it is assumed, that N is not limiting in the studied floodplains because inundation leads to ongoing N input. Also for phosphorus monthly calculations demonstrate the occurrence of hot spots and hot moments, if single river sections are observed. Hydrologic connectivity

of floodplains varies along the rivers, depending on morphologic and anthropogenic conditions (see chapter 6 for an example of the Rhine), leading to regular monthly retention rates of almost  $4 \text{ kg TP ha}^{-1} \cdot \text{yr}^{-1}$  along several river sections of the Elbe in winter time, whereas along the Main a maximum of  $3 \text{ kg TP ha}^{-1} \cdot \text{yr}^{-1}$  is only calculated for two river sections.

### 9.2.2 Effect of inundated floodplains on nutrient retention

The effect of nutrient retention in riparian floodplains depends on the connectivity of the floodplain (Noe & Hupp 2005), which can be expressed by calculating the incoming load as percent of the total river load as well as the extent of inundated area as percent of the active floodplain. Under low and mean discharge conditions, rivers contribute significantly to the nutrient retention (see Venohr (2006), Boyer et al. (2006) for an overview), resulting in loads being significantly lower than the emissions into the system (Behrendt 1996, Kronvang et al. 1999). Under high flow conditions the retention capacity of the river itself decreases, since flow velocity and water depth increase (Alexander et al. 2009). Instead, floodplain inundation increases and flow velocities are lower than in the river which leads to an increased nutrient retention in the floodplain. Presenting floodplain retention in comparison to the transported river load and the riverine retention, the effect of floodplain retention for the river system can be expressed cumulatively.

Retention was calculated for different well connected floodplains (see chapter 7) and during different wet years which had a stronger effect on the application of two different hydro-exponential retention models for  $\text{NO}_3\text{-N}$ . Generally, the resulting incoming nutrient load and inundated floodplain area are the crucial factors for calculating nutrient retention in floodplains. The better connected, the higher the nutrient load which enters the larger inundated floodplain. Consequently, the contribution of Elbe floodplains is highest, whereas floodplains of the Main hardly retain any nutrients. The contribution of floodplains of the Rhine are found to be in between, as at some river stretches floodplains are connected well. On a monthly basis, modelled high flow conditions show retention rates of up to 10 % of  $\text{NO}_3\text{-N}$  and 8 % of TP for the Elbe in the year 2002, whereby river retention decreases (for details see chapter 8) which allows the conclusion that retention is very likely to be significant even if considering all uncertainties regarding load calculations and input data processing. If floodplains are inundated frequently enough floodplains contribute significantly to the nutrient retention. Consequently, the results of this modeling consider

the reconnection of floodplains and adjacent wetlands as a useful measure to reduce nutrient loads.

### 9.2.3 Consideration of disservices

The aim of this work is to quantify nutrient retention in riparian floodplains on a landscape scale. As the results have shown, retention in a floodplain can have a significant effect on nutrient loads, depending on the connectivity of the floodplain. In chapter 1 this purification service was presented as one among manifold services (Constanza et al. 1997, Scholz et al. 2012) but there are also disservices reported in literature, of which some nutrient related disservices are discussed in the following: Especially for P, rewetting of former wetlands can be crucial for water quality issues. Restoration of agriculturally used wetlands can lead to the release of P from degraded peat layers which is reported in several studies (Aldous et al. 2005, Hoffmann et al. 2012) for example in studies of rewetted fens in Northern Germany (Kieckbusch & Schautzer 2007, Zak & Gelbrecht 2007). This nutrient release was described as only temporal (Aldous et al. 2007) until the wetlands are under natural conditions again and might be avoided by removing the upper highly degraded peat layer when fens are rewetted (Zak & Gelbrecht 2007). Fisher & Acreman (2004) reviewed several wetland studies and they even state that  $NO_3-N$  and TP cannot be removed optimally in the same wetland, since reducing conditions, which favour denitrification at the same time might lead to a release of phosphorus bound to iron or aluminium.

Sedimentation is discussed as an important process for TP-retention. But from rivers that have been managed today, suspended solids and sedimentation especially in reservoirs have also been seen as a management problem (SedNet 2005). Among others, sediments are contaminated with heavy metals (SedNet 2005, Vink et al. 1999) and although heavy metal concentrations have decreased (Vink et al. 1999) since the 80's for the Rhine (Middelkoop 2000) and since the 90's for the Elbe (Krüger et al. 2005, Schulz-Zunkel & Krueger 2009) their temporary deposition and remobilization in floodplains leads to contamination of floodplains, their soils and vegetation, even above legal thresholds (Krüger et al. 2005, SedNet 2005, Schulz-Zunkel & Krueger 2009). Especially for the Elbe floodplains, on which inundation occurs frequently as shown in this work, the sedimentation of contaminated suspended solids has to be taken into account.

Complete denitrification is assumed as the main process of retention in flood-

plains that occurs when inundated (Groffman et al. 2009a) but if denitrification is incomplete nitrous oxide is produced, which is known to act as a major greenhouse gas (Hefting et al. 2003, Seitzinger et al. 2006). The role of riparian floodplains regarding greenhouse gas emissions is not known yet, but as recent studies have shown, this aspect should not be neglected in future (Verhoeven et al. 2006).

Transformation processes from inorganic to organic compounds or vice-versa in floodplains are neglected by simple nutrient retention models (Boyer et al. 2006), although mass balance studies of rewetted peatlands have shown, that inorganic N is retained, whereas organic N is released into the surface waters (Kieckbusch & Schautzer 2007). These emissions might be balanced out by strong  $NO_3-N$ -removal by denitrification over longer periods (Davidsson & Stahl 2000), but the complete mechanisms have not been understood so far (Boyer et al. 2006).

Consequently, although regularly inundated and hydrologically well connected floodplains contribute to nutrient retention on landscape scale, all issues, expressed as services and disservices, have to be considered and balanced, before dyke relocations are carried out.

#### 9.2.4 Uncertainties and possibilities for improvement

The results of models are only as good as their input data and understanding of the induced process. Floodplain characteristics and hydrologic conditions depend on temporal and spatial resolution of the input data. Consequently, as spatially and temporally averaged inundated floodplains and incoming loads were calculated, results can be interpreted on a landscape scale for the mentioned temporal scales, but results cannot be downscaled to answer specific questions of areas within a river section and shorter time periods. Very simple assumptions in the beginning of this work were replaced by more complex assumptions, which allow the transfer of results on a German-wide data set. The coupling of simulated 1D results of FLYS with flow velocities, estimated according to the Gauckler-Manning-Strickler algorithm was crucial for obtaining temporally dependent floodplain volumes which improved the relation of a discharge dependent floodplain volume. But measured flow velocities and discharges in inundated floodplains would be necessary to validate results. They have been validated so far with information from the gauges along the test rivers for each river section as a sum of river and floodplain discharge (chapter 6).

Other studies (Arheimer & Wittgren 1994) assume single wetlands to act as one batch reactor dewatering into the next. In contrast, this study assumes that during high flows discharge passes through inundated floodplains from the upstream to the downstream part of the floodplain, and nutrients are equally distributed within the flood water. Thereby, the rivers under consideration are divided into several river sections from gauge to gauge. Floodplain characteristics and flooding conditions within each section are regarded (by the empirical models, too) as equal. For the calculation of the average inundated floodplain no difference was made between a 10  $km^2$  floodplain area, which is inundated only once a year, and a 1  $km^2$  area which is inundated ten times a year. Studies reveal, that denitrifying bacteria work effectively even if inundation occurs only infrequently (Boyer et al. 2006). But there are also other factors contributing to denitrification, such as carbon content in soil (Boyer et al. 2006) about which information is scarce on a landscape scale. The role of soil maps for identifying retention hot spots is not clear yet, and will be discussed in the next section. As the applied empirical models were not developed based on floodplain data of the rivers studied, some assumptions such as inundated floodplain characteristics equaling wetland characteristics had to be made. This can increase uncertainties. Calculating the inundated floodplain extent as well as incoming nutrient load as described in this study and discussed above was derived from empirical relations and improved iteratively. Additional input data for the approach presented by Venohr (2006) and Venohr et al. (2011) is only necessary for  $NO_3-N$  calculations: temperature, which can be provided by the federal monitoring stations and short wave radiation for the monthly approach by a European-wide CM-SAF map as 15 km grid (Venohr et al. 2011). The approach developed by Dortch & Gerald (1995) needs more assumptions concerning the shape of the area and  $NO_3-N$  and TN concentration ratios (Natho & Venohr 2012a, Trepel & Palmeri 2002) since data cannot be provided completely from monitoring stations and available floodplain geometries. However, all exponential models applied assume first order removal kinetics which are derived from recent validation of the respective models (Dortch & Gerald 1995, Venohr 2006, Trepel & Palmeri 2002, Venohr et al. 2011) and could not be calibrated, because there is no measured data available on a landscape scale. The only possibilities so far to close this gap are, to compare results of the models with values reported in literature as well as between the models themselves. In chapter 8 the problem of comparing results of different retention studies was highlighted, since generally flooding conditions of floodplains vary from year to year (and inter-annually) as well as

from floodplain to floodplain. However, by applying the event related retention concept, both hydro-exponential retention models do now produce retention rates comparable to rates reported in literature. On a yearly basis model uncertainties are smaller than the uncertainties in the observed loads (Zessner et al. 2008), whereas on a monthly basis floodplain retention reaches around 10 % of the transported TP, respectively,  $NO_3-N$  load, which is significant. As showed in chapter 4 assumptions about retention could be drawn by simply comparing water quality data of gauges along a river. This is because monitoring frequency of nutrients, as suggested by the EU, is too low for this purpose and additionally, nutrient emissions into river systems exceeding retention do occur (Behrendt 1999) which makes it even harder to identify nutrient retention. This emphasises the necessity of detailed floodplain monitoring to validate the presented results.

### 9.2.5 Implications for future work

Results of this work are promising regarding the strong correlation between hydrological connectivity and retention capacity of floodplains along the rivers Elbe, Main and Rhine. As a next step the transfer of the results to a German-wide data set would allow for the calculation of the effect of average inundated floodplains. Therefore, floodplain characteristics as land use, soil and slope could be applied as indices to explain flooding frequencies, which could be validated by FLYS results, calculated in this study. As shown in chapter 7, flooding frequencies are reflected by land use within the floodplain since arable land is not established where inundation occurs frequently. The aggregation level of land-use maps is crucial since the difference between wet grasslands and drained grasslands can also give information on hydrology, oxygen supply and organic content. Land-use maps reflect current conditions but they do not provide information on hydrologic conditions, since some grasslands are still very wet, acting as some kind of wetland with respect to oxygen supply.

The role of soil maps for predicting the extent of average inundated areas has to be discussed and examined in detail, since soil maps do not provide information on the actual status of hydric soil conditions, but in combination with land-use maps a gain in information might be reached. First analysis of land use and slope as a predictor of the inundation of floodplains in comparison to the active floodplain have been carried out within this study and published as a poster, which can be found in the appendix. To effectively quantify nutrient retention in floodplains, the extent of the floodplain which is actually inun-

dated in contrast to the total active floodplain has to be known. Approaches, concepts and results were presented with this research, but until the role of floodplains can be implemented in nutrient emissions models, far more knowledge on flooding characteristics has to be gained. Therefore, the comparison of models and intensive monitoring is necessary (Böhlke et al. 2009).

## 10 English Summary

The eutrophication of surface waters and the lakes is a problem of international relevance. For this reason the Water Framework Directive was adopted on an European level to achieve a good ecological, chemical and quantitative status of all water bodies (this work focuses on German River Basins). Although several measures have been carried out to reduce nutrient emissions, current nutrient concentration in the surface waters and lakes lead to algae blooms on a regular basis. Under consideration of costs and benefits of any further measures the role of floodplains moves into the focus as natural retention for nitrogen (N) and phosphorus (P) since inundated floodplain are known to retain nutrients. But knowledge gaps arise if the retention capacity of floodplains is assessed in more detail. The most important retention processes, denitrification for N and sedimentation for P are known, and there are several models to calculate nutrient retention in floodplains, but so far, models have seldom been applied for whole catchments. Furthermore, precise information on flooding extent of frequently occurring floods and their discharges, residence times as well as data on nutrient concentrations and nutrient loads in the floodplain area are missing. Although, regular water quality and discharge monitoring is carried out along the respective rivers, and the nutrient load in the river is calculated. Results of the First National Inventory of German Floodplains only provide information on the active floodplain, defined as the floodplain that is inundated at least once in 100 years, which is not representative of the inundated floodplain of every single year. During the data research of this work the average inundated floodplain turned out to be the crucial factor to determine nutrient retention in floodplains. Depending on the connectivity of the floodplain, the inundated floodplain is as variable as the discharge of the river system. The second crucial factor, depending on the inundated floodplain area, is the similarly incoming nutrient load.

Consequently, the aim of this work is to develop a concept and subsequent methods which consider the yearly and monthly hydrological dynamic when deducing input data for empirical retention models from existing information on monitoring data and geographic and modelled data on riparian floodplains. Along three rivers studied (Elbe, Main and Rhine) riparian floodplains were

selected which differ regarding their morphological and physico-chemical parameters. The actual flooding frequency was compared to statistical flooding frequencies, and corresponding inundation extent was calculated with the Software FLYS, which was developed by the Federal Institute of Hydrology. Based on these detailed results the missing average inundated floodplain as well as the average incoming nutrient load could be calculated as percent of the active floodplains, respectively the load transported in the river. Iteratively, both methods could also be improved, from time independent approaches to approaches considering flow velocities, induced from vegetation dependent roughness values in the floodplain. For both, the dimensionless and thus scale independent ratio of current and long-term discharge plays the central role. Consequently, the transfer of the results to other river systems is possible. The crucial step of modelling the inter- and intra-annual dynamic of floods succeeded by the iterative development of an event related concept. Therefore, only these days are considered for calculating the average inundated floodplain and the average incoming nutrient load when discharges are higher than the long-term mean discharge. This means, that the calculated average of inundated floodplain extent represents the average inundated floodplain extent during flooding events at a defined timed period. Different empirical models were compared for calculating nitrate and total phosphorus retention ( $NO_3-N$  and  $TP$ ) in the floodplains of the three sites studied. Models which consider hydrological characteristics by calculating residence times, respectively hydraulic loads, calculate realistic retention rates between 100 and 400  $kg NO_3-N ha^{-1} \cdot yr^{-1}$  respectively between  $<1$  and 28  $kg TP ha^{-1} \cdot yr^{-1}$ . Lower values are calculated for the floodplains of the Main where connectivity is less and highest values are calculated for the relatively natural Elbe floodplains. In comparison to rivers which decrease under high flow conditions, floodplain retention increases under high flow conditions up to 10 % for  $NO_3-N$  and 9 % for  $TP$  of the transported monthly river load.

A transfer of the results to other river systems is possible by considering soil, land use and digital elevation data, so that the presented concept and methods can be applied German-wide where data is available. Though validation of the retention rates could not be carried out with measured data the comparison with retention rates from the literature is very good.

## 11 German Summary

Die Eutrophierung der Gewässer und der Meere ist ein Problem von internationaler Bedeutung. Aus diesem Grund wurde auf europäischer Ebene die Wasserrahmenrichtlinie beschlossen, um für Oberflächen- und Grundwasser aller Mitgliedsstaaten (im Fokus dieser Studie stehen deutsche Flusseinzugsgebiete) einheitliche biologische, chemische und morphologische Zielzustände zu definieren. Obwohl bereits zahlreiche Maßnahmen zur Reduktion der Nährstoffemissionen durchgeführt wurden, führen die derzeitigen Nährstoffkonzentrationen in den Oberflächengewässern und Meeren zu regelmäßigen Algenblüten. Unter Berücksichtigung der Kosten und Nutzen weiterer Maßnahmen tritt die Rolle von Auen als natürliche Retentionsräume für Stickstoff (N) und Phosphor (P) in den Vordergrund, da überflutete Auen Nährstoffe zurückhalten. Bei genauerer Betrachtung der zu bewertenden Retentionsleistung von Auen gibt es noch große Wissenslücken. Zwar sind die wichtigsten Retentionsprozesse, Denitrifikation für N und Sedimentation für P, bekannt, und es existieren zahlreiche Modelle, um die Retentionsleistung in Feuchtgebieten zu berechnen, aber bislang wurden solche Modelle kaum für Auen auf Einzugsgebietsebene angewendet. Des Weiteren fehlen präzise Eingangsdaten bezüglich Überflutungscharakteristika bei kleineren, regelmäßig auftretenden Hochwässern, einströmende Wasservolumina, überflutete Auenflächen, Aufenthaltszeiten sowie Daten zu Nährstoffkonzentrationen und Nährstofffrachten in Auen, obwohl an den zugehörigen Flüssen regelmäßige Wasserqualitäts- und Abflussmessungen durchgeführt werden und somit Nährstofffrachten in Flüssen bekannt sind. Auch die ersten Inventarisierungen deutscher Auen liefern nur Anhaltspunkte zur Ausweisung einer tatsächlich retentionswirksamen Auenfläche, da die aktive Aue ausgewiesen wurde, welche statistisch mindestens ein Mal in 100 Jahren überflutet wird. Während der Datenrecherche für diese Arbeit stellte sich die Berechnung einer mittleren überfluteten Auenfläche als der erste Forschungsschwerpunkt dar, da die überflutete Auenfläche, abhängig von ihrer Konnektivität, ähnlich variabel ist wie der Abfluss in einem Flusssystem. Der zweite damit verbundene Schwerpunkt ist die Berechnung der ebenso variablen einströmenden Nährstofffracht.

Ziel dieser Arbeit ist es, anhand eines übergeordneten Konzepts Methoden zu

entwickeln, die die jährliche und monatliche hydrologische Dynamik bei der Ableitung von Eingangsdaten für empirische Retentionsmodelle berücksichtigen. An drei Testflüssen (Elbe, Main und Rhein) wurden Auen im Mittel- und Unterlauf ausgewählt, die sich in ihrem morphologischen sowie physikalisch-chemischen Zustand stark unterscheiden. Die Datenbasis bilden Messdaten aus den Flüssen und Informationen über Geländehöhen, Geometrien und Landnutzung in den Auen. Das tatsächliche Auftreten verschiedener Abflusshöhen wurde mit statistischen Auftrittswahrscheinlichkeiten verglichen und Überflutungshäufigkeiten der Auen anhand der Software FLYS, entwickelt an der Bundesforschungsanstalt für Gewässerkunde, modelliert. Mittels dieser detaillierten Ergebnisse konnten die gesuchte mittlere überflutete Aue sowie die einströmende Nährstofffracht als prozentualer Anteil der aktiven Auen bzw. der im Fluss transportierten Fracht berechnet werden.

Iterativ konnten beide Ansätze generalisiert und der anfangs zeitunabhängige Frachtansatz weiterentwickelt werden, unter Berücksichtigung der durch die Auenvegetation bedingte Rauigkeit beeinflussende Fließgeschwindigkeit. Hierbei spielt das dimensionslose und damit Größen unabhängige Verhältnis von aktuellem Abfluss und Langzeitmittel die entscheidende Rolle. Dadurch ist eine Übertragbarkeit der Ergebnisse auf andere Flusssysteme möglich. Der entscheidende Schritt in der Modellierung der jahreszeitlichen Dynamik von auftretenden Hochwässern gelang durch die iterative Entwicklung eines Konzeptes, welches die mittlere überflutete Auenflächen und die mittlere einströmende Fracht Ereignis bezogen berechnet. Hierfür finden nur die Tage im Jahr bzw. Monat Eingang in die Berechnung beider Parameter, in denen ein größerer Abfluss als das Langzeitmittel gemessen wird. Dies bedeutet, dass die berechnete mittlere überflutete Auenfläche eine mittlere überflutete Auenfläche während der Überflutungsereignisse der betrachteten zeitlichen Periode darstellt. Hiermit können die starken unterschiedlichen hydrologischen Schwankungen zwischen aber auch innerhalb der Jahre dargestellt werden. Eine Anwendung verschiedener empirischer Modelle zur Berechnung der Nitrat- und Gesamtphosphor-Retention ( $NO_3-N$  und  $TP$ ) in den Auen der drei Testflüsse zeigt, dass die Modelle, welche hydrologische Gegebenheiten durch die Berechnung der Aufenthaltszeit bzw. hydraulischer Belastung berücksichtigen, zu realistischen Retentionsraten von 100 und  $400 \text{ kg } NO_3-N \text{ ha}^{-1} \cdot \text{yr}^{-1}$  sowie zwischen  $<1$  und  $28 \text{ kg } TP \text{ ha}^{-1} \cdot \text{yr}^{-1}$  führen. Niedrigere Werte werden für die Auen des Mains mit geringer Konnektivität und die höchsten Werte für die relativ naturnahen Elbauen berechnet. Verglichen mit der Retention im Fluss, die bei Hochwässern abnimmt, steigt die Retention in der Elbaue auf bis zu 10 % für  $NO_3-N$

und 9% für *TP* bezogen auf die gesamte monatlich transportierte Nährstofffracht an.

Eine Übertragbarkeit der Ergebnisse auf weitere Flusssysteme ist mittels Landnutzungs-, Boden- und Höhenmodelldaten möglich und bereits begonnen, so dass der hier entwickelte Ansatz deutschlandweite Anwendung finden kann. Allerdings steht eine Validierung der in dieser Arbeit berechneten Retentionsraten mit Messdaten aus, da diese fehlen. Mit Literaturwerten stimmen die Retentionsraten sehr gut überein.

## Bibliography

- Aldous, A., McCormick, P., Ferguson, C., Graham, S. & Craft, C. (2005), 'Interaction between water bodies within the floodplains of large rivers: function and development of connectivity', *Restoration Ecology* **13**(2), 341–347.
- Aldous, A., McCormick, P., Stevens, C. J., Barry, M. J. & Bach, L. B. (2007), 'Soil phosphorus release from a restoration wetland, upper Klamath Lake, Oregon', *Wetlands* **27**(4), 1025–1035.
- Alexander, R. B., Böhlke, J. K., Boyer, E. W., David, M. B., Harvey, J. W., Mulholland, P. J., Seitzinger, S. P., Tobias, C. R., Tonitto, C. & Wollheim, W. M. (2009), 'Dynamic modeling of nitrogen losses in river networks unravels the coupled effects of hydrological and biogeochemical processes', *Biogeochemistry* **93**, 91–116.
- Ambus, P. (1993), 'Control of denitrification enzyme activity in a streamside soil', *FEMS Microbiology Ecology* **102**, 225–234.
- Amoros, C. & Roux, A. L. (1988), 'Interaction between water bodies within the floodplains of large rivers: function and development of connectivity', *Münstersche Geographische Arbeiten* pp. 125–130.
- Arheimer, B. & Wittgren, H. B. (1994), 'Modelling Effects of Wetlands on Regional Nitrogen Transport', *Ambio special issue: Wetlands and Lakes as Nitrogen Traps* **23**(6), 378–386.
- Arheimer, B. & Wittgren, H. B. (2002), 'Modelling nitrogen removal in potential wetlands at the catchment scale', *Ecological Engineering* **19**, 63–80.
- Baborowski, M., Büttner, O., Morgenstern, P., Krüger, F., Lobe, I., Rupp, H. & Tümpling, W. (2007), 'Spatial and temporal variability of sediment deposition on artificial-lawn traps in a floodplain of the River Elbe', *Environmental Pollution* **148**, 770–778.
- Bachand, P. A. M. & Horne, A. J. (2000), 'Denitrification in constructed free-water surface wetlands: II. Effects of vegetation and temperature', *Ecological Engineering* **14**(1-2), 17–32.
- Bechthold, J. S. (2007), *Fluvial Sediment Influences on Floodplain Soil Biogeochemistry*, PhD thesis, University of Washington, USA. Thesis.
- Behrendt, H. (1996), 'Inventories of point and diffuse sources and estimated nutrient loads – A comparison for different river basins in Central Europe',

- Water Science and Technology* **33**, 99–107.
- Behrendt, H. (1999), ‘A comparison of different methods of source apportionment of nutrients to river basins’, *Water Science and Technology* **39**(12), 179–187.
- Behrendt, H., Bach, M., Kunkel, R., Opitz, D., Pagenkopf, W.-G., Scholz, G. & Wendland, F. (2003), Nutrient Emissions into River Basins of Germany on the Basis of a Harmonized Procedure, UBA-Report 82/03, UBA.
- Behrendt, H., Kornmilch, M., Opitz, D., Schmoll, O. & Scholz, G. (2002), ‘Estimation of the nutrient inputs into river systems – experiences from German rivers’, *Regional Environmental Change* **3**(1-3), 107–117.
- Behrendt, H. & Opitz, D. (2000), ‘Retention of nutrients in river systems: Dependence on specific runoff and hydraulic load’, *Hydrobiologia* **410**, 111–122.
- BfG (2008), Information on hydraulic modelling (in German only), Technical report, BfG.  
**URL:** last access 16/11/2012: [www.bafg.de/EN](http://www.bafg.de/EN)
- BfG (2009), Wasserstandsinformationsdienste der BfG für Bundeswasserstraßen (water level information service for Federal Water Ways), Technical report, Federal Institute of Hydrology, Germany. on behalf of the German Ministry of Transport, Building and Urban Development.
- Böhlke, J. K., Antweiler, R. C., Harvey, J. W., Laursen, A. E., Smith, L. K., Smith, R. L. & Voytek, M. A. (2009), ‘Multi-scale measurements and modeling of denitrification in streams with varying flow and nitrate concentration in the upper Mississippi River basin, USA’, *Biogeochemistry* **93**, 117–141.
- BMU & BfN (2009), Auenzustandsbericht – Flussauen in Deutschland (Report of the condition of riparian floodplains in Germany), Technical report, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) und Bundesamt für Naturschutz (BfN), eds.
- Boulêtreau, S., Salvo, E., Lyautey, E., Mastroiello, S. & Garabetian, F. (2012), ‘Temperature dependence of denitrification in phototrophic river biofilms’, *Science of the Total Environment* **416**, 323–328.
- Boyer, E. W., Alexander, R. B., Parton, W. J., Li, C., Butterbach-Bahl, K., Donner, S. D., Skaggs, R. W. & Del Grosso, S. J. (2006), ‘Modeling denitrification in terrestrial and aquatic ecosystems at regional scales’, *Ecological Applications* **16**(6), 2123–2142.
- Brunotte, E., Dister, E., Günther-Diringer, D., Koenzen, U. & Mehl, D. (2009), ‘Flussauen in Deutschland - Erfassung und Bewertung des Auenzustandes (Riparian Floodplains in Germany - Inventory and Evaluation of the condi-

- tions of floodplains)', *Naturschutz und Biologische Vielfalt* 87, Bonn - Bad Godesberg.
- Busch, N., Meißner, D., Hammer, M., Hatz, M. & Graf, M. (2009), Flusshydrologische Software Version 2.1.3 (Hydrologic Software Version 2.1.3 - in German only), Technical report, brochure of The Federal Institute of Hydrology (BfG).
- Byström, O. (1998), 'Analysis - The nitrogen abatement cost in wetlands', *Ecological Economics* **26**, 321–331.
- Cabezas, A., Gelbrecht, J., Zwirnmann, E., Barth, M. & Zak, D. (2012), 'Effects of degree of peat decomposition, loading rate and temperature on dissolved nitrogen turnover in rewetted fens', *Soil Biology and Biochemistry* **48**, 181–192.
- Cioc, M. (2002), *The Rhine, An Eco-Biography, 1815-2000*, University of Washington Press, Seattle. ISBN 978-0-295-98254-0.
- CIS (2003), Horizontal Guidance Document on the Role of Floodplains in the Water Framework Directive, Technical report, CIS. Final Draft Version 8.0.
- Constanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R., Paruelo, J., Raskin, R. & Sutton, P. and, v. d. B. M. (1997), 'The value of the world's ecosystem services and natural capital', *Nature* **387**, 253–260.
- Cooper, A. B. (1990), 'Nitrate depletion in the riparian zone and stream channel of a small headwater catchment', *Hydrobiologia* **202**, 13–26.
- Davidsson, T. E. & Stahl, M. (2000), 'The Influence of Organic Carbon on Nitrogen Transformations in Five Wetland Soils', *Soil Science Society American Journal* **64**, 1129–1136.
- Davidsson, T. E., Trepel, M. & Schrautzer, J. (2002), 'Denitrification in drained and rewetted minerotrophic peat soils in northern Germany', *Journal of Plant Nutrient Soil Sciences* **165**, 199–204.
- Dehnhardt, A. & Bräuer, I. (2008), The value of floodplains as nutrient sinks: Two applications of replacement-cost approach, in B. Schweppe-Kraft & G. F. A. for Nature Conservation (BfN), eds, 'Ecosystem Services of Natural and Semi-Natural Ecosystems and Ecologically Sound Land Use', Vol. 237, BfN, Bonn, p. 138.
- Deutsch, B., Mewes, M., Liskow, I. & Voss, M. (2006), 'Quantification of diffuse nitrate inputs into a small river system using stable isotopes of oxygen and nitrogen in nitrate', *Organic Geochemistry* **37**, 1333–1342.
- Dortch, M. S. & Gerald, J. A. (1995), Screening-level model for estimating pollutant removal by wetlands, Technical Report WRP-CP-9 NTIS No. AD

- A302-097, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- European Community (2007), ‘Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks’, *Official Journal of the European Union 2007* pp. L288/27–L288/34.
- Federal Environment Agency, DLR-DFD (2006), ‘CORINE Land Cover’.  
**URL:** *last access 09/06/2012: [http://www.corine.dfd.dlr.de/data-description\\_2006\\_en.html](http://www.corine.dfd.dlr.de/data-description_2006_en.html)*
- Fennel, K., Brady, D., DiToro, D., Fulweiler, R. W., Gardner, W. S., Giblin, A., McCarthy, M. J., Rao, M., Seitzinger, S., Thouvenot-Korppoo, M. & Tobias, C. (2009), ‘Modeling denitrification in aquatic sediments’, *Biogeochemistry* **93**, 159–178.
- Fisher, J. & Acreman, M. C. (2004), ‘Wetland nutrient removal: a review of the evidence’, *Hydrology und Earth System Sciences* **8**, 673–685.
- Frick, W. E. & Sigleo, A. C. (2007), ‘Seasonal variations in river discharge and nutrient export to a Northeastern Pacific estuary Estuarine’, *Coastal and Shelf Science* **73**, 368–378.
- Gren, I.-M. (1993), ‘Alternative nitrogen reduction policies in the Mälars region’, *Ecological Economics* **7**, 159–172.
- Gren, I.-M., Groth, K.-H. & Sylven, M. (1995), ‘Economic Values of Danube Floodplains’, *Journal of Environmental Management* **45**, 333–345.
- Groffman, P. M., Altabet, M. A., Böhlke, J. K., Butterbach-Bahl, K., David, M. B., Firestone, M. K., Giblin, A. E., Kana, T. M., Nielsen, L. P. & Voytek, M. A. (2009a), ‘Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models’, *Biogeochemistry* **93**, 49–77.
- Groffman, P. M., Butterbach-Bahl, K., Fulweiler, R. W., Gold, A. J., Morse, J. L., Stander, E. K., Tague, C., Tonitto, C. & Vidon, P. (2006), ‘Methods for measuring denitrification: diverse approaches to a difficult problem’, *Ecological applications* **16**(6), 2091–2122.
- Groffman, P. M., Davidson, E. A. & Seitzinger, S. (2009b), ‘New approaches to modeling denitrification’, *Biogeochemistry* **93**, 1–5.
- Hamilton, S. K. (2009), Flood plains, *in* G. E. Likens, ed., ‘Encyclopedia of Inland Waters’, Vol. 3, Elsevier, Oxford, pp. 378–386.
- Hefting, M., Beltman, B., Karssenberg, D., Rebel, K., van Riessen, M. & Spijker, M. (2006), ‘Water quality dynamics and hydrology in nitrate loaded riparian zones in the Netherlands’, *Environmental pollution* **139**, 143–156.

- Hefting, M. M., Bobbink, R. & de Caluwe, H. (2003), 'Nitrous oxide emission and denitrification in chronically nitrate-loaded riparian buffer zones', *Journal of Environmental Quality* **32**, 1194–1203.
- Hernandez, M. E. & Mitsch, W. J. (2007), 'Denitrification in created riverine wetlands, Influence of hydrology and season', *Ecological Engineering* **30**, 78–88.
- Hoffmann, C. C., Heiberg, L., Audeta, J., Schönfeldt, B., Fuglsang, A., Kronvang, B., Ovesena, N. B., Kjaergaard, C., Hansen, H. C. B. & Jensen, H. S. (2012), 'Low phosphorus release but high nitrogen removal in two restored riparian wetlands inundated with agricultural drainage water', *Ecological Engineering* **46**, 75–87.
- Hoffmann, C. C., Kjaergaard, C., Uusi-Kämppä, J., Hansen, H. C. B. & Kronvang, B. (2008), 'Phosphorus Retention in Riparian Buffers: Review of Their Efficiency', *Journal of Environmental Quality* **38**, 1942–1955.
- Hoffmann, C. C., Kronvang, B. & Audet, J. (2011), 'Evaluation of nutrient retention in four restored Danish riparian wetlands', *Hydrobiologia* **674**(1), 5–24.
- Hofmeister, F. (2006), Die Rückgewinnung von Feuchtgebieten als eine Lösung für aktuelle Umweltprobleme (Restoration of wetlands as a solution for current environmental problems, PhD thesis, Ruprecht-Karls-Universität Heidelberg, Germany. Thesis.
- ICPER (2009), Action Plan for the Flood Protection in the Elbe River Basin – The implementation results in the years 2006 – 2008, ICPER Information Sheet, ICPER.  
**URL:** last access 08/11/2012: <http://www.iksemkol.org/index.php?id=14&L=2>
- IKSR (2005), Umsetzung des Aktionsplans Hochwasser (Realization of the Agenda Floods), report PLEN-CC 17-06d rev. 20.12.06., IKSR.
- IKSR (2006), Umsetzung des Aktionsplans Hochwasser; Bericht 2005 (implementation of the action plan floods; report 2005), Technical report, International Commission for the Protection of the Rhine.  
**URL:** last access 06/10/2012: <http://www.iksr.org/>
- Jansson, A., Folke, C. & Langaas, S. (1998), 'Quantifying the nitrogen retention capacity of natural wetlands in the large-scale drainage basin of the Baltic Sea', *Landscape Ecology* **13**, 249–262.
- Jansson, M., Andersson, R., Berggren, H. & Leonardson, L. (1994), 'Floodplains and Lakes as Nitrogen Traps', *Ambio Special issue: Floodplains and Lakes as Nitrogen Traps* **23**(4), 320–325.

- Jährling, K.-H. (2009), 'Zur Situation auentypischer Gewässer aus historischer Sicht und Erfahrungen bei der Altarmreaktivierung an der Elbe (About the situation of water bodies in floodplains from a historic perspective and experiences on oxbow reactivation along the river Elbe)', *Naturschutz im Land Sachsen-Anhalt (nature protection in Saxony-Anhalt)* **46**, 17–28.
- Johnes, P. (2007), 'Uncertainties in annual riverine phosphorus load estimation: Impact of load estimation methodology, sampling frequency, baseflow index and catchment population density', *Journal of Hydrology* **322**, 241–258.
- Junk, W., Bayley, P. & Sparks, R. (1989), 'The flood pulse concept in river-floodplain systems', *Canadian Special Publications of Fisheries and Aquatic Sciences* **106**, 110–127.
- Kadlec, R. H., Cuvellier, C. & Stober, T. (2010), 'Performance of the Columbia, Missouri, treatment wetland', *Ecological Engineering* **36**, 672–684.
- Kadlec, R. & Wallace, S. (2008), *Treatment Wetlands*, 2 edn, CRC Press, Boca Raton, FL.
- Kieckbusch, J. J. & Schautzer, J. (2007), 'Nitrogen and phosphorus dynamics of a re-wetted shallow-flooded peatland', *Science of the Total Environment* **380**, 3–12.
- Koenzen, U. (2005), 'Fluss- und Stromauen in Deutschland - Typologie und Leitbilder (Floodplains in Germany - Typology and Guidelines)', *angewandte Landschaftsökologie* 65, Bundesamt für Naturschutz, Bonn-Bad Godesberg. Thesis.
- Krüger, F., Meissner, R., Gröngroft, A. & Grunewald, K. (2005), 'Flood Induced Heavy Metal and Arsenic Contamination of Elbe River Floodplain Soils', *Acta hydrochimica et hydrobiologica* **33**(5), 455–465.
- Krüger, F., Schwartz, R., Kunert, M. & Friese, K. (2006), 'Methods to calculate sedimentation rates of floodplain soils in the middle region of the Elbe River', *Acta hydrochimica et hydrobiologica* **34**, 175–187.
- Kronvang, B., Andersen, I., Hoffmann, C., Pedersen, M. L., Ovesen, N. & Andersen, H. (2007), 'Water Exchange and Deposition of Sediment and Phosphorus during Inundation of Natural and Restored Lowland Floodplains', *Water Air and Soil Pollution* **181**, 115–121.
- Kronvang, B., Bechmann, M., Lundekvam, H., Behrendt, H., Rubaek, G. H., Schoumans, O. F., Syversen, N., Andersen, H. E. & Hoffmann, C. C. (2005), 'Phosphorus Losses from agricultural areas in river Basins: Effects and Uncertainties of targeted mitigation measure', *Journal of Environmental Qual-*

- ity* **34**(6), 2129–2144.
- Kronvang, B. & Bruhn, A. J. (1996), ‘Choice of sampling strategy and estimation method for calculating nitrogen and phosphorus transport in small lowland streams’, *Hydrological Processes* **10**, 1483–1501.
- Kronvang, B., Hezlar, J., Boers, P., Jensen, J. P., Behrendt, H., Anderson, T., Arheimer, B., Venohr, M., Hoffmann, C. C. & Nielsen, C. (2004), Nutrient Retention Handbook. Software Manual for EUROHARP-NUTRET and Scientific review on nutrient retention, EUROHARP report 9-2004 report SNO 4878/2004, NIVA, Oslo, Norway.
- URL:** *last access 06/10/2012: [www.euroharp.org](http://www.euroharp.org)*
- Kronvang, B., Hoffmann, C. C., Svendsen, L. M., Windolf, J., Jensen, J. P. & Dørge, J. (1999), ‘Retention of nutrients in river basins’, *Aquatic Ecology* **33**, 29–40.
- Leonardson, L., Bengtsson, L., Davidsson, T., Persson, T. & Emanuelsson, U. (1994), ‘Nitrogen retention in artificially flooded meadows’, *Ambio special issue: Wetlands and Lakes as Nitrogen Traps* **23**, 332–341.
- Maltby, E., Baker, C., Barker, T., D. U., Hogan, D., McInnes, R., Bishop, K., Blackwell, M., Clement, B., Papadimos, D., Scholz, M., Schulz-Zunkel, C., Seferlis, M., Tellam, J., Verhoeven, J. & Verhoeven, M. (2009), *Functional Assessment of Wetlands. Towards evaluation of ecosystem services*, CRC Press, Boston.
- Mander, Ü. & Mauring, T. (1994), *Functional appraisal of agricultural Landscape in Europe*, Polish Academy of Science, Poznan, chapter Nitrogen and Phosphorus retention in natural ecosystems.
- McClain, M., Boyer, E., Dent, C., Gergel, S., Grimm, N., Groffman, P., Hart, S., Harvey, J., Johnston, C., Mayorga, E., McDowell, W. & Pinay, G. (2003), ‘Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems’, *Ecosystems* **6**(4), 301–312.
- Meyerhoff, J. & Dehnhardt, A. (2007), ‘The European Water Framework Directive and economic valuation of wetlands: the restoration of floodplains along the River Elbe’, *Environmental Policy and Governance* .
- Middelkoop, H. (2000), ‘Heavy-metal pollution of the river Rhine and Meuse floodplains in the Netherlands’, *Netherlands Journal of Geosciences* **79**(4), 411–428.
- Mitsch, W. & Gosselink, J. G. (1993), *Wetlands*, 2 edn, Van Nostrand Reinhold Company, New York.
- Mitsch, W., Gosselink, J. G., Zhang, L. & Anderson, C. (2009), *Wetland Ecosystems*, Wiley, Hoboken, New Jersey.

- Mitsch, W. J., Day, J. W., Zhang, L. & Lane, R. R. (2005), 'Nitrate-nitrogen retention in wetlands in the Mississippi river basin', *Ecological Engineering* **24**, 267–278.
- Mitsch, W. J. & Gosselink, J. G. (2000), 'The value of wetlands: importance of scale and landscape setting', *Ecological Economics* **35**, 25–33. special issue: the values of wetlands: landscape and institutional perspectives.
- Mitsch, W. J., Horne, A. J. & Nairn, R. W. (2000), 'Nitrogen and phosphorus retention in wetlands- ecological approaches to solving excess nutrient problems', *Ecological Engineering* **144**, 1–7.
- Natho, S. & Venohr, M. (2012a), 'Nutrient retention in riparian floodplains on landscape scale, the necessity for a monthly retention approach', *Water Science and Technology* **66**(12), 2800–2807.
- Natho, S. & Venohr, M. (2012b), Modelling spatial and temporal dynamics in floodplains - extent, nutrient loads and retention, in G. Sorial & J. Hong, eds, 'Proceedings of Environmental Science and Technology Volume 2', American Academy of Science, American Science Press PP1-632, pp. 415–420.
- Natho, S. & Venohr, M. (n.d.), 'Active versus potential floodplains –flooding extent as a key to calculate nutrient retention'. submitted for publication.
- Natho, S., Venohr, M., Henle, K. & Schulz-Zunkel, C. (2013), 'Modelling nitrogen retention in floodplains with different degrees of degradation for three large rivers in Germany', *Journal of Environmental Management* . in press.  
**URL:** <http://dx.doi.org/10.1016/j.jenvman.2013.02.049>
- Noe, G. B. & Hupp, C. R. (2005), 'Carbon, nitrogen and phosphorus accumulation in floodplains of atlantic coastal plain rivers', *Ecological Applications* **15**(4), 1178–1190.
- Noe, G. B. & Hupp, C. R. (2009), 'Retention of Riverine Sediment and Nutrient Loads by Coastal Plain Floodplains', *Ecosystems* **12**, 728–746.
- Oeurng, C., Sauvage, S. & Sánchez-Pérez, J.-M. (2010), 'Temporal variability of nitrate transport through hydrological response during flood events within a large agricultural catchment in south-west France', *Science of the Total Environment* **409**, 140–149.
- Olde Venterink, H. O., Hummelink, E. & Van den Hoorn, M. (2003), 'Denitrification potential of a river floodplain during flooding with nitrate-rich water: grasslands versus reedbeds', *Biogeochemistry* **65**, 233–244.
- Olde Venterink, H., Wiegman, F., van der Lee, G. & Vermaat, J. (2002), 'Role of active floodplains for nutrient retention in the river Rhine', *Journal of Environmental Quality* **32**(4), 1430–1435.

- Olde Venterink, H. and Vermaat, J., Pronk, M., Wiegman, F., van der Lee, G., van den Hoorn, M., Higler, L. & Verhoeven, J. (2006), 'Importance of sediment deposition and denitrification for nutrient retention in floodplain wetlands', *Applied Vegetation Science* **9**, 163–174.
- Opperman, J. J., Galloway, G. E., Fargione, J., Mount, J. F., Richter, B. D. & Secchi, S. (2009), 'Sustainable Floodplains through large-scale reconnection to rivers', *Science* **326**, 1487–1488.
- OSPAR (2008), Comprehensive study on nutrient input and Direct Dischargers (RID): Presentation and Assessment of the OSPAR contracting parties' RID 2006 Data, Technical Report Publication number 376/ 2008, OSPAR Commission.
- URL:** last access 06/10/2012: [http://www.ospar.org/documents/dbase/publications/p00376\\_rid%202006%20report.pdf](http://www.ospar.org/documents/dbase/publications/p00376_rid%202006%20report.pdf)
- Pina-Ochoa, E. & Alvarez-Cobelas, M. (2006), 'Denitrification in aquatic environments: A cross-system analysis', *Biogeochemistry* **81**(1), 111–130.
- Pinay, G., Gumiero, B., Tabacchi, E., Gimenez, O., Tabacchi-Planty, A., Hefting, M., Burt, T., Black, V., Nilsson, C., Iordache, V., Bureau, F., Vought, L., Petts, G. & deChamps, H. (2007), 'Patterns of denitrification rates in European alluvial soils under various hydrological regimes', *Freshwater Biology* **52**(2), 252–266.
- Poff, L. N., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. (1997), 'The Natural Flow Regime', *Bioscience* **47**(11), 769–784.
- Ramsar Convention Secretariat (2006), The Ramsar Convention Manual: a guide to the Convention on Wetlands (Ramsar, Iran, 1971), Guide, Ramsar Convention Secretariat.
- Rücker, K. & Schrautzer, J. (2010), 'Nutrient retention function of a stream wetland complex—a high-frequency monitoring approach', *Ecological Engineering* **36**, 612–622.
- Saunders, D. L. & Kalff, J. (2001), 'Nitrogen retention in wetlands, lakes and rivers', *Hydrobiologia* **443**, 205–212.
- Schneider, S. (2010), 'Widerstandverhalten von holzigen Auenpflanzen – Konzept zur Etablierung von Weichholzaunen an Fließgewässern (resistance of riparian forests – concept for the establishment of softwoods along rivers)', Karlsruhe Institut für Technologie. 217 pages.
- Scholz, M., Mehl, D., Schulz-Zunkel, C., Kasperidus, H. & Born, W. and, H. K. (2012), *Ökosystemfunktionen von Flussauen - Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Kohlenstoffvorrat, Treibhausgase-*

- missionen und Habitatfunktion. (Ecosystem services of riparian floodplains-analysis and evaluation of flood retention, nutrient retention, carbon storage, greenhouse gas emissions and habitat functions)*, Vol. 124, BfN, Bonn-Bad Godesberg.
- Scholz, M., Rupp, H., Puhlmann, G., Ilg, C., Gerisch, M., Dziock, F., Follner, K., Foeckler, F., Glaeser, J., Konjuchow, F., Krüger, F., Regner, A., Schwarze, E., von Tümpling, W., Duquesne, S., Liess, M., Werban, U., Zacharias, S. & Henle, K. (2009), 'Deichrückverlegung in Sachsen-Anhalt und wissenschaftliche Begleituntersuchungen am Beispiel des Roßlauer Oberluchs (Dyke relocation in Saxony -Anhalt and scientific studies exemplified by the Roßlauer Oberluch', *Naturschutz im Land Sachsen-Anhalt, special edition* **46**, 103–115.
- Schulz-Zunkel, C. & Krueger, F. (2009), 'Trace Metal Dynamics in Floodplain Soils of the River Elbe', *Journal of Environmental Quality* **38**, 1349–1362.
- Schulz-Zunkel, C., Scholz, M., Kasperidus, H. D., Krüger, F., Natho, S. & Venohr, M. (2012), Chapter Nährstoffrückhalt (Nutrient retention), in M. Scholz, D. Mehl, C. Schulz-Zunkel, H. Kasperidus, W. Born & K. Henle, eds, 'Ökosystemfunktionen von Flussauen - Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Kohlenstoffvorrat, Treibhausgasemissionen und Habitatfunktion. (Ecosystem services of riparian floodplains-analysis and evaluation of flood retention, nutrient retention, carbon storage, greenhouse gas emissions and habitat functions)', Vol. 124, BfN, Bonn-Bad Godesberg, p. 367.
- SedNet (2005), Contaminated sediments in European river basins, final report RTD/1.2/AT/JHB D, European Sediment Research Network.
- URL:** last access 25/01/2013: <http://www.SedNet.org>
- Seitzinger, S., Harrison, J. A., Böhlke, J. K., Bouwman, A. F., Lowrance, R., Peterson, B., Tobias, C. & Van Drecht, G. (2006), 'Denitrification across landscapes and waterscapes, a synthesis', *Ecological Applications* **16**(6), 2064–2090.
- Song, K.-Y., Zoh, K.-D. & Kang, H. (2007), 'Linkages between organic matter mineralization and denitrification in eight riparian wetlands', *Science of the Total Environment* **380**, 13–18.
- Spieles, D. J. & Mitsch, W. J. (2000), 'The effects of season und hydrologic und chemical loading on nitrate retention in constructed wetlands: a comparison of low- und high-nutrient riverine systems', *Ecological Engineering* **14**, 77–91.

- State Ministry of the Environment Baden-Württemberg (2007), The integrated Rhine programme, Technical report, State Ministry of the Environment Baden-Württemberg, Stuttgart.
- Terry, A., Ullrich, K. & Riecken, U. (2006), *The European Green Belt: from vision to reality*, IUCN, Gland, Switzerland, and Cambridge, United Kingdom.
- Thew, P., Ticehurst, C., Lerat, J., Gouweleeuw, B., Gallant, J., Dyce, P. & Walker, G. (2010), Condamine-Balonne project final report, Final report Report Number: EP102876, CSIRO.  
**URL:** last access 06/10/2012: [www.csiro.au](http://www.csiro.au)
- Tockner, K., Malard, F. & Ward, J. (2000), 'An extension of the flood pulse concept', *Hydrological Processes* **14**(16-17), 2861–2883.
- Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F. & Ward, J. (1999), 'Hydrological connectivity and the exchange of organic matter and nutrients in a dynamic river-floodplain system (Danube, Austria)', *Freshwater Biology* **41**, 521–535.
- Trepel, M. & Kluge, W. (2002), 'Analyse von Wasserpfeifen und Stofftransformationen in Feuchtgebieten zur Bewertung der diffusen Austräge (Analysis of water flow and nutrient transformation in wetlands for evaluating diffuse emissions)', Schriftenreihe LUNG MV Regierung Heft 2/2003.
- Trepel, M. & Palmeri, L. (2002), 'Quantifying nitrogen retention in surface flow wetlands for environmental planning at the landscape-scale', *Ecological Engineering* **19**, 127–140.
- Turner, R., Paavola, J., Cooper, P., Farber, S., Jessamy, V. & Georgiou, S. (2003), 'Valuing nature: lessons learned and future research directions', *Ecological Economics* **46**(3), 493–510.
- US Geological Survey (2000), 'SRTM-3; 90m resolution'.  
**URL:** last access 09/06/2012: <http://srtm.usgs.gov/>
- van der Lee, G., Venterink, H. & Asselman, N. (2004), 'Nutrient retention in floodplains of the Rhine distributaries in The Netherlands', *River Research and Application* **20**(3), 315–325.
- Vanderkimpfen, P., Melger, E. & Peters, P. (2009), *Flood modeling for risk evaluation – a MIKE FLOOD vs. SOBEK 1D2D benchmark study*, Taylor & Francis Group, London, UK. ISBN 978-0-415-48507-4.
- Venohr, M. (2006), 'Modellierung der Einflüsse von Temperatur, Abfluss und Hydromorphologie auf die Stickstoffretention in Flusssystemen. (Modelling the influence of temperature, discharge and hydromorphology on nitrogen retention in river systems)', Berliner Beiträge zur Ökologie 14, Weißensee

- Verlag, Berlin. Thesis.
- Venohr, M., Hirt, U., Hofmann, J., Opitz, D., Gericke, A., Wetzig, A., Natho, S., Neumann, F., Hürdler, J., Matranga, M., Mahnkopf, J., Gadegast, M. & Behrendt, H. (2011), 'Modelling of nutrient emissions in river systems - MONERIS, methods and background', *International Review of Hydrobiology* **96**(52), 435–483.
- Verhoeven, J., Arheimer, B., Yin, C. & Hefting, M. (2006), 'Regional and global concerns over wetlands and water quality', *Trends in Ecology & Evolution* **21**(2), 96–103.
- Vink, R., Behrendt, H. & Salomons, W. (1999), 'Development of the heavy metal pollution trends in several European Rivers: an analysis of point and diffuse sources', *Water Science and Technology* **39**(12), 215–223.
- Watts, S. H. & Seitzinger, S. P. (2000), 'Denitrification rates in organic and mineral soils from riparian sites: a comparison of N<sub>2</sub> flux and acetylene inhibition methods', *Soil Biology & Biochemistry* **32**, 1380–1392.
- Zak, D. & Gelbrecht, J. (2007), 'The mobilisation of phosphorus, organic carbon and ammonium in the initial stage of fen rewetting (a case study from NE Germany)', *Biogeochemistry* **85**, 141–151.
- Zak, D., Gelbrecht, J. & C.E.W., S. (2004), 'Phosphorus retention at the redox interface of peatlands adjacent to surface waters in northeast Germany', *Biogeochemistry* **70**, 359–370.
- Zessner, M., Winkler, S. & Natho, S. (2008), Optimierung von Frachterhebungen in Gewässern unter Berücksichtigung von Probenahmehäufigkeit und Berechnungsmethodik (In-stream load optimizations under consideration of sampling frequency and algorithm), final report on behalf of the Austrian Ministry for Agriculture, Forestry, Environment and Water Management, Institut für Wassergüte, Ressourcenmanagement und Abfallwirtschaft, TU Wien.
- Zweynert, U. (2008), Möglichkeiten und Grenzen bei der Modellierung von Nährstoffeinträgen auf Flussgebietsebene (Modelling nutrient emissions on river basin scale - possibilities and limits), PhD thesis, Technischen Universität Dresden, Germany. Thesis.



## List of Figures

1.1	Soil types according to differently detailed soil maps (BÜK 1000 and the BÜK 200) along floodplains of river stretches of the Rhine (left) and Elbe (right). The morphologic and the recent floodplains are also shown. Datasource: BÜK200, ©BGR, Berlin, 2011; floodplains, ©BfN, Bonn. . . . .	13
2.1	Concept of background information and input data . . . . .	18
4.1	Overview of the potential active (diagonal lines with black frame) and the long term average inundated (diagonal lines with grey frame) riparian floodplains from BfG along the river Elbe in Germany; FLYS 2.1.3 validation sections between Wittenberg and Wittenberge are differentiated white framed boxes. Areas, for which retention is calculated, are illustrated by black framed boxes. Digital elevation is presented by 90m SRTM raster in the background (USGS 2000) . . . . .	28
4.2	Inundated area in % of the sections Tangermünde and Wittenberg related to the days of inundation based on the flooding events for the long-term mean as the statistical mean and the years 2002 . . . . .	30
4.3	Comparison of the development of a typical flood event at selected gauges with <i>TP</i> loads (a) and <i>TP</i> concentrations (c), expressed as dimensionless $Q/MQ$ ratio and with $NO_3-N$ loads (b) and $NO_3-N$ concentration (d) versus $Q$ in $m^3/s$ from October 25 <sup>th</sup> 1998 to January 1 <sup>st</sup> 1999. Loads and concentrations are shown cumulatively, taken at the same day . . . . .	35
4.4	Frequency of certain statistical discharge events in days per month at the gauging station Tangermünde between 1999 and 2002; months January (1) to December (12) only are included, if events occurred; each event equals the inundation of a certain share of the potential floodplain . . . . .	35

4.5	Share of inundated riparian floodplain on potential riparian floodplain versus the discharge ( $Q$ ) (left) and versus the relation of $Q/MQ$ (right) illustrating two river sections. Two sigmoidal relationships can be found between $Q/MQ$ and inundated floodplain extent. Three classes were identified regarding the inundation characteristics of the floodplain above $MQ$ ( $Q/MQ = 1$ ): a) less than 25 %, b) between 25 and 75 % and c) more than 75 % share of inundated floodplain on potential floodplain (see also Table 4.4) . . . . .	37
5.1	Illustration of the applied method starting from left to right: FLYS 2.1.3 result with polygons of the same depth for a detailed river section; calculation table; resulting mean depth for a schematic floodplain; the river (dark colour) is not included. . . . .	46
5.2	Illustration of the relationship between % floodplain volume on the total river system volume and the $MQ/Q$ ratio for the Elbe (upper figure) and Main and Rhine (lower figure). . . . .	50
5.3	Comparison of observed $NO_3-N$ loads (left) and $TP$ loads (right) at various gauges along the river Elbe on a yearly basis, calculated according to OSPAR (2008). At Aken and at Tangermünde the influence of tributaries is accounted for by adding the load from the Saale and the Havel respectively. Scales vary according to differences in loads. . . . .	51
5.4	Comparison of a yearly and a monthly approach to calculate the $NO_3-N$ retention in wetlands for the first and the last gauge of the analysed river section of the Elbe. . . . .	52
5.5	Comparison of total $NO_3-N$ retention in $t/yr$ calculated with two different approaches for the total study area along the river Elbe to the $NO_3-N$ river load at the last gauge of the river section in Wittenberge. . . . .	53
6.1	Relations of volume to discharge, characterizing different sections of the river Rhine (left); illustrated by a land-use map (Federal Environment Agency, DLR-DFD 2006) underlain with a SRTM 90m (US Geological Survey 2000) as well as floodplains provided by FLYS 2.1.3 (right). . . . .	58
6.2	Comparison of yearly $NO_3-N$ retention calculations (in floodplains and rivers); yearly river loads are also shown . . . . .	59

6.3	Comparison of monthly nitrogen retention results in 2002, calculated according to Venohr et al. (2011) . . . . .	59
6.4	Cumulative TP retention in 2002; calculated according to Behrendt & Opitz (2000) . . . . .	60
7.1	Studied catchments of the rivers Elbe, Main and Rhine in Germany, under consideration of a digital elevation map (SRTM). Discharge patterns are shown for the year 1999. The map shows mean discharge (MQ) and discharge occurring once a year ( $HQ_1$ ) for the start and end gauges of the analysed river sections.	63
7.2	Decision cascade of the proxy-based approach for assessing nitrogen retention in floodplains . . . . .	67
7.3	Methodology of the model-based approach to derive information on inundated floodplain size (a) and incoming load (b) . . . . .	69
7.4	Relationship between the incoming load expressed as share of volume in floodplain and the ratio of long-term mean discharge and current discharge for the three rivers Elbe, Rhine and Main.	70
7.5	Land-use types and assessed denitrification levels (DNL) for the floodplains of Elbe, Main and Rhine (on right) in comparison to the floodplains statistically inundated on 95, 25 and 5 days per year respectively. Inundation data is derived from FLYS 2.1.3 results. . . . .	72
7.6	Load differences between the rivers and comparison of inundated floodplains (in $ha \cdot 100 km^{-1}$ ) between the rivers and the approaches applied as well as between the total floodplain. . . . .	73
7.7	Comparison of two $NO_3-N$ -retention approaches on a monthly basis for the Rhine, Main and Elbe floodplains for the year 2002.	74
7.8	a: Comparison of days of inundation along the Elbe, Main and Rhine for the year 2002 in comparison to the statistical long-term mean. Flooding probabilities are shown as statistical flooding frequencies on a daily basis. Inundated areas are presented as floodplain extent in percent of the total active floodplain. b: Valuation classes for denitrification as carried out by the proxy-based approach for the floodplains of Elbe, Main and Rhine, expressed as percent of the total active floodplain. . . . .	75

8.1	Concept of average $W_A$ and $W_L$ calculation basing on discharge. In case the discharge leads to inundation, transported load and inundation extent are considered for average $W_A$ and $W_L$ calculations. . . . .	85
8.2	Analysis of concentration and discharge pairs, assumptions of 4 classes to be found, belonging into different discharge classes ( $Q/MQ < \text{or} > 1$ ) and different seasons (summer or winter) . . .	86
8.3	Relationship between discharge and percent inundated floodplain of the active floodplain, FLYS results (miniatures) and deduced Sigmoid relationships (signs with dotted lines) . . . . .	91
8.4	Nitrate (left) and TP concentration (right) versus discharge for the years 1997 to 2004, shown by the example of Rhine (top), Elbe (middle) and Main (bottom). . . . .	92
8.5	Comparison of seasonal load calculations according to the OSPAR method and the average concentration method for the combination of season and discharge class, shown for $NO_3-N$ along the river Elbe (top), Main (middle) and Rhine (bottom). . . . .	93
8.6	Calculated nitrate retention rates in the floodplains of the analysed rivers Elbe, Main and Rhine for dry, wet and mean hydrologic years (represented by the years 2004=lower whisker, 2002=upper whisker respectively 2000 for $NO_3-N$ and 1999 for TP= column). The new methodology of $W_L$ and $W_A$ calculations is applied to two hydro-exponential models in comparison to the formerly applied methodology described in Natho & Venohr (2012a). . . . .	94
8.7	Comparison of in situ river retention and floodplain retention ( $NO_3-N$ left, TP right) for the Elbe, Main and Rhine for the mean year 2000 and for the wet year 2002. . . . .	96

## List of Tables

4.1	Introduction of FLYS 2.1.3 nomenclature (based on the duration curve) applied in this study in comparison to English expressions	30
4.2	Comparison of calculation results by FLYS 2.1.3; the theoretical floodplain width for seven floodplain events for different sections along the river Elbe is shown; Magdeb. = Magdeburg, Tangerm. = Tangermünde, Wittenb. = Wittenberge . . . . .	33
4.3	Calculated $NO_3-N$ and $TP$ retention by proxy values (100 and $5\text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ respectively) for the two distinguished river sections, basing on a mean yearly inundated floodplain calculated from daily discharges, which lead to inundation. Calculations for the year 1999 are shown in brackets . . . . .	38
4.4	Flooding classes upstream and downstream of Magdeburg under consideration of the share of inundated floodplain on potential floodplain . . . . .	39
5.1	Comparison of applied nitrogen retention models from the literature, where $W_L$ = nitrogen load, that enters the floodplain. $W_A$ = wetland area. $k_{TN}$ = first order removal rate for nitrogen and $\tau$ = hydraulic residence time . . . . .	48
5.2	Comparison of river and floodplain characteristics of the rivers Elbe, Rhine and Main along specified sections. $HQ_5$ and $D360$ values based on long term discharges, provided by BfG. . . . .	49
5.3	Result of transferred floodplain sections from FLYS 2.1.3 refers to sections between gauges and their potential size. . . . .	52
6.1	Overview of applied retention models. Beside the necessary incoming nutrient load, following parameters are considered: $HL$ = hydraulic load (discharge/area), $T$ = temperature, $R$ = global radiation, $HRT$ = hydrologic retention time (area, discharge and shape dependent), $c$ = concentration. . . . .	58

---

7.1	Overview of empirical nitrogen retention models which are applicable on landscape scale. If considered in the model, the variables wetland load ( $W_L$ ) and wetland area ( $W_A$ ) are mentioned explicitly, other variables are counted only; bold models are compared in the model based approach. . . . .	68
7.2	Comparison of retention calculations with the proxy-based approach and the model-based approach in $t \cdot 100 km^{-1} \cdot yr^{-1}$ and in % of river load. . . . .	72
8.1	Comparison of decrease of $NO_3-N$ and TP concentration as averages for the rivers Elbe, Rhine and Main between 1992 and 2004. . . . .	91

## Nomenclature

abbreviation	nomenclature	unit
$(I_{S_0})$	mean slope	-
$(k_{st})$	Strickler roughness value	$m^{1/3} \cdot s^{-1}$
$A$	area	$km^2$
$A_{crosssection}$	cross section area of the river	$km^2$
$A_{fl}$	inundated floodplain area	$km^2$
$c_i$	measured concentration in sample $i$	$mg \cdot l^{-1}$ or $g \cdot m^{-3}$
$d_{water}$	water depth	m
$HL$	hydraulic load	$m \cdot yr^{-1}$
$HQ_1$	discharge occurring statistically once per year	$m^3 \cdot s^{-1}$
$HQ_{100}$	discharge occurring statistically once in hundred years	$m^3 \cdot s^{-1}$
$HQ_2$	discharge occurring statistically once in two years	$m^3 \cdot s^{-1}$
$HQ_5$	discharge occurring statistically once in five years	$m^3 \cdot s^{-1}$
$HRT$	hydrologic retention time	$m \cdot yr^{-1}$
$k_{TN}$	first order removal rate for nitrogen	-
$L_{in}$	share of total load	%
$L_r$	length of river stretch	$km$
$l_{riversection}$	length of river stretch	$km$
$MNQ$	long term mean low discharge	$m^3 \cdot s^{-1}$
$MQ$	long term mean discharge	$m^3 \cdot s^{-1}$
$n$	number of samples taken in the observed period	-
$N_{ret}$	N retention	$t \cdot yr^{-1}$
$Q$	discharge	$m^3 \cdot s^{-1}$
$Q_{calculated}$	calculated discharge	$m^3 \cdot s^{-1}$
$Q_{gauge}$	discharge measured at gauge	$m^3 \cdot s^{-1}$
$Q_i$	discharge in sample $i$	$m^3 \cdot s^{-1}$
$Q_{share}$	defined share of the total discharge	%
$R$	global radiation	$W \cdot m^{-2}$
$r_{hy}$	hydraulic radius (ratio of water surface area to sediment-water-surface)	$m^2$ or $km^2$
$T$	temperature	$^{\circ}C$
$\tau$	hydraulic residence time	$s$ or $d$ or $yr$
$v$	flow velocity	$m \cdot s^{-1}$
$V_Q$	floodplain volume	%
$W_A$	inundated floodplain area or wetland area	$m^2$ or $km^2$
$W_L$	incoming nutrient load or wetland load	$t \cdot yr^{-1}$

<b>abbreviation</b>	<b>nomenclature</b>
<i>N</i>	Nitrogen
<i>N</i> <sub>2</sub>	Dinitrogen
<i>NO</i> <sub>3</sub>	Nitrate
<i>NO</i> <sub>3</sub> - <i>N</i>	Nitrate nitrogen
<i>P</i>	Phosphorus
<i>TP</i>	Total phosphorus
<i>TN</i>	Total nitrogen
1D	1 dimensional
BfG	Bundesamt für Gewässerkunde ( <i>Federal Institute of Hydrology</i> )
BfN	Bundesamt für Naturschutz ( <i>Federal Agency for Nature Conservation</i> )
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit ( <i>Federal Ministry for the Environment, Nature Conservation and Nuclear Safety</i> )
BÜK	Bodenübersichtskarte ( <i>German soil map</i> )
C	constant
CLC	Corine land cover
D	Dauerlinie
DNL	denitrification level
DTM	digital terrain model
EC	European Commission
EU	European Union
GIS	Geographical Information Service
IKSE	Internationale Kommission zum Schutz der Elbe ( <i>International Commission for the protection of the Elbe River - ICPER</i> )
IKSR	Internationale Kommission zum Schutz des Rheins ( <i>International Commission for the protection of the Rhine River - ICPR</i> )
IRP	Integrated Rhine Program
N.N.	normal null
OSPAR	Administrator of the Oslo and Paris Conventions for the protection of the marine environment of the North-East Atlantic
SRTM	Shuttle Radar Topography Mission
UFZ	Helmholtzzentrum für Umweltforschung <i>Helmholtz Centre for Environmental Research</i>
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	US Geological Survey
V	variable
WFD	Water Framework Directive
WWTP	Waste Water Treatment Plants

## Acknowledgment

This work is the result of my efforts during the last three years, but it also represents my interest that was awoken almost ten years ago during my studies at the Technical University of Karlsruhe. This is the reason I would like to start my acknowledgments with Prof. Dr. Bernhart and Prof Dr. Diester who impressed me by their personal and professional efforts in the field of hydrology and ecology of river systems.

I would also like to thank Prof. Dr. Zessner from the Technical University in Vienna who paved my way into the field of river basin management and awoke my interest in nutrient loads and nutrient modelling, by an offer to participate in his interesting projects and the great support during my time in his work group. I also thank him for taking over the second evaluator position.

Now, I finally come to Berlin, where the most important assistance took place. First, I would like to thank Prof. Dr. Gunnar Nützmann for taking over the first evaluator position. He also initialized the collation of material to finish this thesis in time. Thanks to Prof. Dr. Haase to immediately took over the third evaluator position.

I also want to thank Dr. Venohr who supervised my work. He always allowed me the liberty to create my own ideas and concepts, finding out that we sometimes developed the same idea in different ways. However, we had many fruitful discussions and his constructive support added interesting aspects and methods to my work.

There are several experts who supported me during the last three years by providing considerable information and leading fruitful discussions regarding my ideas and concepts. I would like to thank Dr. Trepel, Dr. Mehl, Mathias Scholz, Dr. Lehmann, Sina Wunder and Dr. Zak as well as the FLYS team J. Graf, M. Hammer, M. Hatz, N. Busch and D. Meißner from the BfG.

Although retired in the meantime I would like to mention Mr Opitz, the central core of our working group, with whom I lead many discussions in the early morning hours and who opened in sight into the data of our Y-Server. Many thanks to my "Doktorandenzimmer". Without you, the time during the thesis would have been less exciting! Their assistance was manifold, Software and Hardware problems as well as questions regarding emissions, loads and retention could be solved and last but not least: social support.

Next to the support from Berlin I was fortunate to find Christiane Schulz-Zunkel who was working on a retention project resulting in our joint paper for which we had very intensive discussions and a very good cooperation. Since this thesis was written cumulatively, there were several anonymous reviewers who contributed to the work. And I really appreciated the helpful eyes, brains and hands who improved and corrected my work, namely Anika, Judith, Matze, Eli, Angela and my better half Torsten. Last but not least, I want to thank Torsten and my Hamburg-Clan for their support and positive distraction during the last (not only three) years without whom I would not have been able to finish this work.

# Estimating the Size of German Riparian Wetlands on Landscape Scale

Stephanie Natho & Markus Venohr

Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB)  
Department of Shallow Lakes and Lowland Rivers; s.natho@igb-berlin.de



## Introduction

The role of wetlands for nutrient retention is widely accepted (Trepel & Palmeri 2002, Verhoeven et al. 2006, Jansson et al. 1994). But before quantification is possible, knowledge on wetland size has to be gained. Therefore, a riparian wetland inventory was carried out for German rivers, including the extent of recent floodplains (Brunotte et al. 2009, BMU & BfN 2009).

Additionally, Natho & Venohr (2011a, 2011b) applied the Software FLYS 2.1.3 (BfG 2009) to calculate the discharge dependent extent of inundated floodplains for three large German rivers. As a results only parts of the recent floodplain (between 11% and 71% of the recent floodplain) are inundated at least on five days per year, being relevant for nutrient retention. Nevertheless, it is still not known Germany wide, how often and to which extent recent floodplains are inundated and which potential exists for nutrient retention in floodplains.

For this reason this study examines German floodplains and quantifies the share of recent floodplains which is relevant for nutrient retention.

## Material & methods

Digital maps were analysed concerning their relevance to predict the probability for floodplains being inundated. These maps

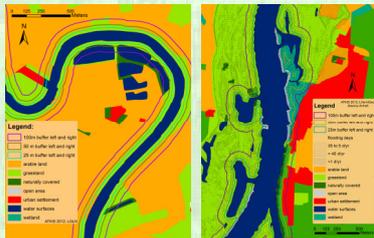


Fig. 2: Land-use data and buffers along two rivers; reference with FLYS data (right figure)

Tab. 1: Agg. flood. frequ. as % of recent floodplain

% of recent floodplain	> 45 d/yr	45-5 d/yr	< 1 d/yr
Elbe	17	71	> 80
Rhine	9	47	> 48
Main	2	11	> 24

cover information on recent floodplains for selected catchments (LANIS-Bund, BfN 2009), on soil types (scale:1:1000 and 1:200 (BGR 2010)) (Fig. 1), on land-use (ATKIS 2012) as well as on elevation (90m raster). Buffers were created in the distance of 25m, 50m and 100m from the river (Fig. 2). The floodplain analysis for selected floodplains was validated with data from Rhine, Main and Elbe, for which detailed information on flooding frequencies (in days/year) is available (Natho & Venohr 2011a). Tab. 1 shows aggregated flooding frequencies and the share of inundated floodplain of the recent floodplains in percent. The theoretical floodplain width (quotient of floodplain and river length and thus supposed to be evenly distributed on both sides of the river) was introduced as parameter to compare the floodplains of the different rivers.

## Results

The highest share of flooded recent floodplain (17%, Tab. 1) from the references is assigned to the study catchments: 325 km<sup>2</sup> riparian floodplain would be flooded on more than 45 d/yr (Tab. 2). This results in theoretical floodplain widths of less than 100m on each side of the river, which are covered by the applied buffer zones.

Considering the general soil map (1:1000) for the floodplains 10 dominant soil type classes can be found (see Fig. 1). Slopes of the recent floodplains vary between 0.6 and 6.6%. From the reference rivers it can be concluded: If the slope exceeds 2%, the theoretical floodplain width generally is less than 50m. When these results are assigned on the study floodplains, the floodplain width is overestimated in the low mountain range up to four fold (e.g. Sieg, Salzach).

Land-use, especially the distribution of arable land, reflects the probability of flooding frequency. Where arable land exceeds 20% of land-use, the reference rivers show a flooding probability of less than 1 day per year. This value is already exceeded within the 50m buffer and 100m buffer for some of the studied rivers respectively (Fig. 3). Thus for these rivers the restriction of the river width can be described by land-use.

## References

BfG (2009) Wasserstandsinformationssysteme der BfG für Bundeswasserstraßen. Colloquium on March 24th 2009 in Koblenz. Bundesanstalt für Gewässerkunde, Koblenz.  
Brunotte, E., Diester, E., Günther-Diringer, D., Koenzen, U. & D. Mehl (2009) Flussauen in Deutschland – Erfassung und Bewertung des Auenzustandes; Naturschutz und Biologische Vielfalt 87, Bonn, Bad Godesberg  
Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) und Bundesamt für Naturschutz (BfN) (Ed.) (2009) Auenzustandsbericht – Flussauen in Deutschland; 36 pages; in German only.  
Natho, S. & M. Venohr (2011a) Analysis of flooding frequency and nutrient retention capacity of riparian wetlands along

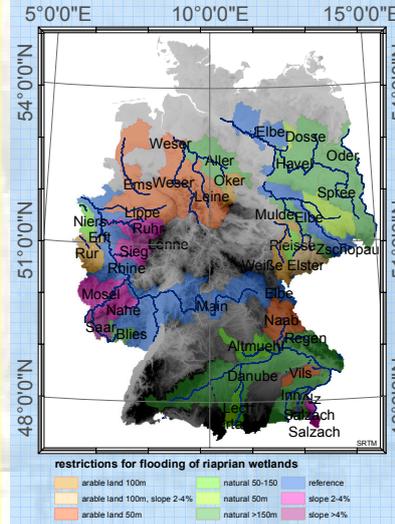


Fig. 4: Resulting restrictions of floodings caused by land-use and slope

## Conclusion

The recent floodplain in the study area is estimated to be 1970 km<sup>2</sup> (without reference floodplains). This value overestimates the regularly inundated floodplain due to restrictions such as topographic features and human alterations, allowing agriculture (Fig. 4).

Applying the basic approach from this study under the assumption of the relative natural flooding conditions from the Elbe, app. 283 km<sup>2</sup>, 856 km<sup>2</sup> and 1573 km<sup>2</sup> are inundated > 45, 45-5 and < 1 d/yr to 1 d/5yr respectively.

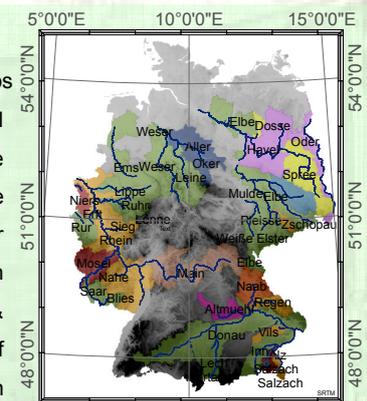


Fig. 1: Overview of study catchments with dominant soil types in the floodplains.

Tab. 2: Flooding frequencies assigned from references to study area in km<sup>2</sup>

km <sup>2</sup>	> 45 d/yr	45-5 d/yr	< 1 d/yr
high	325	1399	1575
mean	167	925	941
low	44	220	476

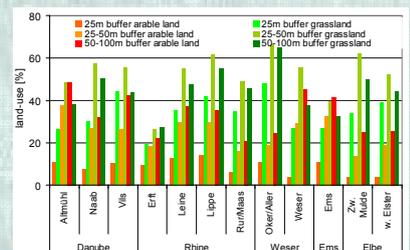


Fig. 3: Land-use of rivers with high shares of arable land in the three buffer zones.

the river Elbe, oral presentation at 15th International Conference, IWA Diffuse Pollution Spezialist Group: Diffuse Pollution and Eutrophication, New Zealand 2011, Rotorua, 18.-23.09.2011  
Natho, S. & M. Venohr (2011b) Nutrient retention in riparian wetlands on landscape scale, the necessity of a monthly retention approach; oral presentation at 15th International Conference, IWA Diffuse Pollution Spezialist Group: Diffuse Pollution and Eutrophication, New Zealand 2011, Rotorua, 18.-23.09.2011  
Trepel, M. and Palmeri, L. (2002) Quantifying nitrogen retention in surface flow wetlands for environmental planning at the landscape-scale; Ecological Engineering 19, 127-140.  
Verhoeven, J. T. A., Arheimer, B., Yin, C. and Heffing, M. M. (2006) Regional and global concerns over wetlands and water quality; Trends in Ecology and Evolution Vol.21 No.2, 96-103.

## **Selbständigkeitserklärung**

Ich erkläre, dass ich die vorliegende Arbeit selbständig und nur unter Verwendung der angegebenen Literatur und Hilfsmittel angefertigt habe.

Berlin, den 26.03.2013; Stephanie Natho