Sink or source? - The effect of hydrology on phosphorus release in the cultivated riverine wetland Spreewald (Germany)
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ABSTRACT

The cultivated riverine wetland region Spreewald faces detrimental changes in the hydrological conditions due to a significant discharge reduction. With its dense network of impounded waterways and a forced tendency of sedimentation of soluble reactive phosphorus adsorbed to large amounts of FeOH/FeOOH available from mining water and groundwater discharges the 320 km² region is favoured to accumulate large amounts of total phosphorus (TR) and thus act as an effective phosphorus sink. The change of conditions strongly challenges this function hereafter. This is especially important because eutrophication of lakes downstream the Spreewald region is controlled by phosphorus. Phosphorus balances at a testfield situated in a polder area typical for the central Spreewald region point out that hydrological and consequently hydraulic conditions are the key factors for the phosphorus sink or source behaviour. This is true for the main processes determine P retention and release at the sediment-surface water transition zone as well as for the dominant phosphorus release and retention pathways: groundwater emissions and sedimentation. In the context of hydrological changes in the Spree river catchment results from point scale and river reach scale point out the need for an adapted water management in the Spreewald region to prevent risk of extended eutrophication tendencies downstream due to forced SRP emissions.

Key words | altered riverine wetland, iron-phosphorus cycle, phosphorus balance, process analysis

INTRODUCTION

Within river basins, riverine wetlands have been recognised globally to retain or reduce nutrients (e.g. Fisher & Acreman 2004). Wetlands have been investigated as retention areas or buffer zones which control fluxes of matter between terrestrial and aquatic interfaces (Dahm et al. 1998; Van der Pijl & Verhoeven 2000). Nutrient retention efficiency in wetland systems is limited by the amount of nutrients transported into the riverine wetland and the dominating forms transported during different hydroperiods (Tockner et al. 1999; Hein et al. 2004) with the particulate nutrient dynamic being mainly influenced by the fine sediment dynamics (e.g. Kronvang 2005). For soluble reactive phosphorus (SRP) a further important mechanism for temporary retention in wetlands is incorporation in biomass (phytoplankton and macrophytes). However, highest proportional P retention (% of P load) was found in shallow rivers with a maximum contact between water and soil surface. Thus, riverine wetlands with their high share of highly diverse water ways provide favourable conditions for sedimentation associated with phosphorus retention. Although riverine wetlands can act as accumulation areas storing large amounts of particulate phosphorus, a certain amount of former P-inputs stored in river sediments (Selig & Schlunbaum 2002) or subaquatic systems can be released due to biogeochemical mobilisation processes (Jarvie et al. 2005). Especially in surface water-groundwater...
transition zones characterised by changing hydraulic conditions microbial activity, process rates and chemical conditions can reach a huge temporary and spatial dynamic (Dahm et al. 1998). This dynamic is mainly controlled by redox status and pH values inducing phosphorus release from the anorganic P pool by desorption processes (Einsele 1936; Mortimer 1941) or from the organic pool by mineralisation (Jensen & Andersen 1992).

Considering aspects of sedimentation, biological uptake, groundwater emission or phosphorus release from sediments and soils it is obvious, that dynamic systems like riverine wetlands can act either as a sink or a source for phosphorus with respect to the prevailing conditions. Especially, altered floodplains which are intensively used by humans (with nutrient sources altered, nutrient cycles interrupted and emission pathways modified) may behave as a source depending on type of organic matter and chemical compound considered (Gergel & Turner 2002).

In the Spree river basin the Spreewald’s function as a phosphorus sink or source is especially important because phosphorus being the limiting nutrient for algae growth in large parts of the Spree system, especially in the lakes (Gelbrecht 2002) downstream.

At present times the 320 km² cultivated floodplain landscape and UNESCO biosphere reserve downstream different extended mining areas, (Figure 1) underlies detrimental changes in its hydrology. A distinct discharge reduction of the Spree (caused by a drawback of mining activities), among others, will lead to significant changes in hydraulic conditions affecting the watercourses, sediment-water interactions but also the intense interaction with the groundwater rich in phosphorus. One further impact may be an alteration of the phosphorus sedimentation behaviour significantly associated with adsorption to FeOH/FeOOH from mining water.

This article aims to contribute to a better understanding of the impact of hydrological changes on the phosphorus sink and source character of the wetland region Spreewald with respect to the current hydrological development.

Using a multi scale approach, release and retention processes are evaluated (point scale) and pathways are quantified resulting in phosphorus balances for a 55 ha testfield (river reach scale) situated in a central polder area. To achieve this, it was necessary to combine geohydraulic modelling with hydrochemical issues, soil and sediment analyses as well as microbiological issues (not discussed here). Phosphorus balances from the testfield were upscaled to the whole polder area, 800 ha in size. The input of testfield results in a regional Water Quality Model (Balla et al. 2004) valid for the whole Spreewald permits us to evaluate the reaction of the Spreewald system at different hydrological conditions on the regional scale (not shown here).

MATERIAL AND METHODS

Study site

On its 380 km way from the Lausitzer highlands to its discharge into the River Havel north east of the German Capital Berlin, the River Spree and its 10.105 km² catchment underlies several detrimental effects. The most evident are water storage in reservoirs, intensive surface mining and the need to refill former surface mining areas in its middle course. Since the 1960s river hydrology was strongly altered with about one third of the mean discharge (18.4 m³s⁻¹) arising from mining activities (Kaden 2002). Obviously, also water quality issues were affected. Direct impacts were emissions of large amounts of sulphate (SO₄²⁻) and iron Fe²⁺ as a product of pyrite oxidation which results in a local decrease of the pH-values (Gelbrecht 2002). Second, high emissions of Fe²⁺ to a freshwater system result in the formation of FeOH/FeOOH with a strong affinity for adsorption of soluble reactive phosphorus (= SRP) and sedimentation in accumulation areas expressed by increased riverbed sediment phosphorus concentrations in the whole Spreewald region (Kalettka et al. 2004). The drawback of mining activities from the 1990s induces a drastic discharge reduction of the River Spree downstream to MQ = 8.9 m³s⁻¹ in 2005 and 11.1 m³s⁻¹ in 2020 forecast (Kaden 2002).

The reduction of the discharge is especially critical for the Spreewald floodplain characterised by a dense network of impounded watercourses with 1.280 km length in total (Figure 1). The extended water surface area and high groundwater levels determine high rates of evapotranspiration which already lead to maximum water balance deficits.
of 5 m$^3$s$^{-1}$ in the Spreewald region (Kaden 2002). Thus, a further discharge reduction will probably lead to a further “potamalisation”, drying of waterways and mineralisation of peat soils by decreasing groundwater tables.

The study area Sommerpolder Nord (800 ha), a typical landscape in the central Spreewald floodplain, as well as the testfield (55 ha) is characterised by impounded ditches with low flow velocities of 0.02–0.16 m$^3$s$^{-1}$, muddy, phosphorus and iron rich sediments and partly inundated peat soils. The sediment phosphorus is significantly correlated to sediment iron, with sediment phosphorus up to 3.9 g kg$^{-1}$ DM$^{-1}$ in the Spreewald region and maximum 7.5 g kg$^{-1}$DM$^{-1}$ at the

Figure 1 | Spree river catchment including Spreewald region and mining areas (above left), Spreewald river system (above right), Sommerpolder Nord and testfield with experimental setup (below).
testfield (Kalettka et al. 2004). Water levels are artificially contro

led, tending to achieve higher water levels from November to March for water storage and lower water levels from April to October due to dotation of the downstream system. From the 1970s to the 1990s the fields have been pastured extensively with intensive agricultural use resulting in peat degradation, subsidence and matter enrichment in groundwater.

Process investigations and phosphorus balances (point scale; river reach scale)

In-situ investigations on the testfield were related to the groundwater-surface water system, with emphasis on the sediment-surface water interface. Hydraulic conditions were analysed based on automatic surface water level and groundwater level recordings (frequency set once in an hour) as well as on fortnightly to monthly manual measurements. To estimate magnitudes of water exchange between the plain and the channel (exfiltration \( Q_{\text{EXF}} \)) or the channel and the plain (infiltration \( Q_{\text{INF}} \)), leakage rates from 2001–2002 were calculated using a geohydraulic model. This model (MODFLOW) was constructed for two groundwater transects representing the western topographical lower polder parts (side A) underlying seasonal flooding and the eastern higher parts (represented by side B) not affected by flooding (Figure 1).

Water quality measurements (\( c_{\text{RIV}} \)) were provided between 1999 and 2002 in a fortnightly to monthly frequency. Sequential P fractioning of the riverbed sediments were operated following Psenner & Pucsko (1988). Depending on hydraulic conditions SRP in interstitial water from Mittelkanal sediments was measured using dialyse sampler (Carignan 1984). Under the assumption that the sediments are seeped through by \( Q_{\text{EXF}} \) or \( Q_{\text{INF}} \) the measured interstitial water concentration (\( c_{\text{INT}} \)) at the transition zone was used to calculate groundwater phosphorus emission. Dimensions of sedimentation rates were evaluated using plate traps (Kozerski & Leuscher 2000) at MK1 and related to the discharge by a regression model \( (r^2 = 0.99, p < 0.0001) \). Sedimentation rates at this side represent maximum sedimentation values because since it is situated in the backwater of a weir. To evaluate P-sedimentation rates (\( F_{\text{SED}} \)) phosphorus concentration at this side were calculated from the trapped material and averaged with \( 3.3 \pm 1.1 \text{ mg g}^{-1} \text{ DM}^{-1} \) (\( n = 6 \)).

Phosphorus emission from groundwater (\( P_{\text{EMI}} \)) was calculated using:

\[
P_{\text{EMI}} = (Q_{\text{EXF}} \cdot c_{\text{INT}}) - F_{\text{SED}}
\]

and phosphorus retention during infiltration (\( P_{\text{RET}} \)) was calculated by:

\[
P_{\text{RET}} = (Q_{\text{INF}} \cdot c_{\text{RIV}}) + F_{\text{SED}}
\]

Phosphorus balances (available on a daily frequency) were aggregated to a monthly base and related to the relevant area resulting in the unit kilogram per hectare per month [kg ha\(^{-1}\) m\(^{-1}\)]. Sedimentation rates for side B were modified by considering the relation of sediment mightiness at side A and side B, which due to extended sedimentation is threefold higher at A. Assuming rather homogeneous conditions in the study area Sommerpolder Nord results from the testfield are upscaled to the whole polder region considering lower polder and upper polder shares.

RESULTS

Geohydraulic conditions

Geohydraulic conditions in the testfield area are mainly influenced by weir regulated ditch water levels (Mittelkanal and Barrankanal) and groundwater levels, which are strongly impacted by the climatic water budget. During inundation at the topographical lower part of the testfield (groundwater transect A) water exchange between channel water and inundation water is controlled by ditch water level elevation. In general water fluxes between ditch water and groundwater are small and the soil column is completely water saturated (October–March). If ditch water levels fall beyond the surface elevation increasing evapotranspiration let the groundwater levels decrease. The establishment of a negative hydraulic gradient between the ditch water level and the groundwater level creates infiltrating conditions throughout this time period (April–September). In 2001 a six month phase of infiltrating conditions establish at side A.
At side B the higher surface elevation and the heightened ditch shoulder generally prevent the plain from inundation by ditch water. The geohydraulic conditions established in this part are dominated by the ditch water levels and the climatic water balance, inducing groundwater level fluctuations. A positive climatic water balance leads to extended groundwater levels compared to the ditch water levels. This results in exfiltration of groundwater into the ditch which is typical for winter months but also during month with high precipitation (e.g. September 2001: 100 mm). A negative climatic water balance especially throughout the summer months results in decreasing groundwater levels and infiltrating ditch water (May – August).

Consequently, the lower parts of the test field are determined by groundwater recharge over the year (2001: ~10,000 m$^{-3}$a$^{-1}$), while the upper parts discharge groundwater (2001: ~18,000 m$^{-3}$a$^{-1}$) to the channel Mittelkanal (Figure 2). Inundation of the lower plain at side A lead to a further water storage of 98,000 m$^{-3}$a$^{-1}$. However, with respect to the phosphorus balances at the testfield the inundation of the plain (considered as an annual average) seems to be of minor relevance. Calculation of diffusive P fluxes from the soils (release) and sedimentation rates on the plain (retention) point out that both processes equilibrate each other.

**Water quality**

The Mittelkanal is characterised by high concentrations of Total Organic Carbon (TOC) and total iron (TFe) as well as total phosphorus (TP) with a significant seasonal variability and increasing concentration in winter as well as significant O$_2$ night-day fluctuations in summer. SRP:TP ratios are low, probably due to adsorption of SRP on FeOOH and humic substances (Gabriel et al. 2006). Discharges are strongly influenced by weir control with low discharges in summer and higher discharges during winter time. During winter the appearance of the channels and ditches of the polder are characterised by precipitation of iron ochre (Figure 3).

**Riverbed sediments and interstitial water**

In general riverbed sediments are characterised by high values of Loss on Ignition (LOI) with significant higher values at side A (46.6%) compared to side B (50.5%). Averaged phosphorus and iron concentrations in the shallow sediment layer (0–2 cm) are high with 2.3 g P kg$^{-1}$ DM$^{-1}$ and 11.1% of Fe at side A but even increase to 5.6 g P kg$^{-1}$ DM$^{-1}$ and 15.5% Fe at side B. Sediment P binding differs significantly at both sides, too. At side B a dominant share of 52% is bound to amorphous iron species and 28% to fresh iron precipitates like ferrioxides. Thus, at side B rather 80% of sediment P is bound to iron species,
while only 10% of phosphorus is available in organic form. Sediments at side A have a much larger share of organic P (20%) but only 22% bound to amorphous iron. However, the major fraction (38%) of P is bound to fresh iron precipitates like ferrioxides emphasizing the influence of hydraulic conditions and sedimentation on sediment phosphorus binding.

During exfiltration at both transects maximum SRP interstitial water concentration range at 2 mg L\(^{-1}\) in 0.10–0.15 m depth. However, at transect A at the sediment-surface water transition zone (0–1 cm sediment depth) a steep SRP concentration gradient established, expressing the effective retention of SRP in the uppermost sediment layer by adsorption on FeOH/FeOOH precipitates which results in average interstitial water SRP concentration of 0.13 mg L\(^{-1}\). This gradient is less steep at transect B resulting in higher SRP concentration at the sediment-surface water transition zone (0.42 mg L\(^{-1}\)). This leads to a forced emission of SRP from the interstitial water. Significant high Fe\(^{2+}\) concentrations in the interstitial water point out the anaerobic status of the side B sediments.

**Phosphorus balances**

Phosphorus balances point out the different functions of the polder regions with respect to their function as phosphorus sink or source.

Groundwater emissions from the upper part (side B) range at 0.007 to 0.22 kg ha\(^{-1}\) m\(^{-1}\) characterised by a significant seasonality. Increasing groundwater emissions were calculated from November to March while decreasing emissions were found from April to October with the exception of the extraordinary wet September where groundwater emissions show maximum values. Increased
groundwater emissions in this month result from a rapid groundwater level increase at the higher region caused by intensive rain events. Sedimentation rates at side B are threefold lower compared to side A modified by the assumption described above. The extended exfiltration of groundwater enriched in SRP in combination with low P sediment rates let the upper side B act as a phosphorus source from November to April and even at the extreme wet September. Retention of P during the summer months is low in general.

The lower region (side A) is characterised by low groundwater emissions from October to March with 0.0005 to 0.02 kg ha\(^{-1}\) m\(^{-1}\) being one order of magnitude lower compared to side B. During a period of intense infiltration (April to September) a slight retention of phosphorus is calculated, which remains low due to low surface water concentration (0.00008 – 0.003 kg ha\(^{-1}\) m\(^{-1}\)). Sedimentation shows maximum values at side A ranging from 0.06 to 0.21 kg ha\(^{-1}\) m\(^{-1}\). Coupled to the discharges by a regression model it is obvious that the highest sedimentation rates appear during the summer months with low flow velocities. Due to high rates of sedimentation and a weak tendency to release phosphorus by groundwater, side A acts as a sink for phosphorus during the whole year.

Aggregation of results from side A and side B points out, that the testfield acts as a P sink. Retention rates range from 0.01 to 0.10 kg ha\(^{-1}\) m\(^{-1}\). A functional change from P sink to P source is restricted by only a few months characterised by coincidence of high groundwater levels and high precipitation. Over the whole year 2001 the testfield retains 0.34 kg P ha\(^{-1}\) a\(^{-1}\).

In contrast, the whole polder area, considering its high share of areas represented by side B, acts as a phosphorus source emitting an annual load of 0.33 kg ha\(^{-1}\) a\(^{-1}\). Only during summer with low groundwater levels and infiltration of groundwater can the polder area resume a sink function for phosphorus. During winter the polder acts as phosphorus source, expressed by increased TP concentration at the outlet while the polder TP input concentrations remain significantly lower (Figure 4). Monthly balances correspond very well to TP concentration and load values of the year 2001. Monthly input output P load estimates for the whole polder area are available only for the year 2007. Results from this investigation strengthen the results presented here. However, due to the extreme weather conditions of 2007 (wet) and 2002 (dry) it is obvious, that P release of 2007 exceeds release of 2002 anyway ranging in the same order of magnitude and showing a comparable seasonality.

**DISCUSSION**

Results from the testfield investigation emphasise that hydrological conditions are a key factor influencing

- phosphorus mobilisation and release processes or retention processes and consequently to determine
- a wetland region to act as a phosphorus sink or phosphorus source.

This is especially true for the Spreewald region characterised by high amounts of sediment iron and iron bound phosphorus which can release phosphorus in case of redox changes at the sediment surface water transition zone induced by hydraulic gradient changes.

Testfield investigations point out different sink and source functions of the same landscape determined by different hydrological/hydraulic conditions at different sides. The phosphorus sink/source function of the lower, partly inundated side A is dominated by significant sedimentation and a high share of infiltrating conditions with oxygen-rich surface water seeping through the sediments. Limited periods of exfiltration combined with low exfiltration rates do not suffice to mobilise high amounts of sediment phosphorus at the transition zone in the highly organic side A sediments. Consequently, the lower polder parts act as an effective sink for phosphorus over the whole year.

Side B is characterised by exfiltration which leads to high emissions of phosphorus and a less effective phosphorus sedimentation, thus acting as a phosphorus source. The discharge of Fe\(^{2+}\) rich groundwater through the sediments at side B leads to a forced accumulation of FeOOH in the riverbed sediments even found in the Oderbruch polder area (Merz *et al.* 2005), suitable to increase the P adsorption capacity. On the other hand increased SRP and Fe\(^{2+}\) concentrations in interstitial water at the transition zone imply that effective exfiltration leads to a mobilisation of SRP although the molar Fe:P ratio
(14–65) found in sediment analyses (Gabriel et al. 2006) seems to be sufficient to prevent an extensive P release from the sediments.

Nevertheless, the amount of SRP available for plant uptake will be weakened by a further precipitation of FeOOH from emitted groundwater Fe$^{2+}$ in the surface water (expressed by precipitation of iron ochre) and adsorption of SRP. Laboratory experiments with anoxic interstitial water imply the potential to convert 85% of the SRP fraction to TP by adsorption on FeOOH and humic substances after aeration underlining the huge retention effect of SRP adsorption in the sediment transition layer or later, by sedimentation. Results from sequential P fractionation in the suspended solids trapped in the Mittelkanal prove this effect by 80% of suspended solid P bound to fresh iron precipitates.

In the Spreewald region precipitation of FeOOH from the Fe$^{2+}$ rich groundwater even at changed hydrological conditions remains likely, thus phosphorus retention capacity by sedimentation will probably be adhered. However, for the mean Spree reach a loss of FeOOH from the mining waters can result in a change of the high TP:SRP values to lower values with more SRP directly available for algae growth and a reduced P sedimentation rate. Behrendt (2002) hypothesise that the reduction of iron-rich mining water to the Spree surface water system will result in a

![Figure 4](http://iwaponline.com/wst/article-pdf/58/9/1813/436547/1813.pdf)

**Figure 4** | P balances aggregated to monthly values in kg per hectare per month (kg ha$^{-1}$ m$^{-1}$) between the testfield and the main channel Mittelkanal for side A and B (sedimentation, groundwater emissions and total balances), upscaled to the whole polder area (below) including TP concentration values.
twofold increase of phosphorus concentrations and loads. In case of a reduced P retention capacity upstream, the catchment related importance of the Spreewald region as an accumulation area for phosphorus would even increase. A general lowering of the water levels in the Spreewald region will probably result in higher P emissions from the groundwater to the surface water. Although sedimentation processes by adsorption on FeOOH from groundwater Fe$^{2+}$ emissions will be favoured, considering reduced flow velocities, polder P balances give strong evidence that retention will not equilibrate the P released. Testfield scenario analyses point out that a water level drawdown of 0.1 m over the whole year will result in an increase of groundwater emissions from the upper parts up to 15%. Even the lower parts will be significantly affected. On the one hand the lower parts will not further underlie extended flooding, thus long periods of exfiltration (time span comparable to the upper parts) will establish. On the other hand the significant oxygen supply at the sediment surface transition zone from extended and frequent phases of infiltration will be diminished. This would result in increased emissions of phosphorus by

- a forced mobilisation of sediment phosphorus to the interstitial water, and
- an increase of groundwater exfiltration rates and phases.

Thus, a water level drawdown will result in an increased phosphorus release from the upper polder parts, while the retention function of the lower polder parts will decrease. To some extend these functional changes of the P sink or source character can be expected for the whole Spreewald region underlining the urgent need for adapted water management strategies. As results from the phosphorus balances clearly address, a prior management strategy must be to prevent increasing emissions of phosphorus from the anoxic groundwater being the dominant pathway for diffuse phosphorus emission. Extended areas with extensive land-use like the investigated polder area are likely to improve the retention capacity of the Spreewald. Suitable management tools for water level regulation like weirs and sluices can be used to prevent extensive exfiltration of groundwater. This challenging task seems to be of exceptional concern considering hydrological and water quality changes in the middle and lower course of the River Spree.

**CONCLUSIONS**

Investigation in a polder in the central Spreewald region clearly point out that groundwater is the main pathway for diffuse phosphorus emissions. Sedimentation, significantly improved by adsorption of SRP on FeOH/FeOOH and humic substances, is the main mechanism to retain phosphorus in the impounded surface waters. Both processes are strongly related to hydrological conditions and determine

- the groundwater-surface water transfer rates
- the sedimentation behaviour, but also
- the availability of FeOH/FeOOH from groundwater Fe$^{2+}$ emissions in the surface water
- the mobilisation of sediment phosphorus into the interstitial water.

While discharge reductions in the Spree middle course will probably not decrease P sedimentation behaviour in the Spreewald region, an increase of groundwater phosphorus emissions can be clearly addressed. Results from the testfield give strong evidence, that P source functions in the whole Spreewald will increase, while P sink functions will be weakened. To prevent the mean and lower Spree course from an increased eutrophication risk the potential sink character for phosphorus in the Spreewald region should be strengthened due to adapted water management strategies.

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**REFERENCES**


