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Phosphorus Retention in Small Constructed Wetlands Treating Agricultural Drainage Water

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ABSTRACT

The construction of artificial wetlands has become a measure increasingly applied to reduce nonpoint-source (NPS) pollution and to contribute to the restoration of eutrophic lakes and coastal waters. In a 2-yr study monitoring fluxes of particulate and dissolved phosphorus (P) in a small artificial wetland for the treatment of agricultural drainage water in Central Switzerland, water residence time was identified as the main factor controlling P retention in the system. Since most of the annual P load (62% as dissolved reactive phosphorus, DRP) was related to high discharge events, it was not average but minimum water residence time during flood events that determined the wetland's P retention. In agreement with a continuous stirred tank reactor (CSTR) model, our investigations suggest a minimum water residence time of 7 d to retain at least 50% of the bioavailable P. The investigated wetland retained only 2% of the bioavailable P, since the water residence time was shorter than 7 d during 61% of time in both years. Settling of phytoplankton rather than DRP uptake into phytoplankton limited the retention of bioavailable P. The overall retention efficiency of 23% total phosphorus (TP), corresponding to a surface related retention of 1.1 g P m^{-2} yr^{-1}, was due to the efficient trapping of pedogenic particles.

Eutrophication of freshwater lakes, rivers, and marine coastal ecosystems in densely populated or agriculturally productive areas is mainly caused by anthropogenic P enrichment in these aquatic ecosystems (Carpenter et al., 1998; Correll, 1998; de Jonge et al., 2002). Loss of biodiversity and toxic algae blooms endangering drinking water supply and limiting recreational activities are its undesirable consequences (Carpenter et al., 1998).

During the last 25 years, P loads from point sources to surface waters have decreased considerably in Switzerland (Gächter and Stadelmann, 1993), as in many cases in Europe and the United States (Carpenter et al., 1998), due to improvements in wastewater treatment. In contrast the nutrient load from nonpoint-source pollution to aquatic ecosystems has increased as a direct result of intensified agricultural production and increased livestock densities (Carpenter et al., 1998). Nutrient balances for the catchment area of Lake Sempach in the Central Swiss Plateau have shown that more than 80% of the P load originates from intensively used agricultural land (Gächter and Stadelmann, 1993).

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Significant losses of particulate and dissolved P via surface and subsurface runoff result from exceeding P sorption capacity of fertilized and manured topsoil (Hansen et al., 2002; Heathwaite and Dils, 2000; Sims et al., 1998). In the loamy grassland soils of the catchment area of Lake Sempach, P-rich pedogenic water from preferential flow paths is collected by extended artificial subsurface drainage systems, which promote its rapid lateral transport and prevent further contact with the P-sorbing subsoil matrix (Gächter et al., 1998; Stamm et al., 1998).

The only sustainable measure to improve water quality of Lake Sempach and to recover its natural oligo- or mesotrophic state is to reduce the external P load (Gächter et al., 1996). Internal measures such as artificial oxygenation have been shown merely to mitigate symptoms of eutrophication (Gächter and Wehrli, 1998; Gächter and Müller, 2003). In 1999, a restoration project for the catchment area of Lake Sempach was initiated that included measures to reduce the P input to the soil and the conception of extensively used areas or riparian buffer strips. Furthermore, several small artificial wetlands were constructed at the interface between subsurface drainage system and receiving waters, which shall collect drainage water and retain bioavailable P.

Natural and artificial wetlands, riparian buffer strips, and ponds are successfully used to treat municipal wastewater with a continuously high content of nutrients and organic matter (Kadlec and Knight, 1996; Mitsch and Gosselink, 2000). Much less is known about the ability of such systems to retain NPS pollution (Raisin, 1996; Woltemade, 2000). Only a few investigations are based on sufficient temporal sampling resolution and provide information about balances of all relevant P species. Episodic flow regime and highly variable nutrient concentrations are characteristic of NPS pollution. Due to these pronounced dynamics, reported retention efficiencies vary considerably (Kovacic et al., 2000; Spieles and Mitsch, 2000) and are lower than in systems characterized by a continuously high nutrient load and a steady-flow regime (Jordan et al., 2003).

To estimate the efficiency of wetlands to retain nutrients supplied by drainage systems, fluxes of different P species were measured in one of the artificial wetlands in the catchment area of Lake Sempach. High temporal resolution monitoring during a 2-yr time period allowed the comparison of different water and phosphorus operating states of the system. The objectives of this study were to (i) evaluate the capacity of the wetland to transform and retain bioavailable P and (ii) identify major

Abbreviations: DNRP, dissolved nonreactive phosphorus; DP, dissolved phosphorus; DRP, dissolved reactive phosphorus; NPS, nonpoint source; PP, particulate phosphorus; TP, total phosphorus.

processes and factors controlling the performance of such systems.

MATERIALS AND METHODS

Study Site

Wetland "Sonnhof" (47°07′44″ N, 8°12′08″ E) is situated in the Central Swiss Plateau at an altitude of 512 m above mean sea level adjacent to the small river "Kleine Aa," a tributary to Lake Sempach (Fig. 1). In 2001 and 2002 mean annual temperature in this region was approximately 10°C. Annual precipitation reached about 1250 mm yr^{-1}. The wetland was constructed in 1999 in a natural topographic depression by removing the loamy topsoil. The artificial water basin has a maximum surface area of 2350 m^2 and a maximum depth of 0.6 m. A sand dam perpendicular to flow and overgrown with macrophytes divides the wetland into two equal parts and slows down flow velocity. The wetland collects water from a subsurface drainage system with a catchment area of about 20.4 ha mainly used as grassland. Grass is mowed up to seven times during the growing season. From 28 February until 15 November, cattle and swine manure is usually applied after each mowing. The outlet of the wetland is regulated with an adjustable standpipe, which discharges to the brook Kleine Aa. A gravel filter covers the opening of the outlet pipe and prevents export of coarse plant material. If the holding capacity of the wetland is exceeded direct surface overflow occurs through a spillway. To maintain a free water surface and reduce internal P loading macrophytes are harvested every 2 yr and sediments are dredged every 4 yr.

In early spring 2001 and 2002, the vegetation of the wetland was dominated by an intense phytoplankton bloom. In summer 2001, the water surface was covered with a dense mat of filamentous algae (mainly *Hydrodictyon reticulatum*). Common cattail (*Typha latifolia* L.), exotic bur-reed (*Sparganium erectum* L.), and common reed [*Phragmites australis* (Cav.) Trin. ex Steud.] planted in 1999 at the shore of the wetland were mowed in December 2001 for the first time, but invaded more than half of the wetland's surface area during 2002.

Hydrological Monitoring

During 2001 and 2002, the water discharge in the drainage inlet Q_{drain} (m^3 d^{-1}) and in the outlet pipe Q_{out} (m^3 d^{-1}) of the wetland was measured every 10 min with inductive flow meters (Promag 33; Endress+Hauser, Reinach, Switzerland). An electronic gauge (ATM/N; STS, Sirnach, Switzerland) was used to monitor the water level in the wetland. Collected data were stored with a CR10 data logger (Campbell Scientific, Logan, UT). Ground water inflow Q_{gw} (m^3 d^{-1}) was calculated using Darcy's law. Scarce surface overflow Q_{over} (m^3 d^{-1}) was quantified manually during sampling. Data for annual precipitation Q_{prec} (m^3 d^{-1}) were obtained from the nearby meteorological measurement station of Sempach (MeteoSwiss). Based on temperature, wind speed, and humidity, evaporation Q_{evap} (m^3 d^{-1}) was estimated from the Dalton equation (DVWK, 1996). Considering changing volume V (m^3) of the wetland during time t (d) the water balance could be established as:

$$Q_{drain} + Q_{gw} + Q_{prec} = Q_{out} + Q_{over} + Q_{evap} + (dV/dt) \quad [1]$$

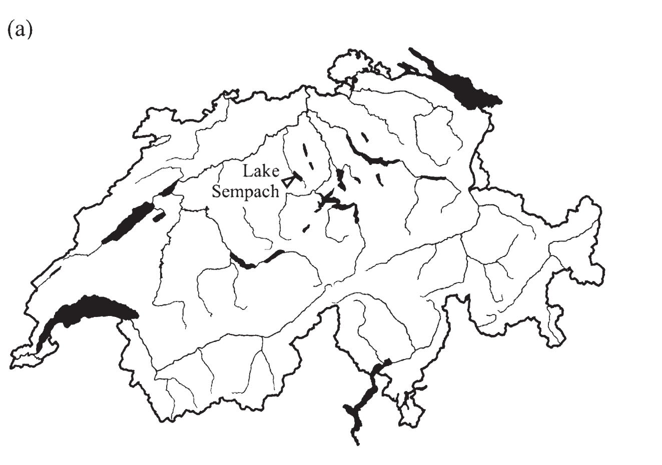
The theoretical water residence time τ (d) was derived from the water volume of the wetland and the total outflow (for abbreviations see also Appendix):

$$\tau = V/(Q_{out} + Q_{over}) \quad [2]$$

Water Sampling and Chemical Analysis

In 2001, inflowing drainage water was sampled manually every second day. In 2002, the sampling frequency was increased using an automatic sampler (Model 6712; ISCO, Lincoln, NE; Manning 4900, TN Technologies, Round Rock, TX). From February to June and from October to December, 4-h composite samples consisting of eight spot samples (sampling interval 0.5 h) were gathered with the automatic sampler. From July until September, 6-h composite samples comprising eight spot samples (sampling interval 1 h) were collected. Samples were removed from the sampler every second day. The outflow was sampled manually every second day in 2001 and 2002.

For analysis of dissolved P species, spot and composite samples were filtered through 0.45-μm cellulose acetate filters and stored at 5°C until analysis. Dissolved reactive phosphorus (DRP) was measured using standard photometric techniques (DEV, 2002). Total phosphorus (TP) and dissolved phosphorus (DP) were analyzed after persulfate digestion (120°C, 1 h) of unfiltered and filtered samples, respectively. The concentration c (mg m^{-3}) of particulate phosphorus (PP) was calculated as the difference between TP and DP. Dissolved nonreactive



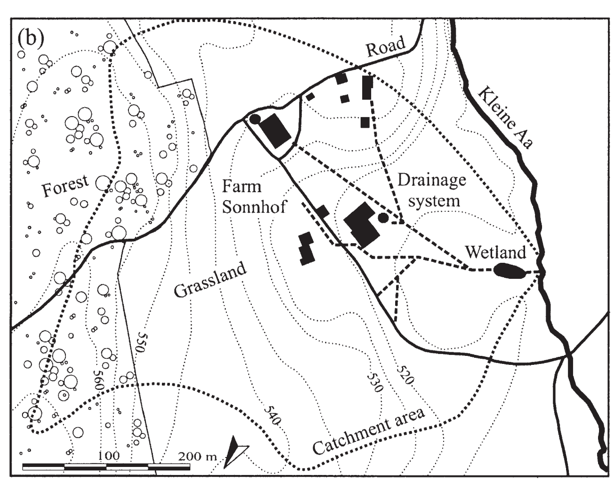


Fig. 1. (a) Map of Switzerland showing location of Lake Sempach. (b) Contour map of the wetland's catchment area including subsurface drainage system (dashed lines) and receiving river "Kleine Aa". Unit of contour lines is m.

phosphorus (DNRP) consisting mainly of organic phosphorus resulted from the subtraction of DRP from DP:

$$c(\mathrm{PP}) = c(\mathrm{TP}) - c(\mathrm{DP}) \quad [3]$$

$$c(\mathrm{DNRP}) = c(\mathrm{DP}) - c(\mathrm{DRP}) \quad [4]$$

To investigate the retention efficiency of Wetland Sonnhof at an elevated P load an additional dose of 8.6 g d^{-1} DRP (equimolar solution of KH_2PO_4 and K_2HPO_4) was continuously added with a peristaltic pump to the inflow starting from June 2001.

Mass-Balance Model for Retention of Bioavailable Phosphorus

Based on the continuous stirred tank reactor (CSTR) theory a mass-balance model for bioavailable P was developed, which assumes complete mixing, constant volume, and surface area A_0 (m^2). As bioavailable P, the model includes P species, which are immediately available to aquatic organisms such as DRP or which become available within hours to days (part of PP, see below). As major driving forces for P cycling in the wetland, TP load *In*(TP) (mg d^{-1}), TP export *Out*(TP) (mg d^{-1}), DRP uptake by phytoplankton *Up*(DRP) (mg d^{-1}), settling of phytoplankton *Set*(PP) (mg d^{-1}), and release of DRP from the sediment *Rel*(DRP) (mg d^{-1}) were considered. Values for maximum DRP uptake rate μ_{max} (mg P mg^{-1} PP d^{-1}), half saturation constant of DRP uptake K_S (mg m^{-3}), PP settling velocity k_{set} (m d^{-1}), and DRP release rate k_{rel} (mg m^{-2} d^{-1}) were gathered from the literature (Table 1). Parameter values used for model calculations were chosen so that the best fit was obtained between predicted and experimentally determined DRP and PP outlet concentrations of time variation curves.

The TP load and export depend on water discharge (Q) and the corresponding TP concentration of inlet c_{in}(TP) and outlet c_{out}(TP), which equals the TP concentration of the wetland c(TP) in a completely mixed system. The PP loaded to the wetland consisted mainly of pedogenic particles settling quickly. As investigations of Lake Sempach have shown only 7% of the pedogenic PP load became bioavailable, whereas 70% of settling biogenous PP produced in the lake was released as DRP during early diagenesis (Hupfer et al., 1995; Wehrli and Wüest, 1996). Pedogenic PP was, therefore, disregarded in the model. All the PP referred to in the model is of biogenous origin and potentially bioavailable. Moreover, as the DNRP inlet concentration did not systematically differ from the DNRP outlet concentration (see below), DNRP was assumed to behave conservatively and was also neglected. Consequently, in the following model the TP load includes only the DRP load, whereas the TP export equals the sum of DRP and PP export:

$$In(\mathrm{TP}) = c_{in}(\mathrm{DRP}) \cdot Q \quad [5]$$

$$Out(\mathrm{TP}) = [c_{out}(\mathrm{DRP}) + c_{out}(\mathrm{PP})] \cdot Q \quad [6]$$

Microbial DRP uptake equal to PP production *Prod*(PP) (mg d^{-1}) is assumed to follow Michaelis–Menten kinetics and thus to depend on DRP and PP concentration. Light limitation due to self-shading was not considered. In a first approximation, DRP uptake by sessile plants was neglected:

$$Up(\mathrm{DRP}) = Prod(\mathrm{PP}) = \frac{\mu_{max} \cdot c(\mathrm{DRP})}{c(\mathrm{DRP}) + K_s} \cdot c(\mathrm{PP}) \cdot V \quad [7]$$

Settling of PP is proportional to PP concentration and the settling velocity:

$$Set(\mathrm{PP}) = k_{set} \cdot A_0 \cdot c(\mathrm{PP}) \quad [8]$$

Dissolved reactive phosphorus release from the sediment due to oxic and anoxic decomposition of settled biogenous PP was assumed to be constant, but was not allowed to exceed PP flux to the sediment in steady state:

$$Rel(\mathrm{DRP}) = k_{rel} \cdot A_0 \leq Set(\mathrm{PP}) \quad [9]$$

Mass balances for DRP, PP, and TP in the wetland were established as:

$$\frac{\mathrm{d}\, c(\mathrm{DRP}) \cdot V}{\mathrm{d}t} = In(\mathrm{DRP}) + Rel(\mathrm{DRP}) - Up(\mathrm{DRP}) - Out(\mathrm{DRP}) \quad [10]$$

$$\frac{\mathrm{d}\, c(\mathrm{DRP}) \cdot V}{\mathrm{d}t} = Prod(\mathrm{PP}) - Set(\mathrm{PP}) - Out(\mathrm{PP}) \quad [11]$$

Inserting Eq. [5] to [9] into the differential Eq. [10] and [11] and solving Eq. [10] and [11] for steady-state [dc(DRP)/dt = dc(PP)/dt = d(TP)/dt = 0] yields:

$$c(\mathrm{DRP}) = \frac{K_s \cdot \left[1 + \tau \cdot \frac{k_{set}}{h}\right]}{\tau \cdot \left[\mu_{max} - \frac{k_{set}}{h}\right] - 1} \quad [12a]$$

and:

$$c(\mathrm{PP}) = \frac{\mathrm{c_{in}}(\mathrm{DRP}) - c(\mathrm{DRP}) + \frac{k_{rel}}{h} \cdot \tau}{1 + \frac{k_{set}}{h} \cdot \tau} \quad [12b]$$

If the water residence time falls below a critical threshold ($\tau \leq \tau_{crit}$), all PP is flushed out of the wetland:

$$c(\mathrm{PP}) = 0 \quad [13a]$$

and:

$$c(\mathrm{DRP}) = c_{in}(\mathrm{DRP}) \quad [13b]$$

Substituting c(DRP) by c_{in}(DRP) in Eq. [12a] and solving for τ yields:

$$\tau_{crit} = \frac{K_S + c_{in}(\mathrm{DRP})}{c_{in}(\mathrm{DRP}) \cdot \left[\mu_{max} - \frac{k_{set}}{h}\right] - \frac{k_{set}}{h} \cdot K_S} \quad [14]$$

Table 1. Model parameters.

	Value range	Values chosen in the model	Reference
Maximum P uptake rate (μ_{max}), mg P mg^{-1} PP d^{-1}	0.15–43.87†	1.3	Hwang et al. (1998)
Half saturation constant of P uptake (K_S), mg m^{-3}	0.1–251	20	Hwang et al. (1998)
Settling velocity (k_{set}), m d^{-1}	0.02–4	0.2	Jörgensen and Bendoricchio (2001), Wetzel (2001)
P release rate (k_{rel}), mg m^{-2} d^{-1}	0.09–51.5	1	Friedrich et al. (2003), Nürnberg (1988), Urban et al. (1997)

† Calculated using Redfield ratio $C_{106}O_{110}H_{263}N_{16}P$.

Table 2. Water balance of Wetland Sonnhof.

	2001	2002
	$m^3\ yr^{-1}$	
Inflow, drainage pipe (Q_{drain})	**75 100**	**73 500**
Inflow, ground water (Q_{gw})	**5 500**	**5 500**
Inflow, total	**80 600**	**79 000**
Outflow, outlet pipe (Q_{out})	**71 800**	**78 500**
Surface overflow (Q_{over})	**8 500**	**1 000**
Outflow, total	**80 300**	**79 500**
Precipitation (Q_{prec})	**3 000**	**2 900**
Evaporation (Q_{evap})	**1 300**	**1 300**

Retention efficiency η (%) of bioavailable P is defined as:

$$\eta = \frac{c_{in}(\mathrm{DRP}) \cdot Q - [c(\mathrm{DRP}) + c(\mathrm{PP})] \cdot Q}{c_{in}(\mathrm{DRP}) \cdot Q} \cdot 100 \quad [15]$$

Steady retention is obtained by substitution of DRP and PP concentration in Eq. [15] by their corresponding steady-state concentrations (Eq. [12a] and [12b]).

RESULTS

Water Balance

The annual drainage water discharge into Wetland Sonnhof was 75 100 m^3 in 2001 and 73 500 m^3 in 2002 (Table 2). Ground water infiltration was estimated to 5500 $m^3\ yr^{-1}$. At the outlet, water discharge of 71 800 m^3 in 2001 and 78 500 m^3 in 2002 was recorded. Surface overflow occurred during 68 d in 2001 and 19 d in 2002 and amounted to 8500 m^3 and 1000 m^3, respectively. In 2001 the water level never dropped below 0.51 m (512.51 m above mean sea level), whereas in 2002 it fell to 0.3 m (512.3 m above mean sea level) because of a leakage at this level. Therefore, the wetland volume varied between 800 and 1300 m^3 in 2001 and between 400 to 1300 m^3 in 2002. Precipitation directly onto the water surface contributed 3000 m^3 in 2001 and 2900 m^3 in 2002, representing less than 4% of the water input of the wetland. Evaporation was estimated to 1300 m^3 in 2001 and 2002.

The flow regime at the inlet of the wetland was intermittent (Fig. 2a). Baseflow of less than 200 $m^3\ d^{-1}$ corresponding to a hydraulic loading rate of 0.09 m d^{-1} prevailed during 430 d (57%) of the investigated 730-d period (Fig. 3). Flood events with water discharge exceeding 400 $m^3\ d^{-1}$ were recorded during 65 d in each year. Maximum hydraulic loading rate was 0.5 m d^{-1}. In 2001 peak discharge values were recorded in March, April, and June. In 2002, inflow also peaked in June, but in addition high values were observed during a rainy period in October and November.

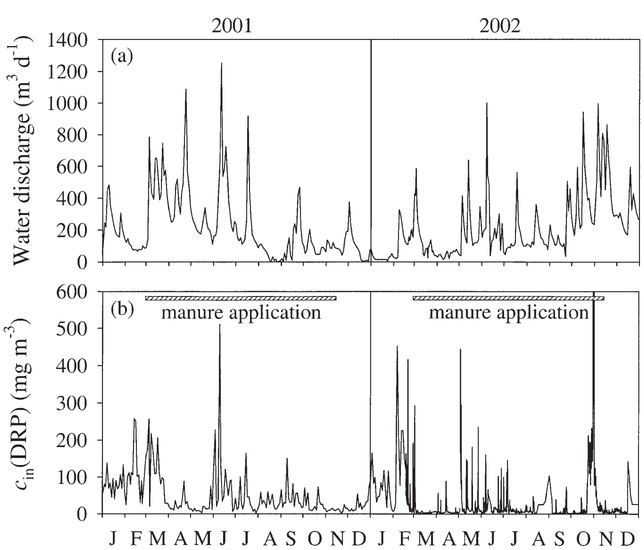


Fig. 2. (a) Water discharge and (b) concentration of dissolved reactive phosphorus c_{in}(DRP) at the drainage inlet to Wetland Sonnhof during 2001 and 2002.

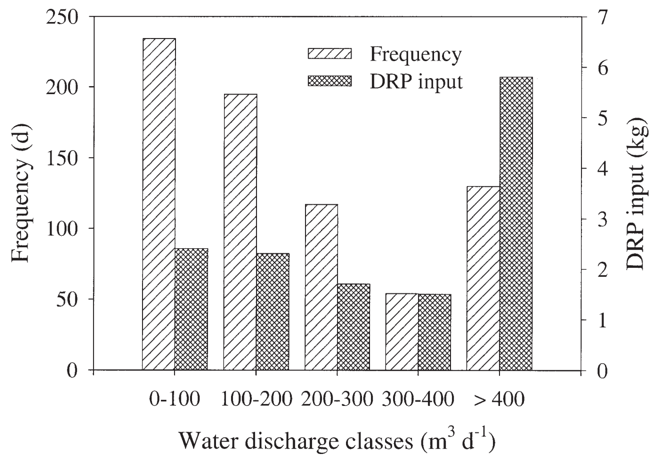


Fig. 3. Frequency scale of water discharge classes for Wetland Sonnhof in 2001 and 2002 and contribution of water discharge classes to input of dissolved reactive phosphorus (DRP).

Theoretical water residence time ranged from 0.9 to about 50 d (Fig. 4). Water residence time values equal or smaller than 4 d accounted for 48% of the studied period.

Phosphorus Concentration Patterns at the Inlet and Outlet of the Wetland

The TP concentration in the drainage inlet to Wetland Sonnhof varied more than a hundredfold between 10 and 1300 mg m^{-3}. Among the P species DRP contributed 62% to the annual TP load; PP and DNRP played only a minor role in the P balance (Table 3). The mainly pedogenic PP fraction with an average PP concentration of 25 mg m^{-3} contributed 25% to the TP load, DNRP 13% (average DNRP concentration: 15 mg m^{-3}).

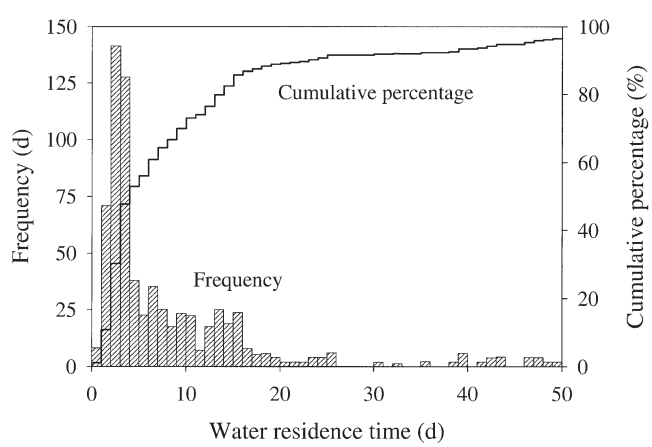


Fig. 4. Frequency distribution of observed water residence time.

Table 3. Phosphorus balance of Wetland Sonnhof.

	Input		Output		Retention	
P form†	2001	2002	2001	2002	2001	2002
	kg yr^{-1}				%	
TP	11.23	10.71	8.61	8.20	23	23
DRP	7.34	6.31	3.77	2.87	49	55
DNRP	1.52	1.41	1.84	1.56	−21	−11
PP	2.37	2.99	3.00	3.77	−27	−26

† DNRP, dissolved nonreactive phosphorus; DRP, dissolved reactive phosphorus; PP, particulate phosphorus; TP, total phosphorus.

The DRP inlet concentration was strongly correlated with the hydrologic regime. During baseflow, DRP inlet concentration was below 50 mg m^{-3}, but it increased sharply, up to 550 mg m^{-3}, with rising water discharge (Fig. 2b). Unusually high values of more than 1000 mg m^{-3} during several days at the end of October 2002 were attributed to a big accidental manure spill into the drainage system. Smaller manure spills influenced nutrient concentration in the inlet to the wetland only during a few hours. They could be verified with ion selective electrodes measuring ammonium, nitrate, and pH with a time resolution of 12 min (Müller et al., 2003).

Particles flushed from the artificial subsurface drainage system into the wetland consisted mainly of fine-grain-sized and P rich aggregates accumulated in preferential flow paths. According to Stokes' law a theoretical settling velocity of 1 m d^{-1} was calculated for fine silt particles, the particle size fraction typical for the silty loamy topsoil of the catchment area (particle diameter = 2–5 μm, particle density = 2.65 g cm^{-3}, temperature = 10°C). Given the hydrologic regime of the wetland at least 80% of these suspended solids and the associated pedogenic PP must have settled in the wetland.

In the outlet of the wetland, TP concentration ranged between 10 and 750 mg m^{-3}. The DNRP inlet and outlet concentrations were quite similar, whereas PP was distinctively more abundant in the outlet than in the inlet (Table 3). On average, DRP and PP accounted each for 40% of the TP output and DNRP accounted for 20%. From February until May, the PP fraction contributed 50 to 75% to the TP export corresponding to peak concentrations of up to 550 mg m^{-3} PP. During the rest of the year, PP concentration was about 35 mg m^{-3}. Particles leaving the wetland were identified in the light microscope as phytoplankton.

The DRP baseflow concentration in the outlet differed slightly between winter and spring compared with summer and fall. From December to May, baseflow DRP concentration was about 5 mg m^{-3}, whereas from June to November, it rarely dropped below 20 mg m^{-3}.

Phosphorus Balance

In 2001 and 2002, the drainage pipe transported 17.04 kg TP into the wetland corresponding to a leaching of 420 g P ha^{-1} yr^{-1} from the catchment. Adding the artificial dosage of 4.90 kg DRP, the total 2-yr load was 21.94 kg TP (Table 3). Annual area specific loading based on the surface area of the wetland was 4.7 g P m^{-2} yr^{-1}. Daily surface related loading was only around 0.005 g P m^{-2} d^{-1} at baseflow, but increased up to 0.4 g P m^{-2} d^{-1} during flood events. Forty-three percent of the annual DRP load entered the wetland during periods with a water discharge of more than 400 m^3 d^{-1} (Fig. 3).

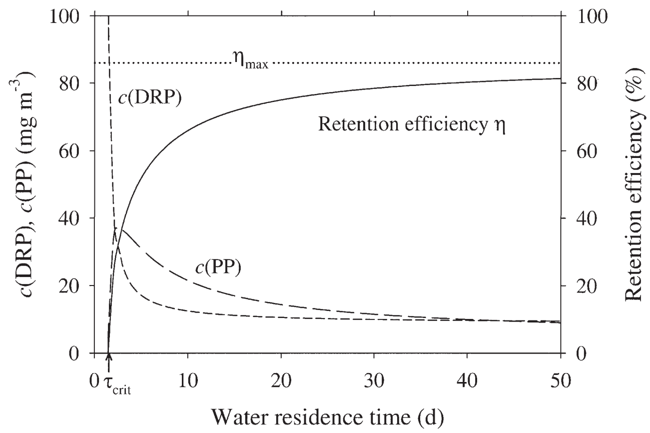


Fig. 5. Model results for steady-state concentration of dissolved reactive phosphorus c(DRP), particulate phosphorus c(PP), and retention efficiency η of bioavailable phosphorus as a function of the water residence time τ. Chosen model parameters were: V = 900 m^3, A_0 = 1800 m^2, c_{in}(DRP) = 100 mg m^{-3}, μ_{max} = 1.3 mg P mg^{-1} PP d^{-1}, K_S = 20 mg m^{-3}, k_{set} = 0.2 m d^{-1}, k_{rel} = 1 mg m^{-2} d^{-1}.

The TP loss from the wetland to the receiving river Kleine Aa was 16.81 kg during the studied period. Daily output rates ranged from 0.08 to 600 g P d^{-1} with maximum values during phytoplankton blooms and intense rainfall in spring.

Altogether, Wetland Sonnhof retained 23% of the TP load (i.e., 5.13 kg TP). Based on the surface area of the wetland, the annual area specific retention accounted for 1.1 g TP m^{-2} yr^{-1} and was similar in both years. Daily retention efficiency varied substantially. Considering the retention efficiency of the different P species, it is remarkable that 51% (7.01 kg) of the DRP load was retained or transformed in the wetland whereas the calculated retention efficiency for DNRP and PP was indifferent or even negative. A load of 5.36 kg pedogenic PP faced a loss of 6.77 kg mainly biogenous PP that presumably entered the microbial P recycling in the receiving water. The DNRP input (2.93 kg) was about balanced by DNRP output (3.40 kg).

Model Predictions

According to model predictions, steady-state DRP concentration in the wetland and in its outlet depends on DRP uptake kinetics, settling velocity of biogenous PP, depth of the wetland, and water residence time (Eq. [12a]). It is independent of the DRP inlet concentration as long as the water residence time exceeds the critical threshold and allows a stable phytoplankton population to be maintained. If the water residence time drops below the critical value, PP loss exceeds PP production, such that the phytoplankton population is extinct. As a consequence, DRP uptake ceases and steady-state DRP outlet concentration approaches DRP inlet concentration (Eq. [13b]). If the critical water residence time is exceeded, DRP concentration declines rapidly with increasing water residence time (Fig. 5) and converges on a minimum DRP concentration of:

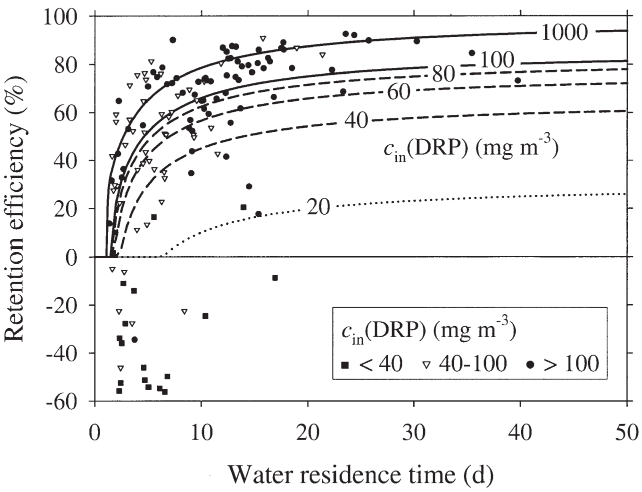


Fig. 6. Retention efficiency of bioavailable phosphorus predicted by the model (lines) and observed in Wetland Sonnhof in 2001 (symbols) as a function of water residence time and concentration of dissolved reactive phosphorus at the inlet c_{in}(DRP). Line styles and symbol types indicate DRP inlet concentration. Two-day retention efficiency was calculated according to Eq. [15]. Twenty-two data points ranging between −60 and −500% (τ: 1–6 d) are not shown.

$$\lim_{\tau\to\infty} c(\mathrm{DRP}) = \frac{K_S \cdot \frac{k_{set}}{h}}{\mu_{max} - \frac{k_{set}}{h}} \quad [16]$$

As shown by Eq. [12b], steady-state PP concentration increases linearly with rising DRP inlet concentration and depends on DRP uptake kinetics, settling velocity, DRP release rate, depth of the wetland, and water residence time. With rising water residence time, it passes a maximum and approaches:

$$\lim_{\tau\to\infty} c(\mathrm{PP}) = \frac{k_{rel}}{k_{set}} \quad [17]$$

For the parameter set chosen (Table 1), steady-state DRP and PP concentrations converge on minimum concentrations of 9 and 5 mg m^{-3}, respectively.

According to Eq. [15], retention efficiency of bioavailable P depends primarily on water residence time and DRP inlet concentration. Furthermore, it is influenced by DRP uptake kinetics, PP settling velocity, and DRP release rate. With increasing water residence time, retention efficiency rises rapidly and converges on:

$$\lim_{\tau\to\infty} \eta = \frac{c_{in}(\mathrm{DRP}) - \left[\frac{K_S \cdot \frac{k_{set}}{h}}{\mu_{max} - \frac{k_{set}}{h}} + \frac{k_{rel}}{k_{set}}\right]}{c_{in}(\mathrm{DRP})} \cdot 100 \quad [18]$$

Seventy-five percent of the maximum possible retention efficiency (η_{max}) is attained at a water residence time of about 9 d for the given parameter set (Fig. 5). However, as indicated by Eq. [18], a retention efficiency of 100% is only reached if DRP inlet concentration is infinitely high. In general, increasing DRP inlet concentration lead to an increase of retention efficiency (Fig. 6). This increase is more pronounced at low DRP inlet concentration, but levels out at DRP inlet concentration larger than 80 mg m^{-3}. Increasing μ_{max} and decreasing K_S values enhance P retention and lower the critical water residence time. Raising k_{set} enhances PP retention, but it lowers DRP retention.

DISCUSSION

Phosphorus Removal Rates of Treatment Wetlands

Considering the different structure and loading characteristics of natural and artificial systems treating point- and nonpoint-source pollution it is not surprising that reported retention efficiencies vary widely. Analyzing the North American Wetland Treatment System Database, Kadlec and Knight (1996) calculated a long-term average removal of 8 g P m^{-2} yr^{-1} with an average removal efficiency of 31% P for the 203 listed wetlands. However, most of these wetlands were used for the treatment of wastewater with continuously high P and carbon concentrations (Bachand and Horne, 2000).

For wetlands receiving low-concentration loads from river water, storm water, or NPS pollution in general, Mitsch and Gosselink (2000) gathered annual retention values ranging from 0.4 to 5.6 g P m^{-2} yr^{-1}. The annual TP retention of 1.1 g m^{-2} yr^{-1} (retention efficiency 23%) observed for Wetland Sonnhof is well within this range. However, the retention efficiency of systems for the treatment of NPS pollution is known to vary temporarily. Investigations of Kovacic et al. (2000) at three constructed wetlands receiving agricultural drainage water showed that due to phases with net TP release, overall 3-yr removal accounted for only 2%, although annual retention of up to 80% (0.4 g P m^{-2} yr^{-1}) was recorded as well. For a restored wetland treating agricultural NPS, Jordan et al. (2003) reported an initial annual retention of 59%. However, in the second year of their study annual retention was insignificant. To explain variations of phosphorus retention efficiency it is essential to perform long-term and high temporal resolution investigations that allow the comparison of different system states.

Factors Influencing Phosphorus Retention

Wastewater treatment wetlands with steadily high inflow concentrations are expected to exhibit higher retention efficiencies than systems designed to treat NPS pollution with lower and highly variable nutrient loads (see Eq. [15]). Higher average retention efficiency of the former systems also results from their generally lower and more uniform hydraulic loading.

In agreement with model predictions, retention of bioavailable P in Wetland Sonnhof calculated according to Eq. [15] increased significantly with increasing water residence time (Fig. 6). If the water residence time exceeded 10 d retention efficiency ranged from 50 to 90%, but decreased drastically and was often even negative, if the water residence time was shorter than 5 d. Negative retention was mostly observed if DRP inlet concentration

was lower than 40 mg m^{-3}, for which the model predicts a sharp increase of the critical water residence time.

When comparing experimental results with model predictions it must be considered that the model applies for steady state and hence predictions may deviate from transient non-steady-state situations. In non-steady-state conditions DRP release from the sediment may temporarily exceed PP settling. Furthermore, high discharge events flushing out phytoplankton resulted in net loss of bioavailable P from the wetland. Nevertheless, on average the model proved to be useful in discussing P retention in constructed wetlands as a function of DRP concentration and water discharge. Even if the wetland does not completely reach steady state, such systems tend toward steady state after each disturbance. The more reactive the substance introduced into a system, the faster steady state is approached and the better model and reality agree.

Short periods with low or even negative P retention are responsible for the low annual retention efficiency of Wetland Sonnhof. Due to the increase of DRP concentration with rising water discharge (Fig. 2b), DRP load increased progressively with increasing water discharge. As a consequence, during periods of intense rainfall and water discharge exceeding 400 m^3 d^{-1}, about 43% of the annual DRP load entered the wetland, although these periods lasted in total only 65 d of each year (Fig. 3). Since the corresponding water residence time dropped to 1 to 3 d, retention efficiency was negative and averaged −34% for the sum of all data points during these periods. During flood events when P load reached maximum values Wetland Sonnhof therefore acted as transient net P source (Fig. 7).

Retention and Transformation Reactions

Phytoplankton, floating macroalgae, and emergent macrophytes are important storage compartments contributing to P retention in wetlands. Due to its large surface area and short reproduction time finely dispersed phytoplankton is able to eliminate phosphorus efficiently from the water and to respond quickly to changing DRP concentration in the surrounding medium (Howard-Williams, 1985). In contrast, emergent macrophytes, such as cattail and common reed, take up phosphorus already accumulated in the sediments with their extensive network of roots (Hoagland et al., 2001; Johnston, 1991). Their reactivity to incoming short-term P loads is, therefore, limited. They may, however, contribute to P retention building up long-term P storage and provide the substrate for periphyton growth. Furthermore, the reduction of the flow velocity stimulates particle settling and prevents resuspension of the accreted sediment (Howard-Williams, 1985; Reddy et al., 1999). The marked increase of the macrophyte stock in Wetland Sonnhof observed in 2002 without an obvious effect on the wetland's P retention suggests that macrophytes played a minor role in short-term P retention. As the P loading of Wetland Sonnhof was mainly driven by short-term flood events, its P retention must have been governed by settling phytoplankton and floating macroalgae.

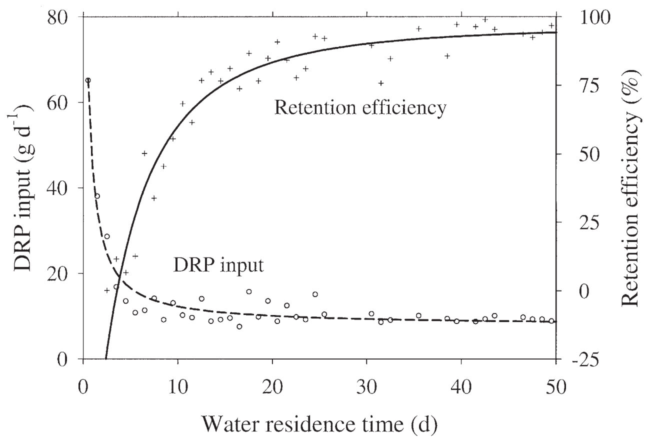


Fig. 7. Input of dissolved reactive phosphorus (DRP) (dashed line) and retention efficiency of bioavailable phosphorus (solid line) as related to water residence time. Curves were fitted to experimental data of DRP input (circles) and retention efficiency (crosses) in Wetland Sonnhof, which were subsumed in water residence time classes.

Mass balance of bioavailable P is summarized in Fig. 8 and highlights the central role of phytoplankton in Wetland Sonnhof. Net DRP uptake into phytoplankton and macroalgae was 7.01 kg. However, as 6.77 kg PP was flushed out of the wetland, only 0.24 kg biogenous PP was permanently buried in the sediment according to this calculation. Due to internal recycling in the water column and DRP release from the sediment, gross DRP uptake and gross PP settling are expected to even exceed these net fluxes. Retention efficiency of bioavailable P was 2%, as calculated by comparing DRP input (13.67 kg) to the sum of DRP export (6.64 kg) and biogenous PP export (6.77 kg) (see Eq. [15]). The fact that 49% of the DRP loaded to the wetland was transformed into PP but only 3% of the biogenous PP was retained in the sediment indicates that the settling of biogenous PP rather than the transformation of DRP into PP limits the retention of bioavailable P in a wetland. The TP retention efficiency of 23% was, therefore, primarily due to the settling of pedogenic PP.

CONCLUSIONS

As shown in this study, a typical nutrient retention wetland is able to retain more than 50% of the incoming DRP load if its water residence time exceeds 7 to 10 d. Since in Wetland Sonnhof, the water residence time was shorter than 7 d during 60% of the time, and in addition 43% of the annual DRP input was loaded during a few high discharge events with a water residence time below 3 d, annual retention of bioavailable P accounted for only 2%. Overall retention of 23% TP was due to the effective settling of eroded soil particles.

Crucial for the retention of NPS pollution in a treatment system is not average but minimum water residence time. To guarantee a minimum water residence time of 7 d, the storage volume of a treatment wetland with a constant water level should exceed the expected maximum daily water discharge about sevenfold. If the wetland is allowed to partially empty during dry periods,

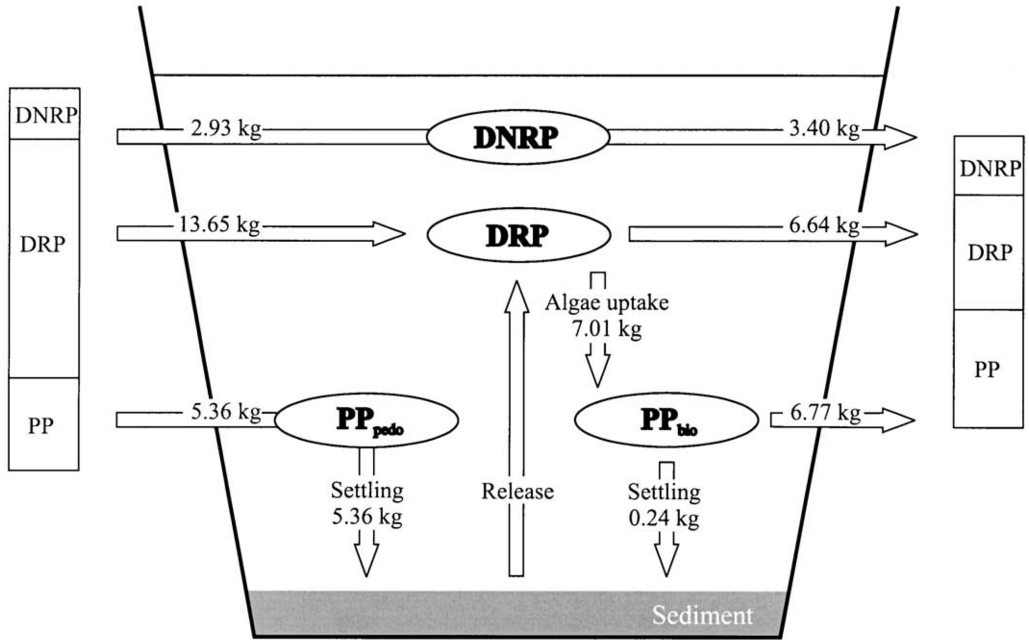


Fig. 8. Mass-balance model for phosphorus retention. Ovals characterize phosphorus (P) reservoirs in the wetland and arrows signify biogeochemical transformations (DRP, dissolved reactive phosphorus; DNRP, dissolved nonreactive phosphorus; PP_{pedo}, pedogenic particulate phosphorus; PP_{bio}, biogenous particulate phosphorus).

the required volume not only depends on the expected instantaneous maximum discharge rate but also on the frequency and duration of the floods. For a maximum runoff of 6 mm d^{-1} a minimum storage volume of 400 m^3 ha^{-1} drainage area was estimated. As in a eutrophic wetland, rich in phytoplankton, photosynthetic radiation is strongly attenuated with increasing depth, and its average depth should probably not exceed 1 m. Consequently, a wetland able to retain about half of its agricultural DRP load requires a surface area that equals about 4% of its catchment area. Any mechanical device suitable to lower the export of phytoplankton would certainly increase a wetland's P retention efficiency and lower its necessary surface area.

APPENDIX

Symbols and Abbreviations Used in the Model

Q	water discharge (m^3 d^{-1})
τ	water residence time (d)
τ_{crit}	critical water residence time (d)
V	volume (m^3)
A_0	surface area (m^2)
h	mean depth (m)
η	retention efficiency (%)
c(P)	phosphorus concentration in the wetland (mg m^{-3})
c_{in}(P)	phosphorus concentration in the drainage inlet (mg m^{-3})
c_{out}(P)	phosphorus concentration in the outlet pipe (mg m^{-3})
In(P)	phosphorus loading (mg d^{-1})
Out(P)	phosphorus export (mg d^{-1})
Up(DRP)	dissolved reactive phosphorus uptake by phytoplankton (mg d^{-1})
Prod(PP)	particulate phosphorus production (mg d^{-1})
Set(PP)	particulate phosphorus settling (mg d^{-1})
Rel(DRP)	dissolved reactive phosphorus release from the sediment (mg d^{-1})

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