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The role of slackwater areas for biogeochemical processes in rehabilitated river corridors: examples from the Danube

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With 7 figures and 1 table in the text

Abstract: Nutrient storage and transformation as well as aquatic production are key ecosystem functions and are related to areas of higher retention in the river corridor. The significance of retention as a main element for understanding ecosystem processes becomes apparent in regulated rivers where both retention and hydrologic connections between the main channel and its slackwater areas and the adjacent riverine landscape have markedly decreased. We give some evidence that in-channel structures and side-arms are important slackwater areas below bankfull level in a braided, anabranched river section, the Danube downstream of Vienna. In that stretch the role of in-channel retention for phytoplankton development and a reopened side-arm and the floodplain for the phosphorus dynamics is discussed. The transformation of phosphate is related to phytoplankton development and increased connectivity below bankfull enhances the transformation capacity of the reopened side-arm. The rate of deposition during floods is still the decisive process in terms of annual total phosphorus budgets and is presented for the years 1997–2002. Up to 1 % of the total annual load transported is retained in the floodplain area. Rehabilitation efforts, like those along the Austrian Danube, which increase the hydrological exchange with slackwater areas, will enhance nutrient processing and the production of autochthonous POM and thereby, also re-establish these ecosystem functions on a larger scale than the local measures.

Key words: Hydrological connectivity, nutrient, phytoplankton, autochthonous carbon, retention area, river rehabilitation.

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Aspects of biogeochemical processes at different scales in rivers

Running waters constitute the links between continents and oceans in the global biogeochemical cycles. These ecosystems transport nutrients and organic matter from terrestrial sources, produce organic material within aquatic environments, and degrade organic matter on their way downstream (Hedges et al. 2000). For instance, riverine inputs of terrestrial organic matter represent a substantial source of terrestrial organic carbon in the oceans (Meybeck 1993), which has been estimated to be 25 % of the global organic matter production of estuaries (Woodwell et al. 1973). The global transport to the oceans amounts to 21 Tg nitrogen (Seitzinger et al. 2002) and 22 Tg phosphorus per year (Bennett et al. 2001), with a still increasing trend of riverine export. The composition and load of matter exported to the oceans mirror the variety of processes operating at various scales and carry the fingerprint of human activities (e.g. Rosenberg et al. 2000). The biogeochemical dynamics in lotic ecosystems are mainly controlled by geomorphology and the hydrological regime at the landscape level (Richter et al. 1997; Ward et al. 2002).

At the catchment level, the importance of in-stream processes and the transformation and storage capacity of the riverine landscape has been recognized for nutrient transport models (Behrendt & Opitz 2000). Biogeochemical active areas in the catchment, so-called hot spots (sensu McClain et al. 2003), are frequently found at transition zones along vertical and lateral connectivity gradients. Along the length of river corridors, storage and processing of matter in aquatic compartments are generally related to the extent of areas of higher hydrologic retention (e.g. Pusch et al. 1998; Van der Lee et al. 2004), summarized as slackwater areas (Thorp & Casper 2002). Floodplains play an especially key role in nutrient retention at the catchment and reach scale level (Robertson et al. 1999; Van der Lee et al. 2004).

In headwater reaches, transient storage at the water/streambed interface and the hyporheic zone determines the nutrient retention and respiration efficiency (Battin et al. 2003). In downstream sections of lotic systems the lateral exchange becomes more prominent for nutrient dynamics and organic matter production (Ward & Stanford 1995). Slackwater areas frequently connected to the riverine flow substantially support the local aquatic production and the associated nutrient transformation at water levels below bankfull (Schiemer et al. 2001a). The distance to the main channel and the level of connectivity explain the duration and frequency of availability as slackwater area during the year (Tockner et al. 2000). In an unregulated anabranched section typically a sequence of retention areas with decreasing duration of connectivity and increasing space in the river corridor can be expected: from in-channel structures to terrestrial components of floodplains.

The hydrologic exchange pattern between the main channel and these areas control the trophic status (Knowlton & Jones 1997) and aquatic carbon production of these subsystems (Hein et al. 2003) as well as can impact downstream reaches. In-channel structures, flow reduced and shallow areas, are important areas for aquatic primary production and zooplankton development and provide this function mainly during lower flows (Reynolds & Descy 1996). With increasing water levels, side-arms contribute to the transformation capacity and productivity (Hein et al. 2003). Terrestrial components of floodplains only receiving surface water during floods play a key role for matter retention and subsequent local aquatic and terrestrial production (Brunet & Astin 2000; Junk & Wantzen 2004). At the lower Rhine for example, a recent study showed that significant phosphorus retention (5 to 18 % of the total annual P load) was estimated for 3 distributaries of the Rhine and sedimentation in the floodplain was the dominant process (Van der Lee et al. 2004).

Present state and aims for rehabilitation in rivers

Rivers and their adjacent aquatic habitats such as floodplains are among the most threatened ecosystems of the world (Tockner & Stanford 2002). Numerous anthropogenic disturbances often result in habitat destruction, system fragmentation, and disruption of lotic ecosystem structure and function (e.g. Covich 1993; Friedl & Wüst 2002). Regulation, canalization and flood protection can significantly decrease the matter storage capacities of riverine landscape by reduction of inundation area as shown for the Danube River downstream of Vienna (Fig. 1). Within the Danube river basin, about 80 % of the pristine floodplain areas are lost today (WWF 1999). The remaining areas are characterized by a reduced hydrologic exchange which restricts the exchange of matter to short periods of high flow (Tockner et al. 1999). Moreover, agricultural practices, livestock grazing, manufacturing and processing operations, mining and smelting, and urban development variously contribute chemical wastes, pesticides, nutrients and inorganic sediments. For instance, a 3-fold increase of phosphorus since pre-industrial times (Bennett et al. 2001) and increased nitrogen loads (Seitzinger et al. 2002) caused the eutrophication of coastal areas.

The deterioration of riverine landscapes has led to an increasing activity of rehabilitation and restoration works in the last decade (Henry et al. 2002). In the beginning, premier aims have been to increase the spatial heterogeneity, while recent works point to the importance of a more integrated approach including also landscape dynamics as well as key ecosystem processes (e.g. Pedroli et al. 2002; Hohensinner et al. 2004). Therefore, large-scale rehabilitation and restoration projects need also to consider altered nutrient dynamics (e.g. Danube Delta: Buijse et al. 2002) or aim to reduce nutrient transport in river corridors by increased nutrient retention (e.g. Kissimmee restoration project: Dahm et al. 1995; Mississippi-Ohio-Missouri: Mitsch & Day 2004). Another example of a medium-scale rehabilitation project increasing the nutrient transformation capacity was at

Fig. 1. The originally braided river stretch of the Danube at Vienna and the changes due to the regulation scheme 1875. Maps from Mohilla & Michlmayr (1996).

one tributary of the Danube in Vienna, the 3rd order stream Wienfluss. The single re-connection of a 1-km long wetland area resulted in a mean phosphate reduction of 10 % and an increase of DOM concentrations in downstream reaches (Hein 2002). Generally, river restoration and rehabilitation schemes integrating biogeochemical processes obtain a functional ecological integrity of lotic networks and associated coastal areas at larger scales (Bradshaw 1996).

Objectives of the paper

In this paper the importance of slackwater areas, their spatial and temporal availability and changes due to human activity are discussed. An integrated approach (sensu Zalewski et al. 1997) combining hydrological metrics with ecological processes was used to quantify the contribution of particular retention areas. The role of lotic habitats with reduced flow velocities and side-channels within a braided floodplain reach at flows below bankfull is presented. We impart work from a floodplain stretch of the Danube River downstream of Vienna, in particular the Danube Restoration Project. On a spatial scale in-channel structures, side-arms and finally terrestrial components are linked to the hydrologic exchange conditions. In more detail the temporal dynamics of phosphate uptake and phytoplankton development will be shown for a side-arm system. The contribution to the overall nutrient storage and transformation is described and their importance in regulated rivers is highlighted.

Description of the research area along the Danube

In the stretch of the upper Danube downstream of Vienna, the side-arms originally showed lotic conditions almost throughout the year, exhibiting a gradient from low to high flow velocities. This natural river system, a typical braided stretch, was relatively shallow and characterized by unstable banks. Large-scale floods occurred in irregular intervals and led to permanent channel migrations as well as to the formation of new channels, gravel banks and islands (Fig. 1). High sediment dynamics created large alluvial fans in this unconstrained section, with floodplains several km wide (e.g. SCHIEMER et al. 2001b; Fig. 2). After the major regulation scheme of 1875, long term development lead to reduced hydrologic connectivity and dramatic loss of riverine habitats. The high nature value and potential for restoring key ecological processes led to the declaration of a national park in 1996. The biogeochemical dynamics in the Danube at present are affected by the reduced quality and quantity of inshore zones and the limited lateral integration of former side-arms. Efforts are now being taken to improve the geomorphologic, hydrologic and ecological conditions in reaction to the present situation (RECKENDORFER et al. 2005).

The former side-arms along the national park stretch of the Danube vary greatly in connectivity and differ in their rehabilitation potential. The Regelsbrunn area, the demonstration site of the Danube Restoration Programme (TOCKNER et al. 1998; SCHIEMER et al. 1999), was characterized by high potential of hydrologic exchange prior to rehabilitation (HEILER et al. 1995). The restoration programme carried out in the late 1990s, included the re-opening of the side-arm at 6 inlets over the entire stretch of 10 km and a lowering of the check-dams and additional culverts within the system, to produce more pristine conditions (Fig. 3). The connectivity was increased between mean water and bankfull level at Regelsbrunn. The proportion of discharge passing through Regelsbrunn after rehabilitation increased non-linearly with riverine flow conditions, ranging from less than 0.5 % at low water ($< 6\ m^3\ s^{-1}$) up to 12 % (about $650\ m^3\ s^{-1}$) at high water. To quantify the changes in ecological processes, a detailed hydrological model was developed (RECKENDORFER & STEEL 2004). The model output metric "water age", a kind of residence time adapted to the multi-input system, explained to a high degree nutrient uptake and pelagic processes in the water column of the reopened side-arm (ASPETSBERGER et al. 2002; BARANYI et al. 2002; HEIN et al. 2003). A part of the ecological evaluation studies focused on changes in biogeochemical processes (HEIN et al. 2004a).

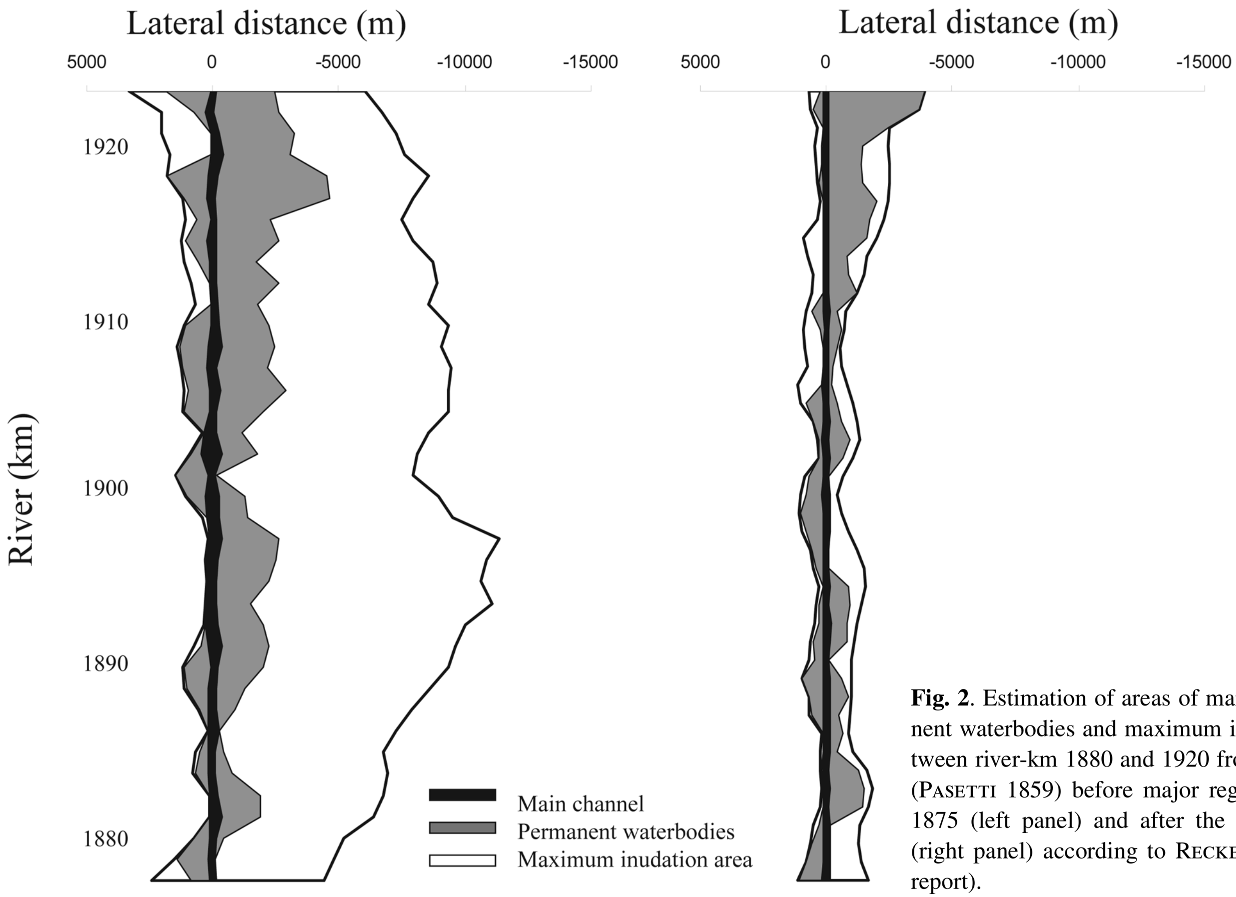

Fig. 2. Estimation of areas of main channel, permanent waterbodies and maximum inundation area between river-km 1880 and 1920 from historical maps (Pasetti 1859) before major regulation scheme of 1875 (left panel) and after the regulation scheme (right panel) according to Reckendorfer (unpubl. report).

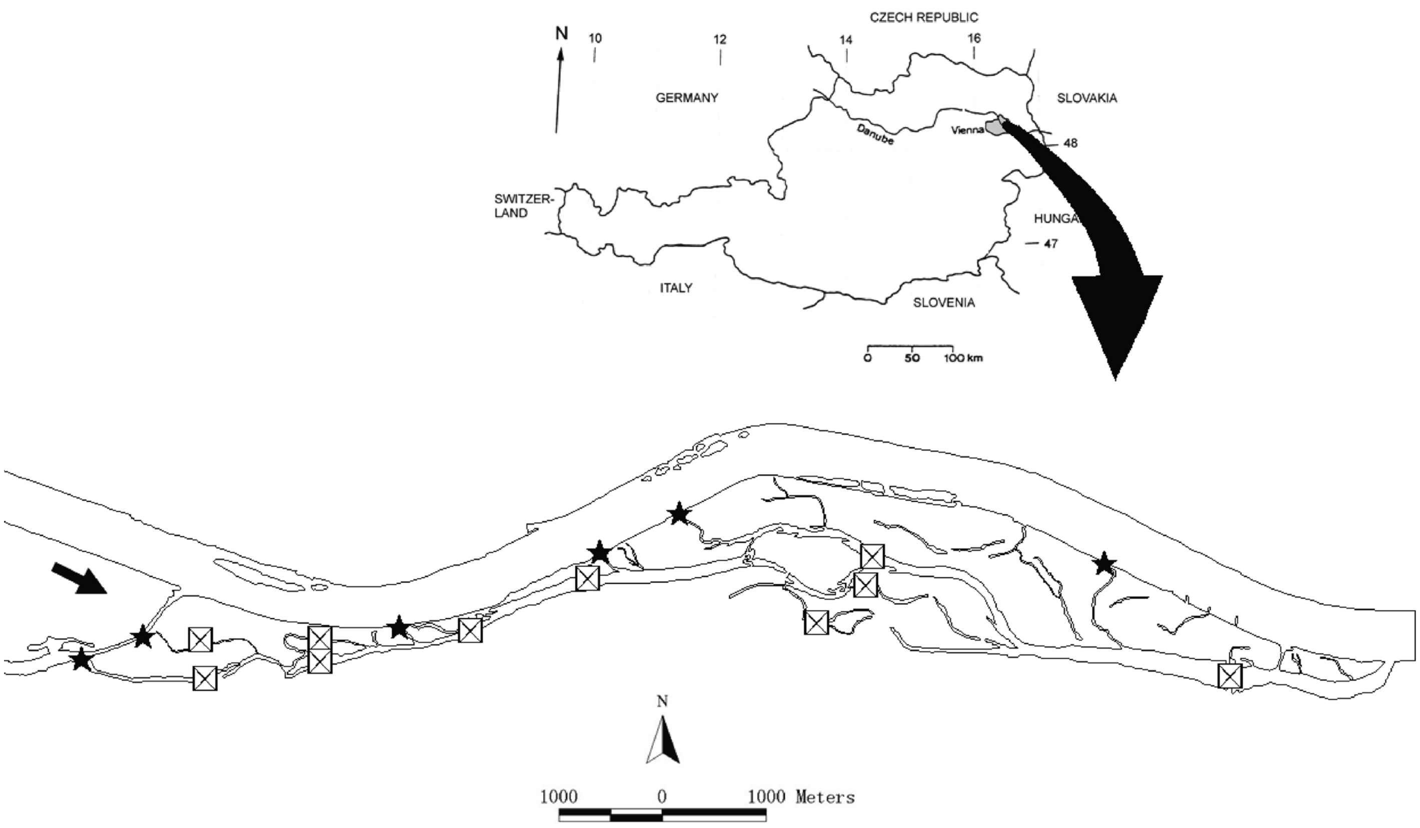

Fig. 3. Map of the rehabilitation area, Regelsbrunn, river-km 1895–1907. Stars mark restored inlets; boxes indicate measures at the check dams within the system according to Schiemer et al. (1999). Arrow on the left indicates flow direction. Insert: location in Austria.

The productivity of in-channel structures

To quantify ecosystem functions in rivers, shore line length as an indicator for heterogeneity in lotic habitats is used. The shoreline length of specific river corridors illustrates clearly the differences between natural and regulated conditions (Tockner & Stanford 2002). In the Danube downstream of Vienna, the shoreline length shows a distinct decline just below high water due to the embankment structure (Schiemer et al. 2001b). Gravel bars in the main channel and bay structures are the most important elements increasing the shoreline length at medium water levels (Reckendorfer et al. 1999). Shoreline length and the availability of shallow and flow reduced areas are the largest around mean water (Fig. 4a). In-channel slackwater areas are important for zooplankton and juvenile fish (Reckendorfer et al. 1999; Schiemer et al. 2001b). These flow-reduced, shallow areas (depth: < 0.5 m; velocity < 0.2 m s^{-1}), also impact the in-stream phytoplankton production in the Austrian Danube (Fig. 4b). The mean concentration of chlorophyll-*a* (20 ± 18 mg m^{-3}, n = 77, data: Hein et al. 2004b) in these storage zones was about 25 % higher than a long-term mean (1997–2003, n = 77) recorded for the main channel (unpublished data Federal Institute of Water Quality). Therefore, the autochthonous carbon supply for the riverine community is mainly supported by the availability of these areas; especially during periods of low flow as observed during summer 2003 (Hein unpubl. data). The importance of these areas in other European rivers, also referred to as storage zones, was demonstrated for nutrient retention (Brunet et al. 1994) and phytoplankton development (Reynolds & Descy 1996).

Phosphorus dynamics and productivity in a reopened side-arm and the adjacent floodplain

The second example deals with the side-arm system in the Regelsbrunn floodplain. The effect of the changed hydrological connectivity on the phosphorus transport and storage, and the relationship between phosphate decrease and phytoplankton development are discussed. Total mass balance calculations revealed an annual load of 7–9 kt P y^{-1} for the Austrian Danube, with a dominance of the particulate fraction (Zessner & van Gils 2002). The particulate fraction in the main channel rises significantly during flooding due to massive soil erosions and, in consequence, during flood events most of the yearly phosphorus transport occurs (Zessner 1999).

The phosphorus mass balance calculation for the side-arm was done according to Tockner et al. (1999). The input was calculated from the relationship between total phosphorus concentration and discharge in the main channel as found by Zessner (1999). Biweekly to monthly measurements in the years 1991 to 1997 of total phosphorus concentration built the database with discharges ranging from 1,000 to 8,000 m^3 s^{-1}.

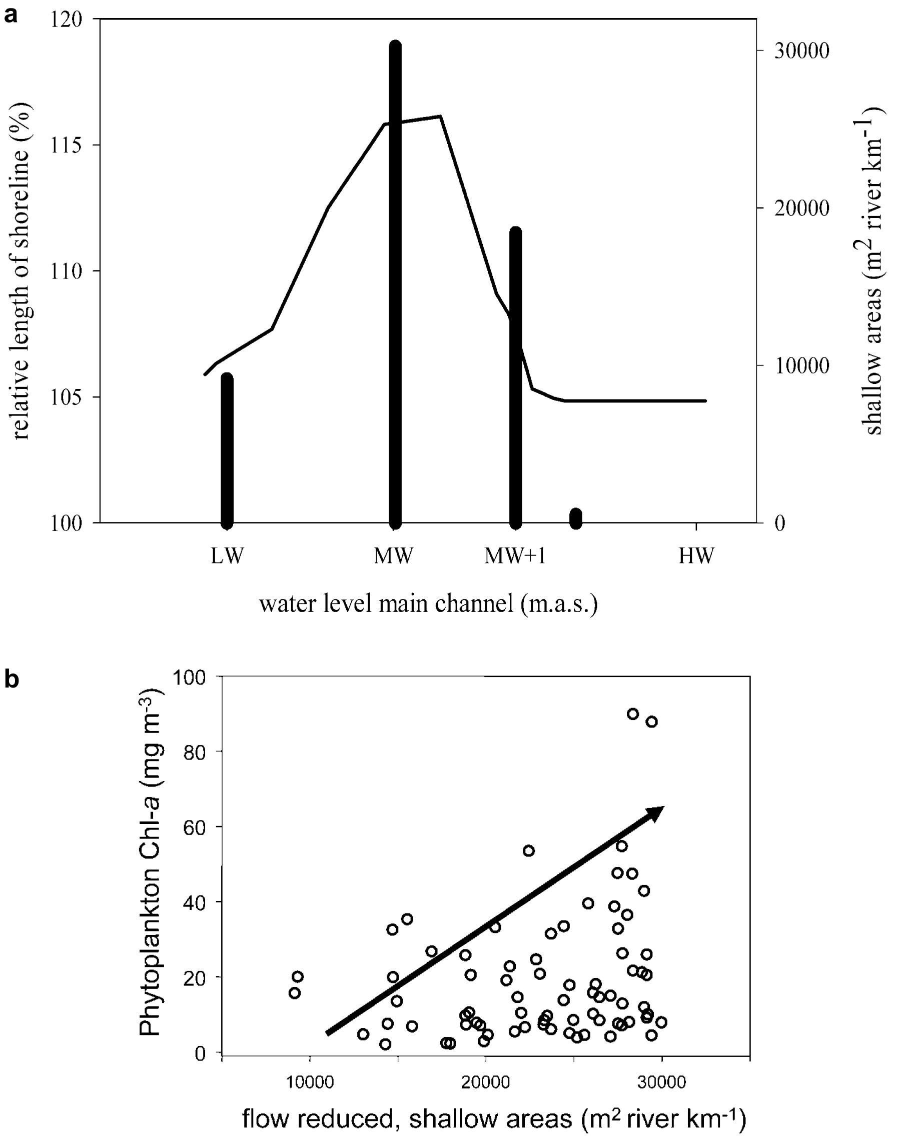

Fig. 4. a: Relationship of water level and mean shoreline length for a 10 km stretch in the main channel of the Danube according to Reckendorfer et al. (1999). Data presented for the shallow areas are estimated by GIS on the basis of a geomorphological model. Line represents shoreline length, bars shallow areas. b: Relationship of slackwater areas, defined as flow-reduced (< 0.2 m s^{-1}) and shallow (< 0.5 m depth) areas, and phytoplankton biomass expressed as Chl-*a*. Data origin: main channel station in one slackwater area at river-km 1901 according to Hein et al. (2004b), downstream of the 10 km reach where the shoreline and the shallow areas have been estimated. Arrow indicates trend of mean Chl-*a* concentrations.

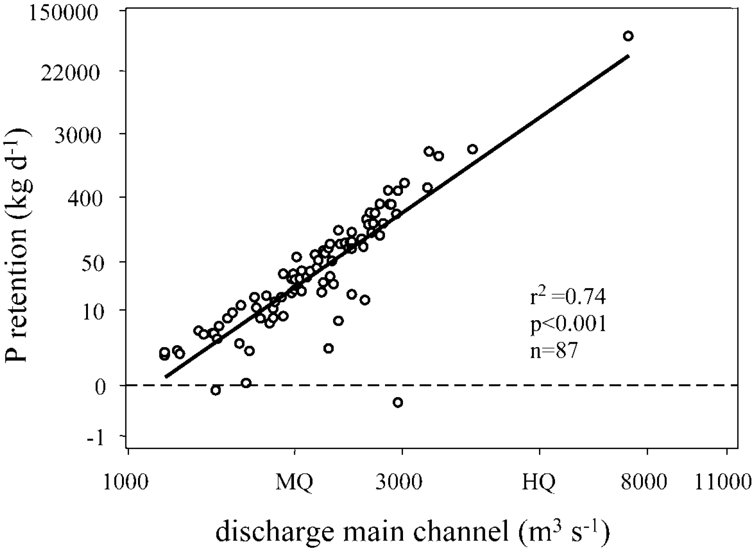

Fig. 5. Total phosphorus retention estimated by input/output mass balance calculations from the years 1997–2000. Data for the main channel (input concentration) was provided by M. Zessner and a significant relationship between discharge and total phosphorus was used to calculate the input flux (Zessner 1999). Station at the outlet of the side-arm and method of calculation for the mass balance according to Tockner et al. (1999). MQ: mean discharge, HQ: annual high water discharge.

Table 1. Discharge characteristics of the side-arm Regelsbrunn and mean daily phosphorus retention and annual sum of phosphorus retention in Regelsbrunn. Basis for the annual phosphorus retention was the relationship presented in Fig. 5, for details see text. Q: discharge in m^3 s^{-1}; STD: standard deviation.

year	Mean Q Regelsbr. m^3	STD Q Regelsbr. m^3 s^{-1}	Mean phosp. retention kg ha^{-1} d^{-1}	Phosphorus retention kg y^{-1}
1997	36	99	19	42,894
1998	28	71	19	11,195
1999	67	125	39	33,943
2000	51	78	40	17,792
2001	41	80	30	16,061
2002	66	134	60	174,619

The output was calculated from discharges revealed from the hydrological model and by measurements of the total phosphorus concentration at the downstream end of Regelsbrunn as reported by HEIN et al. (2004b). No further linear extrapolation was done for discharges exceeding 8,000 $m^3 s^{-1}$, where the whole area of Regelsbrunn was already flooded. This more conservative estimation of total phosphorus deposition at high water limited the calculated retention during the exceptional high floods in 2002.

Discharge weighted concentrations at the outlet (n = 59) were used to estimate the daily phosphorus flux. Based on the difference between input and output flux, a significant positive relationship was found between riverine discharge and total phosphorus retention (Fig. 5). This enabled us to calculate the daily total phosphorus retention for the side-arm and above bankfull for the whole floodplain area for the years 1997 to 2002 (Table 1). Years with higher flows, and especially the year 2002 with two exceptional flood events, increased the total phosphorus retention markedly by an order of magnitude.

At high flows, the inundated terrestrial components of the floodplain determined the retention capacity as also shown for the lower Rhine (VAN DER LEE et al. 2004); up to 1 % of the total annual load can be retained within this area. The total phosphorus retention is mainly explained by physical deposition, comparable to the situation before rehabilitation (TOCKNER et al. 1999). For the dissolved reactive fraction, phosphate, also a decrease in concentration between main channel and side-arm outlet was found (mean: 3+/-7 mg m^{-3}, n = 42). Before rehabilitation, the decrease of phosphate concentration was higher (mean: 18+/-15 mg m^{-3}, n = 15), but in terms of mass fluxes, the phosphate reduction increased after rehabilitation from average values of 10 kg d^{-1} to 15 kg d^{-1} at medium to bankfull water levels due to the higher discharge in the side-arm. During floods the floodplain was a source of phosphate.

Regarding the temporal dynamics, the metric water age significantly explained the rapid decrease of phosphate to 30 % of initial concentrations within 2 days (Fig. 6a). The phytoplankton biomass development followed a hump-shaped curve with maximum phytoplankton biomass values at water ages between 3 and 10 d (HEIN et al. 2003). Linking phosphate concentration to phytoplankton biomass, mainly algal uptake seems to explain the rapid phosphate decrease in concentration (Fig. 6b). Thus, phosphate input is driven by the below bankfull flow pulse and the following biological uptake (sensu TOCKNER et al. 2000), while that of total phosphorus is determined by the supra-bankfull flood regime. The rehabilitation measures enhanced the phosphate transformation at water levels below high water, but still the sedimentation during flood events was at the same order of magnitude and quantitatively decisive for total phosphorus storage.

The aquatic productivity of the reopened side-arm is expected to be shaped by the hydrologic exchange, the morphology of the side-arm itself and light conditions (SCHAGERL et al. 2004). Sufficient light reaches the sediment surface until mean discharge conditions, with increasing discharge light penetration decrease

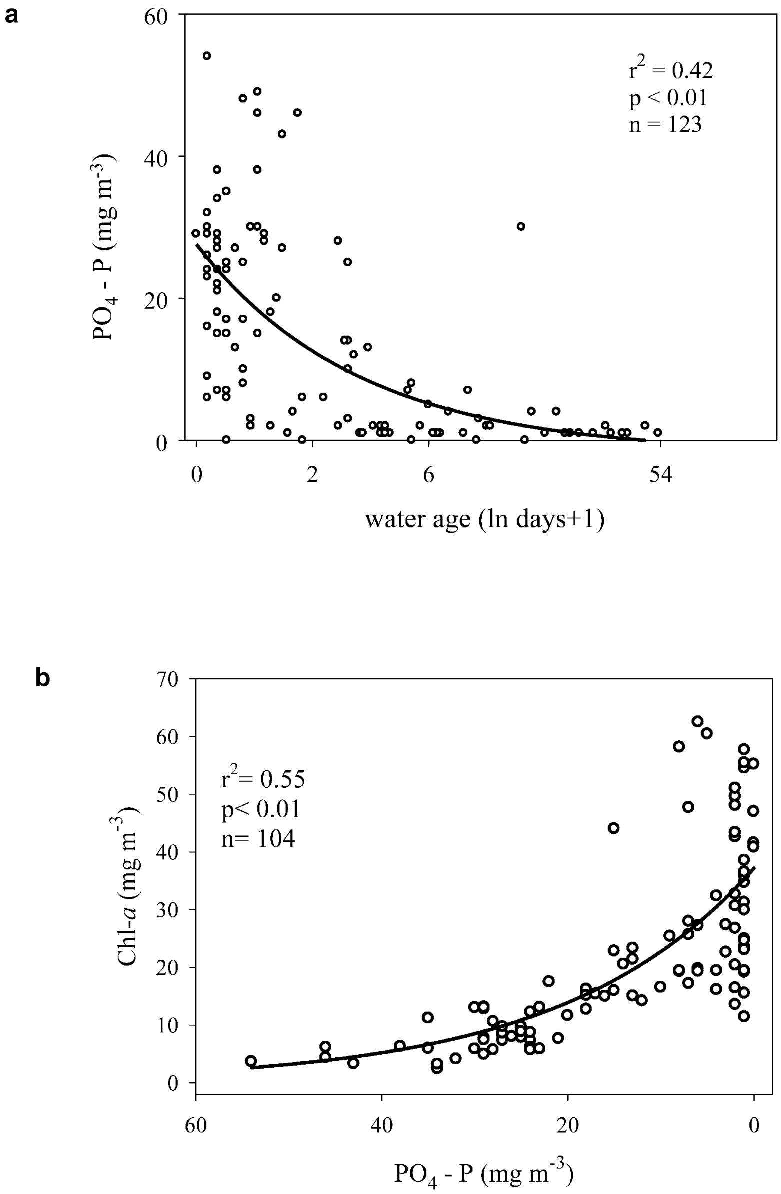

Fig. 6. a: Relationship of water age and phosphate concentrations in the side-arm Regelsbrunn. b: Relationship of phosphate-phosphorus vs. Chl-*a* concentration in Regelsbrunn. Data are from 1999–2000; methods: HEIN et al. (1999); data: HEIN et al. (2004b).

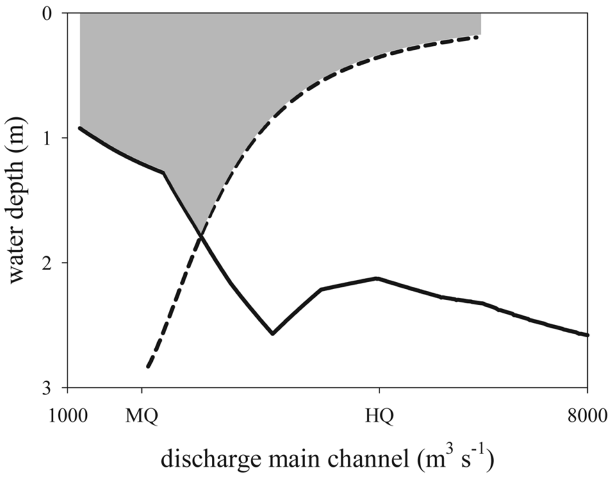

Fig. 7. Conceptual model for the relationship of discharge in the main channel vs. mean depth and zero light level in the side-arm Regelsbrunn. Mean depth was estimated by the hydrologic model (Reckendorfer & Steel 2004). Light availability was estimated by 2 functions: the significant relationship of discharge and suspended solids concentration ($r^2 = 0.81$, $p < 0.001$, $n = 2615$), and the significant relationship between suspended solid concentration and the coefficient of light extinction ($r^2 = 0.70$, $p < 0.001$, $n = 180$), data are from the years 1997–2000. Dashed line represents zero light level, solid line mean depth. Grey area indicates euphotic part of water column.

due to the transported particle load (Fig. 7). The modeled light availability in the side-arm confirms the maximum biomass observed at medium water ages (Hein et al. 2003). Only during lower flows benthic production can be of higher importance as found for a long low water period in 2003 (Preiner unpubl. data). Model estimations as well as direct measurements of pelagic primary production point to the role of connected side-arms as zones of increased aquatic production especially at medium to bankfull water levels (Schagerl et al. 2004). The frequent surface water exchange between side-arms and the main channel increases the potential for plankton production and provides a significant source of autochthonous organic matter, which can support also riverine food webs (Thorp & Delong 2002). A more intense nutrient transformation by plankton biota within reopened side-arms also increases their importance as biogeochemical hot spots in lotic networks.

Implication for rehabilitation

Increased nutrient transformation and retention present a green service of the river corridor which has a socio-economic importance (Gren et al. 1995). The coupling of hydrology and ecological processes should play an important role in understanding large-scale biogeochemical processes and using ecosystem services for more effective river management. In urban and industrial areas, more natural exchange processes with slackwater areas can support other engineering-based solutions to achieve the required water quality goals (McClain 2002). The evaluation of rehabilitation measures can be improved by the development of morphologic or hydraulic metrics, which are easy to estimate during the planning phase and have also a high potential to predict the changes on key ecosystem functions like nutrient processing and organic matter production (Schiemer et al. 1999; Hein et al. 2004b).

In large regulated river systems, rehabilitation efforts should favour slackwater areas at different spatial scales as shown for the Danube stretch in Austria. In-channel structures functioning as storage zones are key elements during lower water tables and can provide substantial support to the riverine food web. With increasing discharge and rising water levels the availability of these in-channel structures decline due to embankment and other riverine landscape elements are needed. The presented side-arm reopening in the Austrian Danube provides an example of rehabilitation on the reach scale where rare lotic elements of the former braided reach were reconnected. Now they function as slackwater areas during medium to high flows. Restoring the hydrological connectivity and increasing the duration of lotic conditions support a higher overall plankton productivity in the side-arm as well as compensate for the existing short falls in the main channel. Within these side-arms a more natural mass balance between storage, transformation and export of nutrients and organic matter is established (Hein et al. 2003). The Danube downstream of Vienna, therefore, is an example of a regulated river stretch where rehabilitation can increase the transformation capacity by reconnecting the remaining slackwater areas.

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