Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-024-32924-8

SHORT RESEARCH AND DISCUSSION ARTICLE

# Different intensities and directions of hyporheic water exchange in habitats of aquatic *Ranunculus* species in rivers—a case study in Poland

**Marek Marciniak**[1] · **Daniel Gebler**[2] · **Mateusz Grygoruk**[3] · **Joanna Zalewska-Gałosz**[4] · **Krzysztof Szoszkiewicz**[2]

Received: 16 May 2023 / Accepted: 11 March 2024


**Abstract**
Hyporheic water exchange driven by groundwater-surface water interactions constitutes habitat conditions for aquatic biota. In our study, we conducted a field-research-based analysis of hyporheic water exchange to reveal whether the hyporheic water exchange differentiates particular *Ranunculus* sp. habitats. We measured the density of the stream of upwelling and hydraulic gradients of water residing in the hyporheic zone in 19 Polish rivers. We revealed that *R. peltatus* and *R. penicillatus* persist in habitats of considerably higher hyporheic water exchange upwelling flux (respectively 0.0852 $m^3•d^{-1}•m^{-2}$ and 0.0952 $m^3•d^{-1}•m^{-2}$) than *R. circinatus*, *R. fluitans*, and a hybrid of *R. circinatus* × *R. fluitans* (respectively $m^3•d^{-1}•m^{-2}$; 0.0222 $m^3•d^{-1}•m^{-2}$ and 0.0717 $m^3•d^{-1}•m^{-2}$). The presented results can be used to indicate aquatic habitat suitability in the case of protection and management of ecosystems settled by *Ranunculus* sp.

**Keywords** River · Groundwater · Surface water · Hyporheic zone · Macrophytes · Water crowfoot

## Introduction

The hyporheic zone is the region of sediment and porous space beneath and alongside a stream bed, where there is the mixing of shallow groundwater and surface water. The hyporheic zone influences the biogeochemistry of stream ecosystems by increasing solute residence times and more specifically solute contact with substrates in environments with spatial gradients in dissolved oxygen and pH (Bencala 2000). Water exchange in the hyporheic zone affects the stability of river flows, water temperature, and associated biogeochemical components of habitats, such as oxygen and nutrient availability (Hester et al. 2017; Pacioglu and Moldovan 2016). Hyporheic water exchange is, therefore, an important factor in shaping habitats for a range of riverine biota including macrophytes (Braun et al. 2012; Grygoruk et al. 2021; Lin et al. 2020; Magliozzi et al. 2019; Marciniak et al. 2023).

The heterogeneity of the hyporheic zone originates from the primary factors (such as types of sediments and their granulation and regional groundwater flow patterns) and secondary factors (evolving hydromorphology of the river induces changes in sediment transport and transmissivity of the river bottom). Among the secondary factors, is the occurrence of macrophyte patches in rivers, which—by impairing flow velocities—determine erosion-sedimentation balance by positive feedback, affecting this way water flow in the hyporheic zone and changing groundwater-surface water interactions (Schulz et al. 2003). Both of these groups of factors affect environmental conditions for various groups of aquatic biota, as it is responsible for oxygen content in the sediment, nutrient concentration in the superficial part of the river bottom, and water

Responsible Editor: Philippe Garrigues

✉ Mateusz Grygoruk
mateusz_grygoruk@sggw.edu.pl

1 Faculty of Geographical and Geological Sciences, Adam Mickiewicz University in Poznań, Krygowskiego 10, 61-680 Poznań, Poland

2 Department of Ecology and Environmental Protection, Poznań University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland

3 Department of Hydrology, Meteorology and Water Management, Institute of Environmental Engineering, Warsaw University of Life Sciences-SGGW, Ul. Nowoursynowska 166, 02-787 Warsaw, Poland

4 Faculty of Biology, Institute of Botany, Jagiellonian University, Gronostajowa 3, 30-387 Kraków, Poland

Published online: 23 March 2024

temperature (Braun et al. 2012). Observing dynamics in the occurrence, disappearance, and reoccurrence of macrophytes in different watercourses (Wiegleb et al. 2014), it is likely that the direction and intensity of water flow in the hyporheic zone could remain an important factor underpinning a range of ecological processes.

Aquatic *Ranunculus* ssp. play a significant role in the ecology and diversity of watercourses. Its patches may modify flow velocity field and water level-discharge relationships, promoting fine sediment deposition within patches as an effect of trapping (Bal et al. 2011; Cassan et al. 2015; Vermaat et al. 2000). *Ranunculus* ssp. patches can therefore be an excellent habitat for abundant invertebrates and provide vital refuge and cover for fish and other aquatic species (Pinto et al. 2006). Moreover, *Ranunculus* ssp. can serve as bioindicators of water quality parameters. Recent studies have demonstrated that there is generally no unambiguous relationship between plant species composition and specific environmental conditions in rivers (Weekes et al. 2021). Watercourses with the *Ranunculus* ssp. vegetation are, therefore, natural habitat types of the EU community interest, whose conservation requires the designation of special areas of conservation. That is why, rivers colonized by the *Ranunculus* ssp. are listed in Annex I of the Habitats Directive (Habitat 3260).

In our study, we attempted to measure and quantify hyporheic water exchange in river stretches colonized by the *Ranunculus* ssp. In our field-research-based approach spanning for 2 years, we differentiated hyporheic zone flow patterns in rivers with stable populations of *R. peltatus*, *R. penicillatus*, *R. circinatus*, *R. fluitans*, and one hybrid: *P. circinatus* × *R. fluitans*.

## Materials and methods

We measured the density of stream of upwelling and hydraulic gradients of water residing in the hyporheic zone with the use of a filtrometer (Fig. 1A) and gradientometer (Fig. 1C) (Marciniak and Chudziak 2015; Supplementary Materials No.1). Our research was done in 19 rivers located in diverse regions of Poland, which are known habitats of *Ranunculus* ssp. (Fig. 1B). Gradientometric tests were taken in 19 rivers, but filtrometric tests were carried out in 17 rivers (it was not possible to insert a filtrometer in two rivers). However, in Fig. 2, there are 18 results presented (still from 17 rivers), because in one river (nr 11) two taxa (*R. circinatus* and *R. circinatus* × *R. fluitans*) were recorded. Similarly, Fig. 3 shows 21 results from 19 rivers because in two rivers (nr 11 and nr 19) two taxa were found (in both cases *R. circinatus* and *R. circinatus* × *R. fluitans* were present). The water bodies researched are shallow (up to 1 m deep), sandy-gravel rivers and streams with flow velocities reaching up to 0.6 m•s$^{-1}$. Their width varied between 2 and 25 m. Gradientometric and filtrometric research was conducted in 2018–2019 during the warm period of the year (from May to October), wading in the river (Marciniak et al. 2023). At each site, gradientometric and filtrometric sampling points were located in a *Ranunculus* patch and distinctive

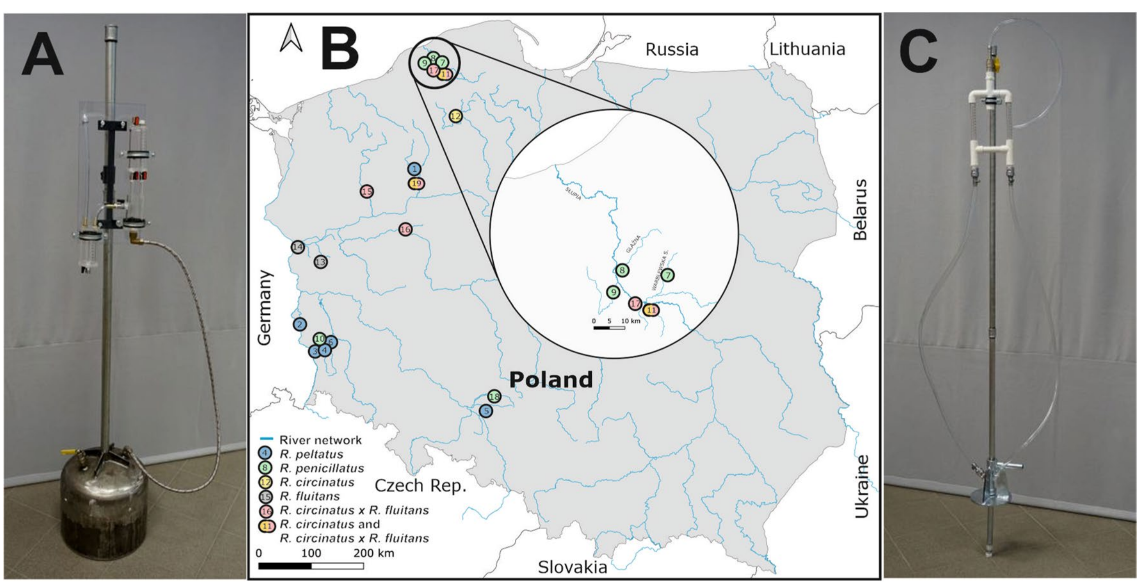


**Fig. 1** **A** Filtrometer (Marciniak and Chudziak 2015). **B** Survey sites, where hyporheic water exchange in *Ranunculus* habitats was measured. **C** Gradientometer (Marciniak and Chudziak 2015). A more detailed description of a filtrometer and gradientometer is presented in Supplementary Materials No. 1

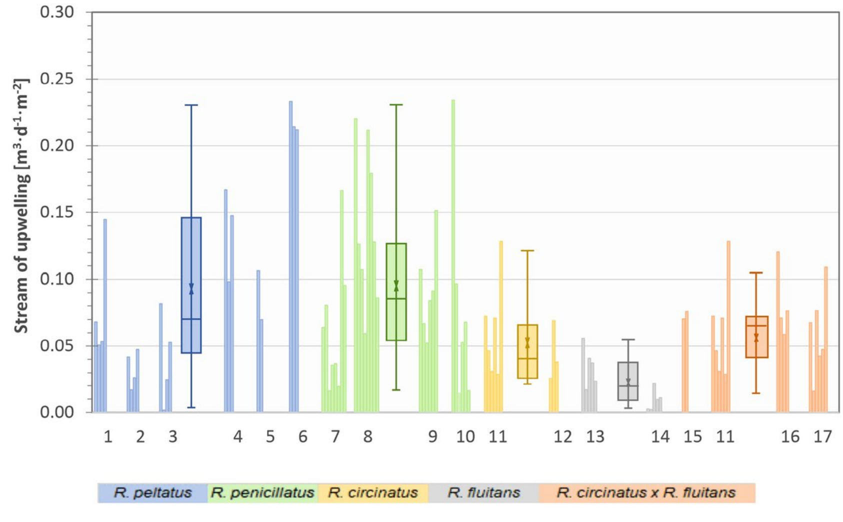


**Fig. 2** Results of filtrometric tests. Numbers on the *x*-axis represent particular research sites. The identification numbers of field sites are given on the horizontal axis (locations are provided in Fig. 1). In box plots, horizontal lines from the bottom indicate minimum, first quartile, median, third quartile, and maximum, and the x sign indicates the average. Top and bottom whiskers represent 5–95 percentiles of the distribution

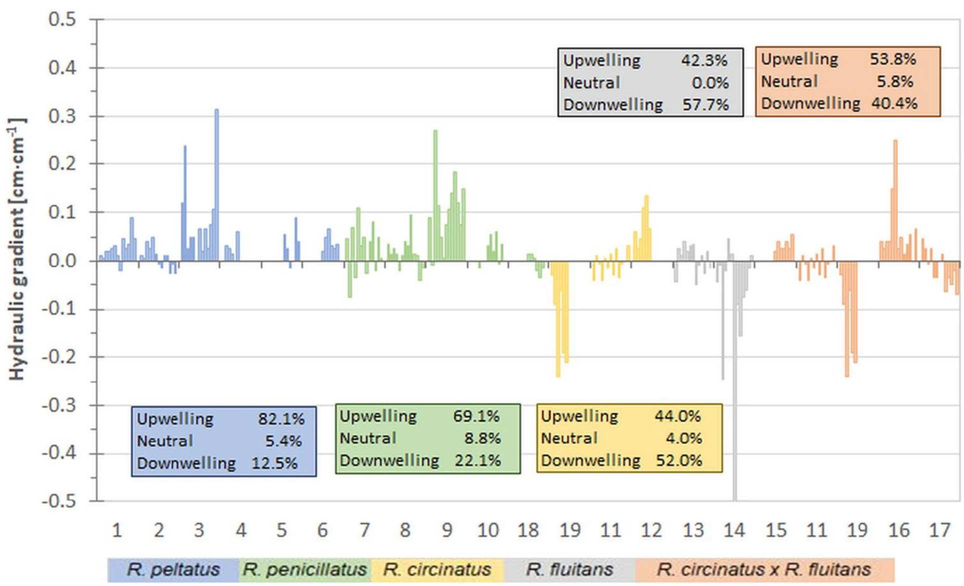


**Fig. 3** Results of gradientometric tests. The values in the text boxes indicate the percentage of positive (upwelling), zero (neutral), and negative (downwelling) gradients in the total number of gradientometric measurements performed for individual *Ranunculus* taxa

hydromorphological units: run, pool, and riffle (if they were only present in the studied fragment of the river). The varying number of repetitions of the measurements taken in different locations was due to field capabilities (including the ability to drive the measuring devices into the bottom of the watercourse several times, the width and depth of the watercourse, and the bottom substrate). Due to significant morphological variation, frequent hybridization, and polyploidization occurring within the *Ranunculus* sect. *Batrachium* (Wiegleb et al. 2017), the classical identification of the *Ranunculus* species is difficult or indecisive. Therefore, for this work, taxa were identified based on molecular features, according to the methodology presented by Gebler et al. (2022).

## Results and discussion

We revealed that *R. peltatus* and *R. penicillatus* persist in habitats of considerably higher hyporheic water exchange stream of upwelling (respectively 0.0852 $m^3 \cdot d^{-1} \cdot m^{-2}$ and 0.0952 $m^3 \cdot d^{-1} \cdot m^{-2}$) than *R. circinatus*, *R. fluitans*, and a hybrid of *R. circinatus* × *R. fluitans* (respectively 0.0568 $m^3 \cdot d^{-1} \cdot m^{-2}$; 0.0222 $m^3 \cdot d^{-1} \cdot m^{-2}$ and 0.0717 $m^3 \cdot d^{-1} \cdot m^{-2}$) (Fig. 2). In light of the presented results, we hypothesize that *R. peltatus* and *R. penicillatus* prefer riverbeds with a clear dominance of upwelling in the hyporheic zone, which is characteristic of the conditions of groundwater drainage through the river (82.1% and 69.1% positive gradient values in the hyporheic zone, indicate groundwater drainage through the river) (Fig. 3).

Raw and detailed data presented in Figs. 2 and 3 are included in Supplementary Materials No. 2 (Table SM1 and SM2, respectively). *R. circinatus*, *R. fluitans*, and *R. circinatus* × *R. fluitans* prefer (or tolerate) the conditions of bidirectional hyporheic water exchange, in which both upwelling and downwelling occur (44.0%, 42.3%, and 53.8% positive gradient values, respectively). The tolerance of individual *Ranunculus* taxa to conditions of hyporheic exchange may indicate their ability to inhabit flowing or standing waters. This may be confirmed by the known fact of the frequent occurrence of *R. circinatus* in lakes. Our field-research-based study showed that the average vertical hydraulic gradients in the hyporheic zone are as high as 0.1 cm/cm, one to two orders of magnitude higher than the horizontal groundwater gradients of adjacent aquifers. Due to the lack of hyporheic water exchange data from rivers uninhabited by the *Ranunculus* ssp., we cannot state whether the hyporheic water exchange in rivers colonized by these macrophytes presents somewhat different patterns than in rivers uninhabited by the *Ranunculus* ssp. However, the results of gradientometric studies indicate the dominance of upwelling in zones inhabited by *Ranunculus* spp.

The presented results can be used to indicate aquatic habitat suitability in the case of protection and management of ecosystems settled by *Ranunculus* ssp. Although our study does not allow us to state whether the revealed differences in hyporheic water exchange formulate tolerance of particular *Ranunculus* species either to upwelling or to downwelling fluxes, these patterns likely present differences of this process that should be considered when describing habitat parameters of these species. Banks et al. (2023) found that the ecological response of stream ecosystem to groundwater supply manifested in specific habitat types and that ecological patterns revealed were not associated with other typical stream ecosystem's physical parameters (surface water temperature, nutrient availability, chemical characteristics). Similarly, we conclude that downwelling/upwelling fluxes can explain the habitat quality of particular species. Yet, links should be found between the intensity of hyporheic water exchange and other parameters of the streambed and river water parameters. That is why, we suggest that more attention should be paid to hyporheic water exchange in regular river management measures, supporting in this matter the statement of Lewandowski et al. (2019). Such as in a range of other cases (e.g., urban riverscapes; Lawrence et al. 2013), field studies on hyporheic water exchange in *Ranunculus* habitats are likely to help in overcoming barriers to understanding ecological processes governing the occurrence and disappearance of these species. Searching for correlations between hyporheic water exchange patterns and ecological processes such as the recolonization of river stretches by *Ranunculus* ssp. and their stability over time may significantly expand the definition of environmental relevance of groundwater-surface water interaction provided by Bencala (2000). Thus, hyporheic water exchange, when properly quantified, can be used as an objective indicator of habitat quality for different species of *Ranunculus* ssp., and—wider—any other species of riverine ecosystems.

It is likely that *Ranunculus* ssp. patches due to the sediment trapping effect and root development are affecting the original hyporheic water exchange by decreasing the density of the stream of filtration. This factor can, therefore, indicate that these macrophytes and hyporheic water exchange can keep in a feedback. Dynamics of *Ranunculus* ssp. patches can result from decreasing intensity of water exchange in the hyporheic zone. After a certain amount of time, hyporheic water exchange can be changed so much that the habitat conditions for *Ranunculus* ssp. are not optimal, so the macrophyte has to disperse. This hypothetical biological adaptation is expected to occur mainly among *R. peltatus* and *R. penicillatus* who seem to prefer intensive hyporheic water exchange. As for now, we do not have a significant amount of data that would allow us to test this hypothesis. If confirmed, however, this mechanism would be different from the known macrophyte dispersion mechanisms and adaptations (Sand-Jensen and Madsen 1992).

Although traditional technical river management measures impair a range of elements of aquatic ecosystems (e.g., bottom sediment structure, macrophyte diversity, and fish abundances; Bączyk et al. 2018), we conclude that dredging and macrophyte removal can also affect hyporheic water exchange. Presented results allow us to hypothesize that the negative responses of aquatic ecosystems to technical river management measures can also originate from the changed balance in groundwater and surface water interactions. Verification of this hypothesis would, however, require a targeted approach and field-based research on how technical river management measures change the directions and density of filtration fluxes in the hyporheic zone.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11356-024-32924-8.

**Acknowledgements** We thank Joanna Chmist-Sikorska, Stanisław Zaborowski, and the staff of Pomeranian Landscape Parks Complex for support in field sampling and laboratory work. Taxonomic issues were discussed with Gerhard Wiegleb.

**Author contribution** All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Marek Marciniak, Daniel Gebler, and Joanna Zalewska-Gałosz. The first draft of the manuscript was written by Marek Marciniak, Mateusz Grygoruk, and Krzysztof Szoszkiewicz. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. We thank the reviewers for their detailed and thoughtful comments that allowed us to improve this manuscript.

**Funding** The research was funded by a Grant from the National Science Centre, Poland: UMO-2016/23/B/NZ9/03600.

**Data availability** Data presented in the manuscript can be shared upon the written request to the corresponding author. Raw data analyzed in this study are presented in Supplementary Materials No. 2.

## Declarations

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** The authors confirm that the manuscript has been read and approved by all authors. The authors declare that this manuscript has not been published and is not under consideration for publication elsewhere.

**Competing interests** The authors declare no competing interests.

## References

Bal K, Struyf E, Vereecken H, Viaene P, De Doncker L, de Deckere E, Mostaert F, Meire P (2011) How do macrophyte distribution patterns affect hydraulic resistances? Ecol Eng 37:529–533. https://doi.org/10.1016/j.ecoleng.2010.12.018

Banks LK, Lavoie I, Robinson CE, Roy JW, Yates AG (2023) Effects of groundwater inputs on algal assemblages and cellulose decomposition differ based on habitat type in an agricultural stream. Hydrobiologia 850:3517–3537. https://doi.org/10.1007/s10750-023-05251-1

Bączyk A, Wagner M, Okruszko T, Grygoruk M (2018) Influence of technical maintenance measures on the ecological status of agricultural lowland rivers – systematic review and implications for river management. Sci Total Environ 627:189–199. https://doi.org/10.1016/j.scitotenv.2018.01.235

Bencala KE (2000) Hyporheic zone hydrological processes. Hydrol Process 14:2797–2798

Braun A, Auerswald K, Geist J (2012) Drivers and spatio-temporal extent of hyporheic patch variation: implications for sampling. PLoS ONE 7(7):e42046. https://doi.org/10.1371/journal.pone.0042046

Cassan L, Belaud G, Baume JP, Dejean C, Moulin F (2015) Velocity profiles in a real vegetated channel. Environ Fluid Mech 15:1263–1279. https://doi.org/10.1007/s10652-015-9417-0

Gebler D, Zalewska-Gałosz J, Jopek M, Szoszkiewicz K (2022) Molecular identification and habitat requirements of the hybrid *Ranunculus circinatus* × *R. fluitans* and its parental taxa *R. circinatus* and *R. fluitans* in running waters. Hydrobiologia 849:2999–3014. https://doi.org/10.1007/s10750-022-04909-6

Grygoruk M, Szałkiewicz E, Grodzka-Łukaszewska M, Mirosław-Świątek D, Oglęcki P, Pusłowska-Tyszewska D, Sinicyn G, Okruszko T (2021) Revealing the influence of hyporheic water exchange on the composition and abundance of bottom-dwelling macroinvertebrates in a temperate lowland river. Knowl Manag Aquat Ecosyst 422:37. https://doi.org/10.1051/kmae/2021036

Hester ET, Cardenas MB, Haggerty R, Apte SV (2017) The importance and challenge of hyporheic mixing. Water Resour Res 53:3565–3575. https://doi.org/10.1002/2016WR020005

Lawrence JE, Skold ME, Hussain FA, Silverman DR, Resh VH, Sedlak DL, Luthy RG, McCray JE (2013) Hyporheic zone in urban streams: a review and opportunities for enhancing water quality and improving aquatic habitat by active management. Environ Eng Sci 30:480–500. https://doi.org/10.1089/ees.2012.0235

Lewandowski J, Arnon S, Banks E, Batelaan O, Betterle A, Broecker T, Coll C, Drummond JD, Gaona Garcia J, Galloway J et al (2019) Is the hyporheic zone relevant beyond the scientific community? Water 11:2230. https://doi.org/10.3390/w11112230

Lin Q, Song J, Gualtieri C, Cheng D, Su P, Wang X, Fu J, Peng J (2020) Effect of hyporheic exchange on macroinvertebrate community in the Weihe River basin. China Water 12:457. https://doi.org/10.3390/w12020457

Magliozzi C, Usseglio-Polatera P, Meyer A, Grabowski RC (2019) Functional traits of hyporheic and benthic invertebrates reveal the importance of wood-driven geomorphological processes in rivers. Funct Ecol 33:1758–1770. https://doi.org/10.1111/1365-2435.13381

Marciniak M, Chudziak Ł (2015) A new method of measuring the hydraulic conductivity of the bottom sediment. Przegląd Geologiczny [geological Review] 63:919–925 (In Polish)

Marciniak M, Gebler D, Grygoruk M, Zalewska-Gałosz J, Szoszkiewicz K (2023) Hyporheic flow in aquatic Ranunculus habitats in temperate lowland rivers in Central Europe. Ecol Ind 153:110422. https://doi.org/10.1016/j.ecolind.2023.110422

Pacioglu O, Moldovan OT (2016) Response of invertebrates from the hyporheic zone of chalk rivers to eutrophication and land use. Environ Sci Pollut Res 23:4729–4740. https://doi.org/10.1007/s11356-015-5703-0

Pinto P, Morais M, Ilhéu M, Sandin L (2006) Relationships among biological elements (macrophytes, macroinvertebrates, and ichthyofauna) for different core river types across Europe at two different spatial scales. In: Furse MT, Hering D, Brabec K, Buffagni A, Sandin L, Verdonschot PFM (eds) The ecological status of European rivers: evaluation and intercalibration of assessment methods. Developments in Hydrobiology, vol 188. Springer, , Dordrecht. https://doi.org/10.1007/978-1-4020-5493-8_6

Sand-Jensen K, Madsen TV (1992) Patch dynamics of the stream macrophyte, Callitriche cophocarpa. Freshw Biol 27:277–282

Schulz M, Kozerski HP, Pluntke T, Rinke K (2003) The influence of macrophytes on sedimentation and nutrient retention in the lower River Spree (Germany). Water Res 37:569–578. https://doi.org/10.1016/S0043-1354(02)00276-2

Vermaat JE, Santamaria L, Roos PJ (2000) Water flow across and sediment trapping in submerged macrophyte beds of contrasting growth form. Arch Hydrobiol 148:549–562

Weekes L, Fitzpatrick Ú, Kelly-Quinn M (2021) Assessment of the efficiency of river macrophytes to detect water-column nutrient levels and other environmental conditions in Irish rivers. Hydrobiologia 848:2797–2814. https://doi.org/10.1007/s10750-021-04598-7

Wiegleb G, Bröring U, Filetti M, Brux H, Herr W (2014) Long-term dynamics of macrophyte dominance and growth form types in two northwest German lowland streams. Freshw Biol 59:1012–1025. https://doi.org/10.1111/fwb.1232

Wiegleb G, Bobrov AA, Zalewska-Gałosz J (2017) A taxonomic account of *Ranunculus* section *Batrachium* (Ranunculaceae). Phytotaxa 319(1):001–055. https://doi.org/10.11646/phytotaxa.319.1.1