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Assessing habitat exposure to eutrophication in restored wetlands: Model-supported *ex-ante* approach to rewetting drained mires

Mateusz Grygoruk [a, *], Agnieszka Bańkowska [a], Ewa Jabłońska [b], Georg A. Janauer [c], Janusz Kubrak [a], Dorota Mirosław-Świątek [a], Wiktor Kotowski [b]

[a] Department of Hydraulic Engineering, Faculty of Civil and Environmental Engineering, Warsaw University of Life Sciences – SGGW, ul. Nowoursynowska 159, 02-776 Warsaw, Poland

[b] Department of Plant Ecology and Environmental Conservation, Institute of Botany, Faculty of Biology, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland

[c] Department of Limnology and Biological Oceanography, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria

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ABSTRACT

A multi-model-based study was performed in order to unravel valuable fen meadow habitats' possible exposure to eutrophication, which is expected to occur as a result of the re-saturation of degraded peat soils. The framework was tested in a 3000-ha fen-drain system to be restored in the Middle Biebrza Basin (northeast Poland), where the datasets and related models were used to delineate prospective eutrophication hotspots and nutrient transport. A 1-d hydrodynamic model and a 3-d groundwater flow model were applied to constitute the hydrological response of the fen-drain system to the prospective construction and function of weirs and spillways, which are expected to induce the increase of groundwater levels in degraded fens. A groundwater particle-tracking postprocessor was applied to delineate flow pathways and discharge zones and to determine water residence time in modelled layers. Soil and habitat maps, a high-resolution digital elevation model and historic groundwater level observations were applied to the model performance, calibration and spatial analysis of prospective eutrophication hotspots where increased eutrophication of groundwater can be expected due to the re-saturation of degraded peat soils. The study revealed that the large-scale fen rewetting that occurred as a result of surface water bodies' damming can potentially result in groundwater-driven nutrient dispersion along with an enhanced nutrient transport from a fen to the adjacent water bodies. Spatial analyses showed that, although the rewetting-driven eutrophication of *Molinia* fen meadows located in the study area is not likely, one can expect increased nutrient discharges to adjacent drains, inducing the contamination of ox-bow lakes located along the rivers. We propose the presented methodology to be applied *ex-ante* to fen-rewetting projects in strategic environmental assessments of restoration projects in order to manage the potentially negative environmental consequences of fen and river eutrophication with special regard to nutrient hotspots that are likely to occur within the rewetted fens.

1. Introduction

The restoration of degraded fens is recommended in order to increase water retention, decrease amounts of CO_2 emitted to the atmosphere and to restore habitats for threatened wetland species (Klimkowska et al., 2010; Van Diggelen et al., 2006). The drainage, a reduction of water supply to fens and declining groundwater levels are the main reasons for the loss of these ecosystems worldwide (Joosten and Clarke, 2002); therefore, the first thoughts on fen restoration circulate around the re-establishment of former hydrological conditions within these wetlands. However, as is widely recognized, the rewetting of formerly dehydrated organic soils entails the enrichment of groundwater in phosphates that become released from insoluble complexes with iron hydroxides when Fe^{3+} is reduced to Fe^{2+} under suddenly decreasing soil redox potential (Kjaergaard et al., 2012; Meissner et al., 2008; Rupp et al., 2004; Sapek et al., 2006; Zak and Gelbrecht, 2007; Zak et al., 2010). As a result, the eutrophication of habitats subjected to rewetting, as well as adjacent aquatic ecosystems of water bodies that drain particular wetland, can be expected (Baart et al., 2010; Cabezas et al., 2013;

* Corresponding author.
E-mail address: m.grygoruk@levis.sggw.pl (M. Grygoruk).

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Hessen, 2013; Wassen and Olde Venterink, 2006; Zak et al., 2004). Increased availability of phosphates within the rewetted fen (through the intensive nutrient release, transport and discharge) stimulates the productivity of the ecosystem, which might underpin — in contrast to nutrient-poor natural fens — ecosystem succession in an undesired direction (Rupp et al., 2004). Aquatic ecosystems of rivers and streams that receive nutrient-rich waters from rewetted fens face intensive macrophyte development (O'Hare et al., 2010), which alters the hydraulic features of the river channel (Bal et al., 2011; Madsen et al., 2001) and the conditions of sedimentation (Madsen et al., 2001; Schoelynck et al., 2011), resulting in changed habitat conditions for biota (Geer et al., 2012). Increased nutrient concentrations in such water bodies are likely to affect the composition of plant communities by favouring stronger competitors (shifting from submerged to emerged or floating macrophyte communities), which often leads to a loss of biodiversity of aquatic ecosystems (Scheffer et al., 2003). Such a process is especially critical for ox-bow lakes, when limited water exchange reduces their resilience to buffer eutrophication. Enhanced development and growth of in-stream macrophytes also becomes a challenge for flood mitigation (Bal et al., 2011; Geer et al., 2012; Mioduszewski and Okruszko, 2012). The increased roughness of the channel alters the flow velocity distribution and limits the active hydraulic profile, which induces the increase of water levels during summer floods.

In this regard, although the restoration of degraded fens by rewetting is generally found to be the measure that results in the improvement of the quality of the environment, the eutrophication-related challenges resulting from the rewetting of degraded fens listed above can also entail ecosystem deterioration, which should be foreseen at the level of strategic environmental assessments of fen restoration projects. The risk of ecosystem loss due to eutrophication in result of the re-mobilisation of phosphates in the resaturated muck soil is difficult to assess, due to the nonlinearity of interactions between soil solution, groundwater flow in changing saturated-unsaturated conditions, redox potential variability, geochemistry (variable availability of nutrients in soils), changing land use and the complexity of hydrological processes (Baart et al., 2010; Cabezas et al., 2013; Kjaergaard et al., 2012; Meissner et al., 2008; Rupp et al., 2004; Sapek et al., 2006; Wassen and Olde Venterink, 2006; Zak and Gelbrecht, 2007; Zak et al., 2004, 2010). However, bearing in mind that the release of phosphates from the resaturated, formerly degraded fens depends on the scale of rewetting (the increase and variability of groundwater levels), the state of the soil decomposition and the fact that nutrient dispersion depends on the directions and velocities of groundwater flow, the initial assessment of this process in a rewetted fen can be attempted *ex-ante*. As a majority of the processes driving phosphates release from the rewetted fen can be described with the use of hydrological models, the results of the modelling can be applied in the following analytical steps and integrated with the analysis of other environmental features (soils, vegetation). The results of the integrated framework analysis can be used to delineate zones of the biggest eutrophication potential – eutrophication hotspots. Moreover, such an *ex-ante* evaluation of possible nutrient dynamics in time and space of the rewetted fen-drain system also allows researchers to quantify solute transfer along with the groundwater flow towards the adjacent rivers, thus underlying the decision-making process on whether the additional measures of nutrient management in a fen-drain system are required in order to mitigate the negative effects of eutrophication. Therefore, the *ex-ante* estimation of the spatial and temporal scale of possible fen-drain system eutrophication appears to be a useful approach in environmental impact assessment procedures of wetland restoration projects.

The main goal of our study is to present the *ex-ante*, model-based framework for assessing spatial and temporal patterns of potential groundwater and surface water eutrophication with phosphates originating from the degraded peat soils (muck) subjected to the rewetting. We focus on solute discharge dynamics, both within the fen and in adjacent drains. In our study, we (i) estimate the hydrological response of the fen to rewetting with the use of hydrodynamic modelling tools, (ii) identify potential eutrophication hotspots within the rewetted fen with the use of the groundwater flow model and (iii) reveal the probable temporal, spatial and qualitative scale of eutrophication of groundwater and surface water of the subjected fen-drain system by using the groundwater flow mapping postprocessor. We apply our framework in a flag fen restoration project that started in the Biebrza Valley. The results from the model-based study are discussed as to the possible consequences of the solute-discharge-driven eutrophication of terrestrial and aquatic ecosystems, which is expected to vary in time and space and is critically important in strategic environmental impact assessments of any fen restoration project worldwide. We focus on the most valuable ecosystems of *Molinia* meadows and eutrophic ox-bow lakes, which have a high conservation priority, both in the analysed area of research as well as within international wetland conservation policies.

2. Materials and methods

2.1. Study area – fens and rewetting

The Middle Biebrza Basin, a central part of the Biebrza Valley (Fig. 1), is a vast lowland depression, formed by the glacifluvial waters of the Wurm Glaciation and filled with the peat that formed in the Holocene (Żurek, 1975). While the Biebrza Valley is the largest conservation area of alkaline fens in the EU, their status has considerably deteriorated in the Middle Biebrza Basin since the early drainage efforts. Our study area is located between the Jegrznia and Ełk Rivers, which were artificially connected by the Woznawiejski Canal (Fig. 1). The construction of this canal, along with some additional drainage facilities, started in the 1840s (Okruszko and Byczkowski, 1996). Later on, from the 1950s onward, the Middle Biebrza Basin was systematically drained, and numerous canals and ditches were designed and constructed in the area until the 1980s. Once the Woznawiejski Canal was constructed, the hydrological role of the Lower Jegrznia (downstream of Woznawiejski Canal bifurcation – Fig. 1A) and the Ełk River steadily decreased. The aquatic ecosystems of these rivers were exposed to the decreasing inflow of water from the Upper Jegrznia. Multiple, natural ox-bow lakes appeared, as the reduced flow energies even in the peak discharge seasons were not strong enough to facilitate water exchange between the main channel and side arms of the rivers. Discharge measurements revealed that approximately 80% of the Jegrznia's discharge was captured by the Woznawiejski Canal (Fig. 1A), and only the remaining 20% has flowed into the old channel of Jegrznia (Mioduszewski et al., 1996).

The intensive draining role of the Woznawiejski Canal resulted in the continuing dehydration of adjacent fens whose soils had turned into muck. Drained fens have been transformed into fen meadows, turning from peat-forming into peat-losing (decomposing) systems, releasing CO_2 into the atmosphere and gradually losing nutrients from the mineralised peat into the ground and surface water (this process is, however, spread in time in contrast to the sudden nutrient flush that occurs after fen rewetting). Drainage, combined with the long-term hay removal by mowing, have induced P and K limitations in part of the analysed system (De Mars, 1996, Olde Venterink et al., 2009), thus developing relatively low-productive habitat conditions (Wassen, 1995). Thanks to this scenario, despite extensive drainage, a considerable part of the study