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Effects of salinity gradients on benthic invertebrate and diatom communities in a German lowland river

Maria Schröder[a,*], Martin Sondermann[a], Bernd Sures[a,b], Daniel Hering[a,b]

[a] Department of Aquatic Ecology, University of Duisburg-Essen, Universitätsstraße 5, 45141 Essen, Germany
[b] Centre of Water and Environmental Research (ZWU), University of Duisburg-Essen, Universitätsstraße 5, 45141 Essen, Germany

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ABSTRACT

The Lippe is a lowland river located in the Western part of Germany and has been heavily impacted by coal mining activities ever since. Although mining activities significantly decreased during the last decades, the associated discharge of salt-enriched mine water into the river still poses a persistent threat to the local benthic invertebrate and diatom communities. To analyze the effect of salt pollution on invertebrate and diatom species, biological and chemical data were compiled for this study from a publicly available database. Changes in the community composition due to increased salt concentrations were explored by Non-Metrical-Multidimensional Scaling. Indicator species and salinity thresholds for single species and communities were identified using the method TITAN (Threshold Indicator Taxa Analysis). The method is an analytical approach to detect changes in frequency and abundance of species along an environmental gradient by combining the methods of change point analysis (nCPA) and indicator species analysis. The obtained salinity preferences and individual and community thresholds were compared to the literature and existing salinity classifications. For both diatoms and benthic invertebrates, Non-Metrical-Multidimensional Scaling showed a clear split between samples of high and low salinities. Significant salinity thresholds were determined for 50 invertebrate and 58 diatom species of which 23 respectively 18 species were described as 'reliable' indicators according to the specifications given by Baker and King (2010). A majority of salt-tolerant indicator organisms were invasive species. For both organism groups, major changes in community composition were detected at a conductivity value exceeding 900 μS/cm. A reduction of the average salinity to below this threshold may have positive effects on the overall species richness and the persistence of sensitive taxa in the river Lippe. Individual and community thresholds may however be data-dependent to a certain degree and subjected to fluctuations considering the potential interdependencies between salinity and additional physico-chemical and environmental parameters (e.g. water temperature, lime content).

1. Introduction

Salinity is a principal component of all water bodies and has been regarded as one of the most important factors influencing biological assemblages (Williams, 1987; Piscart et al., 2005; Kefford et al., 2012b). Salinity tolerance varies profoundly between species. While some species are known to be salt-tolerant, others react sensitively to increasing salinity levels sometimes even ending up in a decline or disappearance of the population (Williams and Williams, 1998; Piscart et al., 2006b). Accordingly, aquatic biota have been commonly classified by salinity preferences. Beside a general division between freshwater, brackish and marine taxa (Remane and Schlieper, 1971), many classification schemes, which evolved over the last decades, more explicitly describe the salinity preferences of macroinvertebrate (e.g. Wolf et al., 2009) and diatom species (e.g. Hustedt, 1953; Ziemann, 1971; Van Dam et al., 1994; Dell'Uomo, 2004).

Salinity refers to the total concentration of dissolved inorganic ions in water and is usually measured as the capacity to conduct electrical current (electrical conductivity, EC). The composition and quantity of dissolved ions is highly variable and related to natural sources and anthropogenic pressures within the catchment. The key natural drivers of salinity in freshwater systems reflect climate conditions and the geology within a catchment, as well as its topography, vegetation and proximity to the sea (Cañedo-Argüelles et al., 2013). As opposed to the gradual natural salinization of rivers, various anthropogenic pressures are posing an immediate threat to freshwater communities. Consequently,

* Corresponding author. Tel.: +49 2011834724.
E-mail address: maria.schroeder@uni-due.de (M. Schröder).

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human-induced salinization has been considered one of the crucial factors to impact freshwater ecosystems (Millennium Ecosystems Assessment, 2005). In a recent review, Cañedo-Argüelles et al. (2013) emphasize various sources of secondary salinization, including irrigation measures for agriculture (Williams, 1999; Crosa et al., 2003), mining activities (salt and coal) and the discharge of industrial waste water into the river (Kefford, 1998a).

Adverse effects of salinization for aquatic species include the impairment of physiological processes such as the maintenance of their osmotic homeostasis and associated changes in community composition (Waterkeyn et al., 2008). Salinization is a major factor affecting species richness by causing shifts from salinity-sensitive taxa to communities with few tolerant taxa adapted to increased salinity levels (Piscart et al., 2005). Many freshwater species are osmoconformers; thus, their energy demand increases with salinity to maintain an adequate internal osmotic pressure relative to the surrounding environment. The osmoregulatory mechanisms are likely being affected if salt concentrations in the surrounding medium become too high, requiring an increasing osmoregulatory effort and associated energy demand, and leading to cellular damage and ultimately death of single specimens and entire populations. Beside an increased osmotic stress directly determining the viability of populations, stress induced responses of aquatic organisms include shifts in feeding type composition (Kefford et al., 2012), the impediment of growth (Roller and Stickle, 1985), as well as the impairment of different stages within the insect live cycle such as oviposition, pupation and emergence (Piscart et al., 2006). Moreover, salinization was found to enhance the establishment of exotic invasive species (Piscart et al., 2005b; Braukmann and Böhme, 2011), with brackish water species (i.e. osmoregulators) colonizing freshwater ecosystems.

Recent studies highlight the need to identify threshold values of salt stress for river biota (King and Baker, 2010; Petty et al., 2010). Compiling quantitative and statistically significant information about species-specific salinity thresholds and cumulative community response seems crucial to estimate the biological impact associated with the commonly predicted increase in salt pollution. Species-specific thresholds for example may prove useful to further delineate and describe the conservation value of single sensitive species. They provide an indication, as to whether and when species are likely to be affected by changing salinities or on future invasions of salinity-tolerant species. Especially community thresholds may prove useful for river management to link present conditions or predicted changes in salinity to community composition and thus adjust measures or prioritize areas of special conservation need. Information about community thresholds may furthermore be used to adjust generalized levels of salt pollution for rivers in Germany as they are given in the chemical guidelines implemented under the Water Framework directive.

Respective case studies about how river biota associate to salinity are, however, rare. This might be due to the lack of rivers showing a distinct salinity gradient within a small geographical scale. Against this background, the lowland river Lippe represents an ideal system to study the effects of salinization on aquatic organisms. During the last century, the Lippe catchment has been significantly influenced by the preceding development of coal mining activities (Brüggemeier, 1994). To gain access to the coal seams in deeper ground layers (>1000 m) it was necessary to continuously pump saline groundwater from the nearby mining shafts to the surface. The drainage of salt-enriched mine water involved subsequent flooding measures of adjacent areas or the direct discharge into the river, which both led to increased NaCl concentrations. Although coal mining activities significantly decreased over the last decades, pumping activities and the salt concentration still remains high and frequently exceeds the reference concentration for chloride of <200 mg/L (~1200 μS/cm) set by German national authorities as a quality target under the Water Framework Directive (LAWA, 2014) in large lowland rivers.

The main objective of this study was to analyze the effect of salt pollution on the macroinvertebrate and diatom communities of the river Lippe. More specifically, we attempt to derive salinity thresholds for single species and communities in order to determine ecological change points related to increasing salt concentrations more accurately. Furthermore, we aimed at identifying indicator taxa that are influenced by either increasing or decreasing salinity loads and at comparing our results to existing classifications.

2. Material and methods

2.1. Catchment and data

The Lippe is a large lowland river and a tributary of the Rhine situated in the Western part of Germany with an overall length of 220 km and a catchment area of approximately 4890 km^2. Our study focused on the lower and middle course of the Lippe, where water quality is frequently impaired by coal mining activities causing increased salinity concentrations (Petruck and Stöffler, 2011). Predominant bottom substrates are sand and loam, interspersed with a variable amount of organic material (Pottgiesser and Sommerhäuser, 2004).

We compiled macroinvertebrate and diatom samples and corresponding chemical data (electrical conductivity, total phosphorus) from the publicly available database "ELWAS-WEB" (www.elwasweb.nrw.de, Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (LANUV)). We included all stations in the middle and lower course of the Lippe where biological samples were taken (macroinvertebrates and/or diatoms) and electrical conductivity was measured. In case of macroinvertebrates, the data was collected using Multi-Habitat-Sampling (Haase et al., 2004). A total of 20 sampling units were taken based on the relative proportion of different habitats on the river bottom using a 25 cm × 25 cm frame shovel sampler (500 μm mesh). All samples were pooled and preserved with 96% ethanol in the field and subsequently processed in the lab. At least, 350 specimens were identified to species level (for a detailed description of the method, see Haase et al., 2004). Diatoms were collected based on the PYHLIB method (Schaumburg et al., 2004). A total number of 10 stones were removed from the river bottom from zones of intermediate current velocities at low flow conditions. Overall, 400 specimens were determined to species level.

The electrical conductivity measured at times of sampling reflects the NaCl content of the river (linear regression with $R^2 = 0.959$) and was used as a proxy for the overall salinity. Salinity values ranged between 664 μS/cm and 2360 μS/cm. Our analyses are based on a dataset for macroinvertebrates comprising 16 monitoring stations with 41 samples and a dataset for diatoms covering 19 monitoring stations with 31 samples recorded between 1995 and 2013.

We calculated the saprobic index for all macroinvertebrate samples prior to our analyses to exclude samples from sites strongly affected by organic pollution using the assessment software ASTERICS (AQEM Consortium, 2006, version 4.0.2). The calculations yielded good or moderate saprobic results, hence no samples were omitted. As high nutrient loads may mask the effect of salinity on the biota, we calculated the Spearman correlation coefficient for total phosphorus and EC using the Software R (R Development Core Team, 2005, version 3.1.0). This calculation refers to 31 samples where total phosphorus has been measured in addition to the electrical conductivity.