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Editorial

Aquatic interfaces and linkages: An emerging topic of interdisciplinary research

Motivation

The interfaces between terrestrial and aquatic ecosystems have recently been the subject of several interdisciplinary special issue publications (Fleckenstein et al., 2010; Krause et al., 2014, 2009) as well as key seminal review and vision papers (Boano et al., 2014; Cardenas, 2015; Harvey and Gooseff, 2015; Krause et al., 2011; 2017; Lewandowski et al., 2015; Rosenberry et al., 2015; Ward, 2016). This special issue makes new contributions to limnology and water science by presenting 15 papers that investigate the complex interactions between the physical, biogeochemical, and ecological processes occurring at aquatic interfaces across a range of different spatial and temporal scales. Aquatic interfaces are of increasing interest in aquatic science because they play a key role in the interlinking of inland waters to the terrestrial environment as well as in the regulation of matter and energy fluxes within aquatic ecosystems. Therefore, the processes that occur at aquatic interfaces not only control the ecological state of freshwater ecosystems but also act as sinks and sources for matter fluxes at the landscape level (Blodau et al., this issue; Krause et al., 2017; Premke et al., 2016).

What are aquatic interfaces?

Aquatic interfaces are often characterised by steep physical and biogeochemical gradients that lead to disproportionally high reaction and turnover rates (Belnap et al., 2003; Krause et al., 2017; McClain et al., 2003). These steep gradients are formed through the hydraulic connectivity between contrasting environments. Owing to their high turnover and processing rates relative to those for the surrounding environments, aquatic interfaces are often described as biogeochemical “hot spots” (McClain et al., 2003) or, more recently, as “control points” (Bernhardt et al., 2017). Aquatic interfaces create distinctive habitats and are hot spots with regards to organism density and diversity. Vice versa, micro- and macro-organisms can actively alter the structure and functioning of aquatic interfaces (Lewandowski et al., 2007), thus acting as the primary drivers for the establishment of redox gradients (Lau et al., this issue). Tube-dwelling chironomids, for instance, were found to act as “ecosystem engineers” (Hölker et al., 2015), generating hot spots for element cycling both by forming new oxic-anoxic interfaces in sediments (Kristensen, 2000) and, in the case of a few species, by biodepositing pelagic organic particles (Graf and Rosenberg, 1997). Aquatic interfaces cover a broad spectrum of spatial scales, spanning several orders of magnitudes from the millimetre scale to the kilometre scale (Krause et al., 2017; Marion et al., 2014). Examples of interfaces highly relevant for aquatic ecosystems are wetlands, which act as semiaquatic boundaries between the terrestrial and aquatic environments (Zak et al., 2011); the groundwater-surface water interface and the hyporheic zone (Krause et al., 2017, 2011); the littoral zones of lakes (Périllon et al., this issue); the air-water interface (McGinnis et al., 2015); pelagic boundaries such as different pycnoclines (Kreling et al., 2017); the sediment-water interface (Jensen et al., 2017; Lau et al., this issue); and biofilms or particle (aggregate)-water interfaces (Simon et al., 2002). Larger-scale interfaces usually include a multitude of smaller-scale ones. Based on several new interdisciplinary studies as well as the existing theories for terrestrial ecosystems, new concepts are currently being developed for aquatic interfaces (Krause et al., 2017; Marion et al., 2014). The collection of articles in this special issue confirms that the application of field data and novel monitoring techniques (Folegot et al.; Johansen et al., both this issue) as well as the progress made in analytical experimental methods (Graeber et al,; Vu et al., both this issue) in combination with the development of novel mathematical modelling approaches (Broecker et al,; Hajati et al.,; Pöschke et al., all this issue) and the use of the appropriate statistical tools (Lischeid et al., this issue) has yielded new insights into the processes that determine the impact that aquatic interfaces have on matter flow between the interacting adjacent ecosystems.

Importance of aquatic interfaces for functioning of aquatic ecosystems

Although aquatic interfaces play a pivotal role in controlling the ecological state of freshwater ecosystems and their resilience to environmental changes, they occupy a comparably small area or volume (Cadenasso et al., 2003). The localisation and quantification of their turnover capacities at various spatial scales is a crucial prerequisite for predicting the development of aquatic systems under changed climate and land use conditions as well as for the refinement of sustainable management strategies. Aquatic interfaces perform several ecosystem services, and the maintenance of “healthy” and “functional” interfaces should be included when proposing management strategies (e.g., as basis for the definition of critical loads and

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thresholds for regime shifts). The focus of ecological engineering is often on modifying processes in aquatic interfaces such that water quality targets are achieved in the most efficient manner. Well-known examples of efforts to influence natural interfaces include the rewetting of wetlands to restore their function as sinks for nutrients and carbon (Zak et al., 2017), the use of precipitants for lake restoration in order to increase the capacity of the sediments as a sink for phosphorus (Lürling et al., 2016), the planting of macrophytes in the littoral zone to re-establish the clear-water state of a lake (Hilt et al., 2006), and the hydrological reconnecting of streams with their terrestrial environment to revitalise their sink function (Graeber et al., this issue). Wetlands constructed for removing nutrients (Vymazal, 2007), buffer zones along streams in agricultural landscapes for nitrate removal (Mander et al., 2005), and technical interfaces such as waste water treatment plants in urban environments (Gessner et al., 2014) are all examples for artificial interfaces designed to optimise natural processes. On the other hand, the effects of anthropogenic factors and other disturbances on such interfaces modify their function, often with negative consequences for the aquatic environments and the usage of water resources (Briggs et al.; Johansen et al.; Périllon et al; Vu et al., all this issue). Aquatic interfaces and their interactions often mitigate the impact of the surrounding such that disturbances or changes lead to a nonlinear response in the aquatic systems. For example, a statistical analysis of a comprehensive data set for 62 kettle holes (glacially formed small natural ponds), which were strongly linked with the terrestrial environment, has shown that the internal interface processes can mask the expected strong effects of external nutrient loading (Lischeid et al., this issue).

Impact of flow pattern and water level fluctuations on aquatic organisms

The localisation of the relevant interfaces is often complicated because of small and large scale heterogeneity and the short-term hydrological changes in the landscape. Disproportional high activity at a few sites may be irrelevant in the cases where these points are not connected strongly with the transport processes across the systems. Therefore, recent research efforts have been directed towards determining the water flow pattern (source area contributions, residence time contributions, and dynamic mixing ratios under transient forcings) mainly across the groundwater-surface water interface using tracers and different types of mathematical models in combination (Broecker et al,; Hajati et al.; Pöschke et al.; Vu et al., all this issue). Pöschke et al. (this issue) showed that, in the case of Lake Stechlin, the geologic structure of the catchment aquifer may influence the lake's mass balance more than the variability in the precipitation, evaporation, and other hydrologic quantities. In contrast, in a comprehensive study of Lake Hampen, the authors reported a flow reversal after a three-year period with low precipitation, so that the exchange fluxes across the lake-groundwater interface changed flow directions from the discharge (or inflow) to the lake to outflow from the lake (Hajati et al., this issue). The hydrological dynamic arising owing to seasonal changes and episodic events (floods) connect and reconnect systems and interfaces (Harjung et al., this issue) and can result in the development of "hot moments," which are defined as short periods of enhanced reaction rates within a longer time span (McClain et al., 2003). Such hot moments could include the pulse-like mass transport across aquatic interfaces triggered by heavy precipitation or the first flush after the rewetting of dried sediments.

Impact of aquatic interfaces on freshwater organisms

Organisms and ecological communities at aquatic interfaces are strongly influenced by water level fluctuations (Wantzen et al., 2008). Data from 35 Danish wetlands indicate that their water level variability limited the species diversity of macrophytes in the wetlands (Johansen et al., this issue). The impact of contaminated groundwater on benthic communities is the subject of a paper by Roy et al. (this issue). This study is important for the further development of field methods because the tests were affected by the complexity of the investigated problem and the associated uncertainties, such as small-scale heterogeneities and the appropriate method for finding suitable reference sites. In contrast, Périllon et al. (this issue) found clear indications that epiphyton growth is enhanced at sites where there is an influx of groundwater into a lake. It was hypothesised that the stimulation of epiphyton growth because of the nutrient supply via the groundwater may have induced a feedback mechanism, leading to a shift in the macrophyte composition from charophyte species to macrophytes typical for eutrophic lakes. In addition to the substances transported via groundwater, the temperature could be an abiotic factor of importance for the organisms found by Briggs et al. (this issue) in the case of cold fish species living in niches influenced by groundwater. They concluded that the impact of climate change will substantially reduce the cooling capacity because of groundwater seepage. Related to temperature controlling by interfaces, Folegot et al. (this issue) show experimentally that the interactions between water level variations and macrophyte coverage affect stream bed and water temperature patterns. Based on a comparison of contrasting forested microcatchments and using leaf bag studies, Guevara et al. (this issue) show that riparian vegetation and forest activities can affect the functional role of plants and benthic invertebrates and the nutrient fluxes downstream.

Future challenges

As shown in the special issue an improved understanding and a quantification of the matter flux across various reactive zones in the landscape needs both empirical investigations at the field and laboratory scales and new modelling approaches. Currently, the gap between ever-more detailed basic research at the very small scale and the use of these findings to elucidate the quantitative role of aquatic interfaces at the landscape level seems to be increasing. The upscaling of these processes remains a largely unresolved challenge and can only be tackled by forging a closer link between studies on the processes and modelling. Additionally, groundwater and lake water models are still poorly linked. There is a need for development and application of reactive transport model that can help improve our understanding at the aquatic interfaces by linking hydrological and biochemical processes and for better-linked regional-scale groundwater-surface water models that can help predict the turnover and export of matter in and from a catchment. More systematic research need to be paid to the previously disregarded role of groundwater as a source of nutrients in lakes. One of the central problems related to research on aquatic interfaces is the spatial heterogeneity. Neglecting this heterogeneity can lead to the over- or underestimation of the quantitative importance of matter transport. Therefore, there is an urgent need to identify the effects of the small-scale spatial heterogeneity of aquatic interfaces on the exchange fluxes as well as transformation. In addition, the monitoring of processes at such interfaces requires the determination of patchiness through novel and innovative sensing technologies that can cover different spatial heterogeneities and short-term temporal fluctuations. These include using automatic sensors loggers and remote sensing methods for recording data in real-time and to monitor rapid flow alterations or changes in water quality. Research on aquatic interfaces is of increasing importance for sustainable water management. However, this will require the fast transfer of new scientific knowledge into practice. On the other hand, the sites manipulated for management measures are ideal as "field labs" for empirical research for understanding the function and efficiency of aquatic interfaces. A promising direction in the research on aquatic interfaces is the focus on their function as a "control point" in a changing world. The impact of climate change is