Environ Earth Sci (2017) 76:549
DOI 10.1007/s12665-017-6863-7

EDITORIAL

Water research in Germany: from the reconstruction of the Roman Rhine to a risk assessment for aquatic neophytes

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Received: 24 May 2017 / Accepted: 26 July 2017

Abstract Germany does not only have a long tradition in water research, but a very active community of scientists and practitioners working on a vast range of "water topics." This thematic issue, which was initiated by four water-related research associations (German Hydrological Society; German Limnological Society; Hydrological Sciences Commission within German Water Association; Working Group Hydrology within German Geographical Society), is a testimony of both the quality and diversity of the water research currently undertaken by Germany's scientific community. Key topics include hydrology and hydromorphology; water quality; aquatic and riparian ecosystems; water in agriculture and forestry; and water management and supply. The manuscripts contained in this thematic issue do not only cover a period of more than two millennia, but also address all types of water resources and a multitude of both established and newly developed methods that help us to better understand the processes governing the hydrological cycle, aquatic ecosystems and the management and operation of various water infrastructures.

Introduction

Located in the heart of Europe, Germany is characterized by a moderately humid and temperate climate. While the average precipitation is about 790 mm per year, the higher mountain ranges receive significantly more rain and snowfall (sometimes more than 2000 mm per year), whereas the North German Lowlands are drier with typical averages between 500 and 700 mm. Moreover, with an increasingly continental climate from west to east, precipitation decreases eastward (Irmer and Kirschbaum 2010).

Germany is generally considered to be a country that is rich in water resources, with an annual water availability of about 188 billion m^3, and a usable water availability of 2292 m^3 per person and year. Even though some regions have temporarily limited water supplies, the extraction and distribution systems are currently able to meet the water demand throughout the country (Irmer and Kirschbaum 2010).

Three major international river basins occupy significant parts of Germany. While the Rhine and the Danube are fed by several tributaries from the Alps, the Elbe has its source in the Giant Mountains (Krkonoše) in the Czech Republic. Both Rhine and Elbe flow into the North Sea, while the

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Published online: 14 August 2017

Danube is the only major river system draining into the Black Sea (Irmer and Kirschbaum 2010).

Germany's rivers have a long history of usage and modifications. Anthropogenic influences accelerated greatly during the industrial age and have completely changed the landscapes and ecosystems in and around all major lowland rivers in Germany. It is therefore no surprise that the massive degree of this human impact on nature even became the topic of the bestseller "The Conquest of Nature: Water, Landscape, and the Making of Modern Germany," which describes the modification of the Rhine with the following words:

> The river itself looked quite different in 1750. It did not even flow in the same places. Unlike the familiar modern artery, engineered to flow swiftly in a single channel, between embankments, the eighteenth-century river meandered over its floodplain or made its way through hundreds of separate channels divided by sandbars, gravel banks and islands (Blackbourn 2007:2).

However, Germany does not only have a long history of environmental—including hydrological—modifications, but also a rich tradition of water-related research. This thematic issue provides insights into current research in hydrology, hydrogeology, water quality, aquatic and riparian ecosystems, water usage in agriculture and forestry, and water management and supply in Germany. The diversity of contributions, which range from the reconstruction of hydrology in ancient times to the development of next generation methods in water monitoring, and from specific regional case studies to national-level syntheses, are all exemplary for the multidisciplinary approaches that characterize contemporary water research in Germany. Figure 1 visualizes the thematic range based on the occurrence of keywords in the titles and abstracts of the manuscripts.

The idea for this thematic issue was jointly developed by co-editors representing four water-related research associations in Germany: the Working Group Hydrology within German Geographical Society, Hydrological Sciences Commission within German Water Association, German Limnological Society and German Hydrological Society (see Table 1).

The following sections provide a structured overview of both the current state of knowledge and the contributions contained in this thematic issue.

Hydrology, hydromorphology and hydrogeology

Germany's landscape ranges from *high alpine terrain* in the south to *extended lowlands* in the north. The lowlands in Northern Germany are underlain by unconsolidated quaternary sediments with extended groundwater resources. Their hydrological conditions are mainly characterized by complex groundwater–surface water interactions, and the presence of many lakes of various scales even complicates the situation. Contrastingly, the Bavarian Alps show isolated, often unproductive groundwater resources including some karstic aquifers. In the higher mountainous and alpine regions, snow plays a major role. The delayed release of meltwater supports a reliable water supply for ecosystems and human needs, and influences streamflow (including the occurrence of floods and low flows) even much further downstream. Significant precipitation amounts, which can exceed 2000 mm/a in high elevations, and frequent and heavy rainfall during summer regularly result in fast and strong hydrological responses including flash floods. A number of *low mountain ranges* (called *Mittelgebirge* in German), where elevations reach a maximum of 1500 m a.s.l., extend between these contrasting landscapes. According to their orientation with regard to the large-scale circulation patterns, precipitation conditions

Fig. 1 Word cloud showing the most frequently used expressions in this thematic issue (based on titles and abstracts)

Table 1 Water-related research associations in Germany which initiated this thematic issue

German Hydrological Society (DHG)	
Founded in	2011
Main goals	Improvement of hydrological knowledge as part of environmental protection
	Investigation of the hydrological processes and water balance
	Exchange of knowledge and experiences between research and practice
	Support of young academics in hydrological sciences
Web site	http://www.dhydrog.de/
Representing co-editors	Prof. Dr. Lucas Menzel, Department Hydrology and Climatology, Institute of Geography, Heidelberg University, Germany
	Prof. Dr. Markus Weiler, Chair of Hydrology, Freiburg University, Germany
German Limnological Society (DGL)	
Founded in	1984
Main goals	Exchange between researchers and practitioners involved in aquatic ecosystem management, the scientific exploration and protection of inland waters
	Organization of scientific conferences including proceedings; co-publication of books and journals in cooperation with other organizations (e.g., Limnologica, Limnologie Aktuell)
	Training and education, funding of excellent students
Web site	http://www.dgl-ev.de
Representing co-editors	Dr. Uta Raeder, Limnological Research Station Iffeldorf, Aquatic Systems Biology, Technical University Munich, Iffeldorf, Germany
	Dr. Mario Sommerhäuser, Emschergenossenschaft/Lippeverband, Essen, Germany
Hydrological Sciences Commission (FgHW) within German Water Association (DWA)	
Founded in	1998
Main goals	Fostering knowledge exchange and transfer between all parts of the hydrological sciences community
	Extending and integrating the expertise of hydrologists, engineers, geographers, ecologists and limnologists in research and practice
Web site	http://www.fghw.de
Representing co-editors	Prof. Dr. Bernd Cyffka, Applied Physical Geography, Institute of Geography, Catholic University Eichstätt-Ingolstadt, Germany
	Prof. Dr. Heribert Nacken, Department Engineering Hydrology, RWTH Aachen University, Germany
Working Group Hydrology (AK Hydrologie) within German Geographical Society (DGfG)	
Founded in	1961
Main goals	Expert group for hydrological topics within German Geographical Society
	Regular exchange and discussion between junior and senior scientists working on geographically relevant water-related topics
	Cooperation with the International Geographical Union's Water Sustainability Commission and geohydrological working groups from other countries
Web site	https://akhydrologie.wordpress.com/
Representing co-editors	Prof. Dr. Peter Chifflard, Marburg University, Germany
	Dr. Daniel Karthe, Helmholtz Centre for Environmental Research, Magdeburg, Germany

can be very different, with mean annual values ranging from 500 mm on the leeward valleys of mountain ranges to more than 2000 mm on the mountain tops. The specific physiographic characteristics of most low mountain ranges, such as hillslopes with layered subsurfaces of different hydraulic conductivity, make them to important source areas for floods of different magnitude. Furthermore, the small- to meso-scale patterns of topography, precipitation, air temperature and solar radiation result in a variety of ecological conditions and complex hydrological dynamics (Chifflard et al. 2004, 2008).

Climatic variability in Germany is governed by fluctuations in large-scale pressure systems, among which the North Atlantic Oscillation (NAO) plays a dominant role (Beniston 1997). A high frequency of positive anomalies of the *NAO-index*, as observed over the last three decades, has led to milder winters and increased winter precipitation in Western Europe, with pronounced winter precipitation rises in Southern Germany and the Northern Alpine region (Schönwiese and Rapp 1997; Kunz et al. 2017). However, winter snow storage as well as snow cover duration have decreased (KLIWA 2005), and small- to meso-scale winter floods occurred frequently (Bronstert et al. 2017), with increasing rain-on-snow events (Freudiger et al. 2014). Contrastingly, drier summers have arisen in major parts of Central Europe (Schönwiese and Rapp 1997), altering low-flow conditions (Kundzewicz et al. 2005; Stahl et al. 2010). These processes are exacerbated by significantly increasing trends in air temperature which have been recorded both on the large and local scales (Deutschländer and Mächel 2017; Liu and Menzel 2016). The impact of rising air temperatures and extending vegetation periods (with higher evapotranspiration totals) on the regional hydrology are, however, not yet clear. Nevertheless, future climate change in Germany is likely to accelerate the already observed tendencies (Deutschländer and Mächel 2017; Hausmann and Nacken 2011; Kunz et al. 2017; Menzel et al. 2006). In surface water and in particular in lakes, rising temperatures are expected to modify the thermal and hydrochemical stratification as well as the ecology (Büche 2016; Büche and Vetter 2015).

In this thematic issue (see Table 2), investigations by Weber et al. in a small high alpine catchment in the Bavarian Alps show a clear correlation between snow cover duration and surface pressure, with positive anomalies of the NAO-index being accompanied by lower snow depth maxima. They predict that the future climatic conditions in the Bavarian Alps probably lead to pronounced decreases in snow storage and snow cover duration which might lead to higher probabilities of low flows, but also to the occurrence of more frequent floods when rain-on-snow events occur. The manuscript by Büche et al. discusses the suitability of a hydrodynamic model (GLM) for simulating the thermal stratification of Lake Ammersee in South Germany. The authors found the model to accurately reflect water temperatures even under unusual conditions such as the very warm summer of 2003. Their results are not only relevant for the understanding of limnophysical processes, but also for the assessment of the climate change impacts on lake ecology.

The importance of selected physiographic characteristics of low mountain ranges for flood formation is demonstrated by numerous experimental studies in German headwater basins. Heller & Kleber investigate runoff processes in the Ore Mountains, on hillslopes underlain by periglacial cover beds, one of the typical structural elements of many lower mountain ranges of the mid-latitudes. Their small-scale measurements verify the different water flow paths under changing soil moisture conditions. They identify the deepest layer of the periglacial cover bed as critical with regard to runoff and flood formation. When antecedent soil moisture is high, this layer may trigger

Table 2 Manuscripts in the section "Hydrology, hydromorphology and hydrogeology"

Büche, T.; Hamilton, D.P. & Vetter, M. (2017): Using the General Lake Model (GLM) to simulate water temperatures and ice cover of a medium-sized lake–a case study of Lake Ammersee, Germany. Environ Earth Sci. doi:10.1007/s12665-017-6790-7

Burs, D.; Bruckmann, J. & Rüde, T.R. (2016): Developing a structural and conceptual model of a tectonically limited karst aquifer: a hydrogeological study of the Hastenrather Graben near Aachen, Germany. Environ Earth Sci. doi:10.1007/s12665-016-6039-x

Heller, K. & Kleber, A. (2016): Hillslope runoff generation influenced by layered subsurface in a headwater catchment in Ore Mountains, Germany. Environ Earth Sci. doi:10.1007/s12665-016-5750-y

Lamberty, G.; Zumbroich, T.; Ribbe, L. & Souvignet, M. (2016): Quantifying bias in hydromorphological monitoring: An assessment of the German LAWA-OS method. Environ Earth Sci. doi:10.1007/s12665-016-6241-x

Lischeid, G.; Balla, D.; Dannowski, R.; Dietrich, O.; Kalettka, T.; Merz, C.; Schindler, U. & Steidl, J. (2016): Forensic hydrology: What function tells about structure in complex settings. Environ Earth Sci. doi:10.1007/s12665-016-6351-5

Pütz, T.; Kiese, R.; Wollschläger, U.; Groh, J.; Rupp, H.; Zacharias, S.; Priesack, E.; Gerke, H.; Gasche, R.; Bens, O.; Borg, E.; Baessler, C.; Kaiser, K.; Herbrich, M.; Munch, J.-C.; Sommer, M.; Vogel, H.J.; Vanderborght, J. & Vereecken, H. (2016): TERENO-SOILCan a Lysimeter-Network in Germany Observing Soil Functions Influenced by Climate Change. Environ Earth Sci. doi:10.1007/s12665-016-6031-5

Pyka, C.; Jacobs, C.; Breuer, R.; Elbers, J.; Nacken, H.; Sewilam, H. & Timmerman, J. (2016): Effects of water diversion and climate change on the Rur and Meuse in low-flow situations. Environ Earth Sci. doi:10.1007/s12665-016-5989-3

Roggenkamp, T. & Herget, J. (2016): Middle and Lower Rhine in Roman times: a reconstruction of hydrologic data based on historical sources. Environ Earth Sci. doi:10.1007/s12665-016-5909-6

Steinbrich, A.; Leistert, H. & Weiler, M. (2016): Model-based quantification of runoff generation processes at high spatial and temporal resolution. Environ Earth Sci. doi:10.1007/s12665-016-6234-9

Trabert, A. & Opp, C. (2016): Long-term trends in flood discharges of the Ulster and Upper Fulda–a statistical review. Environ Earth Sci. doi:10.1007/s12665-016-6169-1

Weber, M.; Bernhardt, M.; Pomeroy, J.W.; Fang, X.; Härer, S. & Schulz, K. (2016): Description of current and future snow processes in a small basin in the Bavarian Alps. Environ Earth Sci. doi:10.1007/s12665-016-6027-1 rapid interflow and surface runoff. During heavy rainfall, flash floods frequently evolve on hillslopes and sealed surfaces. The damage potential of flash floods in Germany is enormous as recent examples demonstrate. Steinbrich et al. developed a runoff generation model which works on high spatial and temporal scales. It aims at better reproducing such extreme flooding events without the need of model calibration. Model testing on hillslopes with sprinkler experiments and model application in small catchments show a promising suitability of this approach. The impact of changing large-scale circulation patterns and winter rainfall regimes on the occurrence of floods was investigated by Trabert & Opp for two catchments in hilly Eastern Hesse. Their statistical analysis supports findings from similar studies distributed over Germany: upward trends of precipitation and extreme rainfall correspond with significant trends toward annual and winter maximum discharges. They detected change points for such upward trends in the late 1970s.

After a number of dry summers, low-flow analysis has become another emerging topic in Germany. Pyka et al. investigated the relationship between the frequent low-flow conditions and water quality of the Maas (Meuse) River in an explorative study. During low flow, the inflow of the Rur River, a major tributary of the Maas, helps to maintain acceptable water levels and sufficient water quality. However, it is envisaged to divert water of the Rur to flood abandoned brown coal quarries in Germany. In a scenario study of the near future, they show that the selected climate change scenarios lead to a significant reduction of summer discharge in the Maas, while rising air temperatures will adversely impact water quality. However, the reduced inflow into the Maas will have only small impacts on average. Water level recordings at major German rivers have existed for several 100 years, while very little is known about water levels and discharges of preceding times. A historical approach by Roggenkamp & Herget combined archeological findings with written documents from Roman times in order to reconstruct discharge conditions of the Middle and Lower Rhine. Their study verifies that compared with modern times mean discharge of these river sections was significantly lower during Roman times. They conclude that this can be traced back to two reasons: First, the investigated period was clearly drier as today. Second, during this time natural and spacious flood retention existed along the Upper Rhine (which got lost during the drastic river regulation measures in the nineteenth century).

The often complex nature of natural regions and hydro(geo-)logical conditions in Germany is demonstrated in three contributions within this issue. Hard rock aquifers comprise about 53% of Germany's territory. For a highly fractured and partly karstified aquifer used for public drinking water supply, Burs et al. describe the development of a 3D structural modeling with hydrogeological conceptual model building based on hydraulic and geophysical experiments. This allowed the calculation of groundwater flow volumes across lateral cross sections, but also showed the high heterogeneity of hydraulic properties in this hard rock aquifer generating high uncertainty. Lischeid et al. applied a set of complementary methods and tools of hydrological system analysis (labeled forensic hydrology) to reveal some hydrogeological features of the complex setting of unconsolidated sediments and layered aquifer systems of Northeast Germany. Pütz et al. describe the design of a new generation of lysimeters (SOILCan) applied for long-term and large-scale experiments carried out within the TERENO framework. The focus is on the quantification of the impact of climate and land-use change on typical soils and crops found across Germany. A contribution in this issue is dedicated to hydromorphological monitoring systems in Germany. Since the EU Water Framework Directive requires information for water body assessment, the monitoring of the river ecology status has become an important information source for various water management issues. Lamberty et al. discuss the applicability of different versions of hydromorphological assessment methods in Germany. A pairwise comparison between the assessment results of two representative versions of the popular LAWA-OS method show that this method is very robust against deviation factors on the overall score level.

Water quality

In natural systems, the geological background and soils on the one hand, and runoff dynamics on the other hand, are key drivers of water quality (Cyffka et al. 1989). However, in a densely populated country like Germany which is characterized by intensive agriculture and major industrial agglomerations, it is not surprising that ground and surface water bodies are also exposed to a multitude of manmade pollutants.

Even though wastewater treatment in Germany has massively improved after the 1960s (e.g., Water Act of 1960, introduction of tertiary wastewater treatment in the 1980s; Seeger 1999), high *nutrient* concentrations continue to be a major challenge. Nitrogen compounds, and in particular nitrate, are the most common deficit in groundwater quality in Germany, with about half of all monitoring sites showing signs of contamination (nitrate concentrations of 10–50 mg/l) and almost 15% exceeding the limit of the German Drinking Water Ordinance (50 mg/l) (Irmer and Kirschbaum 2010). Today, diffuse emissions from agriculture are a key source of nutrients in most receiving water bodies (Pfannerstill et al. 2012). Moreover, high nutrient loads transported into coastal waters impede the successful implementation of the EU Marine Strategy Framework Directive by Germany (Borchardt et al. 2012; Ferreira et al. 2011).

Heavy metals are sometimes still problematic in water bodies affected by heavily industrialized and mining areas. Even though emissions have considerably reduced in the recent past, river bottom sediments and floodplain soils often still contain elevated concentrations of heavy metals, including the risk of their remobilization (Zachmann et al. 2013). In major rivers such as the Rhine, bioaccumulation of such metals reached levels that led to public health concerns about the consumption of some freshwater fish such as eels (Guhl et al. 2014; Hendriks et al. 1998).

In the more recent past, "*emerging pollutants*" and their transformation products have been recognized as new challenges for water management. These often chemically complex pollutants are problematic because of their poorly understood ecological and human toxicity (e.g., pesticides or pharmaceuticals and their residues), sometimes low elimination rates by municipal waste water treatment plants, and the difficulty to assess pollution by thousands of chemical compounds via a limited set of indicator substances (Deblonde et al. 2011, Farré et al. 2008). Both in freshwater and marine ecosystems, microplastic particles are another cause of concern, partly because they are ingested and accumulated by fish and other aquatic animals (Foekema et al. 2013; Wagner et al. 2014)

Microorganisms such as bacteria and viruses have a high natural abundance and diversity in ground and surface water bodies and play an important role for matter turnover and self-purification. Both wastewater discharge and influx via diffuse sources may lead to shifts in the composition of microbial communities via increased loads of fecal bacteria and potential pathogens (Graw and Borchardt 1995). This is problematic when water bodies are used as a source for drinking or irrigation water, or when water bodies are used for water sports. Moreover, rivers are relevant as pathways for the transport of pathogenic microorganisms (Karthe et al. 2017; Reder et al. 2015), including antibiotic-resistant bacteria which originate from wastewater inputs which contain antibiotics and their metabolites (Bessa et al. 2014; Schreiber and Kistemann 2013). In aquatic ecosystems, there can even be interactions between different pollutants. For example, certain heavy metals were found to influence antibiotic resistance pathways (Seiler and Berendonk 2012).

In this thematic issue (see Table 3), Pfannerstill et al. propose a solution to the problem of nitrate exports from (fertilized) agricultural areas, which is highly necessary in regions were streams, rivers and coastal water bodies suffer from eutrophication. The authors describe "reactive ditches" as relatively inexpensive and close-to-natural bioreactors, which have the added advantage of facilitating nutrient recycling by using the natural filter materials for soil melioration on farmland. The manuscript by Hahn et al. addresses the issue of heavy metals in floodplain soils downstream a former mining area on the Lahn River. More specifically, the authors investigated the impacts of impoundment on the adsorption and mobilization of different elements, including As, Cd, Cu, Fe, Mn, Pb and Zn. Their results are relevant for both future river regulations and renaturalizations. Schimmelpfennig et al. investigated the pathways of micropollutants in Lake Tegel, Berlin, from where drinking water is produced via river bank filtration. Several pharmaceuticals were detected in the lake in problematic concentrations, and their source could be traced back to a wastewater treatment plant on one of the lake's tributaries. While carbamazepine and sulfamethoxazole concentrations were mostly reduced by dilution with water from the Havel River, diclofenac was found to be affected by both dilution and photodegradation. Three manuscripts address challenges related to waterborne pathogens. In their synthesis, Schreiber et al. sum up the results of 20 years of research on surface water microbiology in the catchment of the Swist, a small stream in the Rhine river basin. Besides presenting the results of some of the most comprehensive and systematic investigations on surface water hygiene anywhere in the world, the authors also describe the development of an event-driven sampling system (triggered by rainfall). Even more extensive is the review by Seidel et al., which provides an account of recent research findings on freshwater hygiene in Germany. Besides waterborne bacteria and parasites, the paper also addresses the role of numerous waterborne viruses, which are not only excreted in very large quantities by infected people or animals, but which are also highly infectious. A specific challenge for water surveillance is that according to WHO recommendations, very large amounts of water have to be screened. For example, even a single rotavirus particle in 90 m^3 would be considered potentially problematic for human health. This monitoring challenge is considered in the manuscript by Karthe et al., who describe a novel rapid testing system for pathogens in raw and drinking water. The system consists of several concentration stages, which can not only handle water volumes of several m^3, but also detect several types of hygienically relevant bacteria and viruses within less than 5 h, using a lab-on-chip-based sample preparation and discrimination between infectious and non-infectious microorganisms and a microarray-based isothermal amplification and detection unit.

Table 3 Manuscripts in the section "Water quality"

Hahn, J.; Opp, C.; Zitzer, N. & Laufenberg, G. (2016): Impacts of river impoundment on dissolved heavy metals in floodplain soils of the Lahn River (Germany). Environ Earth Sci. doi:10.1007/s12665-016-5950-5
Karthe, D.; Behrmann, O.; Blättel, V.; Elsässer, D.; Heese, C.; Ho, J.; Hügle, M.; Hufert, F.; Kunze, A.; Niessner, R.; Scharaw, B.; Spoo, M.; Tiehm, A.; Urban, G.; Vosseler, S.; Westerhoff, T.; Dame, G. & Seidel, M. (2016): Modular Development of an Inline Monitoring System for Waterborne Pathogens in Raw and Drinking Water. Environ Earth Sci. doi:10.1007/s12665-016-6287-9
Pfannerstill, M.; Kühling, I.; Hugenschmidt, C.; Trepel, M. & Fohrer, N. (2016): Reactive ditches: A simple approach to implement denitrifying wood chip bioreactors to reduce nitrate exports into aquatic ecosystems? Environ Earth Sci. doi:10.1007/s12665-016-5856-2
Schimmelpfennig, S.; Kirillin, G.; Engelhardt, C.; Dünnbier, U. & Nützmann, G.: Fate of pharmaceutical micro-pollutants in Lake Tegel (Berlin, Germany): the impact of lake-specific mechanisms. Environ Earth Sci. doi:10.1007/s12665-016-5676-4
Schreiber, C.; Rechenburg, A.; Koch, C.; Christoffels, E.; Claßen, T.; Willkomm, M.; Mertens, F.M.; Brunsch, A.; Herbst, S.; Rind, E.; & Kistemann, T. (2016): Two decades of system-based hygienic–microbiological research in Swist river catchment (Germany). Environ Earth Sci. doi:10.1007/s12665-016-6100-9
Seidel, M.; Jurzik, L.; Brettar, I.; Höfle, M.G. & Griebler, C. (2016): Microbial pathogens in freshwater–current research aspects studied in Germany. Environ Earth Sci. doi:10.1007/s12665-016-6189-x

Aquatic and riparian ecosystems

Aquatic and riparian ecosystems play an important role not only for nature conservation but also for human well-being. This explains why the Water Framework Directive (WFD 2000/60/EC; WFD) and the Habitat Directive (FFH 92/43/EEC; HD) of the EU address both topics. In fact, the protection and development of both aquatic and riparian ecosystems are key objectives of both directives.

Currently, *riverine floodplains* receive considerable attention by both scientists and water managers in the context of climate change adaptation. In Germany, massive losses of ecologically functional floodplains have occurred over the last two centuries, with significant consequences for flood retention. At the same time, their remnants of riparian ecosystems often suffer from reduced flow dynamics, which are results of hydrological modifications such as embankment or channelization (Mosner et al. 2015). Even though various drivers influence riparian vegetation pattern and diversity, seasonal flow timing and dynamics are of particular importance (Greet et al. 2011; Fraaje et al. 2015).

The complex human impacts on river systems are not restricted to floodplain vegetation but also affect *aquatic biota* (Peipoch et al. 2015; Stendera et al. 2012). For example, flow regulations due to hydropower dams frequently lead to the phenomenon of "hydropeaking" with abrupt runoff changes occurring at controlled intervals (which may even be several times per day). However, the consequences for affected aquatic and riparian ecosystems may be ameliorated by mitigation measures (Hauer et al. 2016). An aspect that is strongly interlinked with hydrological dynamics is *hydromorphology*. The geometry of river beds and floodplains is shaped by the sequence of different flows and in particular by recurrent floods (Eltner et al. 2016). Recent studies often focused on specific phenomena such as bar–bank interactions and their role in channel forming (Klösch et al. 2015).

In recent years, it has been recognized that despite massive improvements in water quality, the ecological state of many streams and rivers in Germany has not improved likewise; only about 10% of all surface water bodies currently have a good ecological status (Borchardt et al. 2012; Völker et al. 2013). While hydromorphological modifications were identified as a key reason for these ecological deficits, it also became clear that river/stream and floodplain restoration are necessary (Jähnig et al. 2011). *Ecological indicators* are required for both management planning and the evaluation of restoration success (Pander and Geist 2013; Müller et al. 2014). These include in particular the fish, benthic invertebrates, macroalgae, phytobenthos and phytoplankton communities (Arle et al. 2016; Hering et al. 2003; Kail et al. 2015; Seele et al. 2000). While a high biodiversity in these groups is generally desirable, the introduction and establishment of invasive species in German rivers and lakes appears to be a growing and probably underestimated problem (Hoffmann et al. 2013).

Hydromorphological improvements were found to be more difficult to realize than improvements in water quality, partly because it is difficult to assess the benefits of hydromorphological river restoration at different timescales (Sewilam et al. 2007; Pander et al. 2017). Another difficult task is the *ecological restoration of floodplains*, but results from a large field laboratory along the Danube River have shown promising results (Stammel et al. 2012; Cyffka et al. 2016).

In this thematic issue (see Table 4), several manuscripts advance the current state of knowledge on aquatic and riparian ecosystems and their management in Germany. Two papers deal with specific habitats, namely groundwater and spring ecosystems.

Table 4 Manuscripts in the section "Aquatic and riparian ecosystems"

Griebler, C.; Brielmann, H.; Haberer, C.M.; Kaschuba, S.; Kellermann, C.; Stumpp, C.; Hegler, F.; Kuntz, D.; Walker-Hertkorn, S. & Lüders, T. (2016): Potential impacts of geothermal energy use and storage on groundwater quality, biodiversity and ecosystem processes. Environ Earth Sci. doi:10.1007/s12665-016-6207-z
Hoffmann, M. & Raeder, U. (2016): Predicting the potential distribution of neophytes in Southern Germany using native Najas marina as invasion risk indicator. Environ Earth Sci. doi:10.1007/s12665-016-6004-8
Reiss, M.; Martin, P.; Gerecke, R. & von Fumetti, S. (2016): Limno-ecological characteristics and distribution patterns of spring habitats and invertebrates from the Lowlands to the Alps. Environ Earth Sci. doi:10.1007/s12665-016-5818-8
Stammel, B.; Fischer, P.; Gelhaus, M. & Cyffka, B. (2016): Restoration of Ecosystem Functions and Efficiency Control: Case Study of the Danube Floodplain between Neuburg and Ingolstadt (Bavaria/Germany). Environ Earth Sci. doi:10.1007/s12665-016-5973-y
Wollschläger, U.; Attinger, S.; Borchardt, D.; Brauns, M.; Cuntz, M.;D ietrich, P.; Fleckenstein, J.H.; Friese, K.; Friesen, J.; Harpke, A.; Hildebrandt, A.; Jäckel, G.; Kamjunke, N.; Knöller, K.; Kögler, S.; Kolditz, O.; Krieg, R.; Kumar, R.; Lausch, A.; Liess, M.; Marx, A.; Merz, R.; Müller, C.; Musolff, A.; Norf, H.; Oswald, S.E.; Rebmann, C.; Reinstorf, F.; Rode, M.; Rink, K.; Rinke, K.; Samaniego, L.; Vieweg, M.; Vogel, H.J.; Weitere, M.; Werbau, U.; Zink, M. & Zacharias, S. (2016): The Bode hydrological observatory: a platform for integrated, interdisciplinary hydro-ecological research within the TERENO Harz/Central German Lowland Observatory. Environ Earth Sci. doi:10.1007/s12665-016-6327-5

Griebler et al. examined the impact of geothermal energy use on groundwater biodiversity and ecosystems. The authors identified a temperature rise of 5 K as potentially problematic for the groundwater fauna, with species emigration or extinction as potential consequences. They predicted the most severe consequences for groundwater bodies with high nutrient and/or heavy metal contents (e.g., in urban or agricultural areas) but acknowledged that additional research on this topic is necessary. The colonization of spring habitats with invertebrates was analyzed via a synopsis of case studies by Reiss et al. While the authors identified a regional faunistic differentiation of such habitats, they predicted changes in the faunistic composition and a loss of crenobionts due to climatic and land-use trends. Even though springs are suitable sentinels for environmental change, more long-term monitoring is essential to come to scientifically sound conclusions.

Reporting on the Bode hydrological observatory, Wollschläger et al. demonstrate how major research institutions can contribute to the *hydroecological knowledge* by the results of long-term measuring programs. The study region of the Bode catchment in Central Germany is currently one of the best monitored river basins in Germany, with research facilities for meteorology, hydrology and hydrogeology.

The current challenge of invasive species is addressed by Hofmann & Raeder, who investigated the occurrence of the macrophyte *Najas marina* (spiny water nymph) as an indicator of neophyte invasion risks in Bavarian Lakes. While 11 aquatic neophyte species are currently known to exist in South Germany, the authors identified rising temperatures as the key reason for a greater invasion potential in the future.

The manuscript by Stammel et al. addressed the restoration of floodplains along the Danube and highlighted the necessity to (a) consider ecosystem functions and (b) to constantly monitor the efficiency of restoration measures via an integrative set of indicators. Besides ecological floodings, the authors investigated the role of groundwater control and its influence on the growth of different wetland plant species and concluded that the latter is an important parameter for managed floodplain restoration.

Water in agriculture and forestry

Germany is a country where forests and agricultural land cover about 31 and 52% of the total surface area, respectively. It is therefore not surprising that research in forest and agricultural hydrology has a long tradition (e.g., Friedrich 1967; Mitscherlich 1971). Forests are not only relevant for the hydrological cycle at various scales, but play a particularly important role for water retention, typically delaying the effects of strong rainfall and runoff generation. Moreover, in densely settled countries such as Germany, forests are important zones for the formation of unpolluted groundwater (Chang 2013). Agriculture, on the other hand, is not only one of the most important water users, but also plays a significant role for pollution by nutrients and agrochemicals.

Forest hydrology deals with two natural resources that are crucial for the environment and human survival (Chang 2013), and their interlinkages have traditionally been an important aspect for hydrological research in Germany. Some of the earliest research studies worldwide in forest hydrology were carried out in Germany, including investigations into the links between precipitation and interception (Friedrich 1967). Today, the field of forest hydrology covers both basic scientific and applied research. Numerous experimental studies are characterized by a *cause-and-effect approach*. The objective of these studies is mainly to understand the functioning of the hydrological cycle in forest watersheds (e.g., Herbst et al. 2015), to compare the differences of hydrological phenomena among forest catchments (Chifflard et al. 2014), or to find explanations for the linkages and the controlling factors between the different ecological components (climate, water, soil, topography) (e.g., Kane et al. 2015). In this context, a lot of experimental forest catchments in Germany were instrumented (e.g., Krofdorfer Forst in Hesse, Lange Bramke in Lower Saxony) to analyze among other aspects the impact of *forest management practices* on the water cycle as well as on the transport mechanisms of dissolved solutes (e.g., nitrate, carbon) (Führer 1990; Herrmann and Schumann 2009). Management studies are essential to seek or develop methods and strategies to react to global changes such as climate trends (Lindner et al. 2010). The strategies are further used to reduce watershed deterioration, augment water supply, restore stream habitats or in general reduce the vulnerability of forests to climate change. This includes the detailed study and detection of all components of the forest water balance in conjunction with typical vegetation characteristics such as their root water uptake (Blume et al. 2016).

Links between *water and agriculture* exist in multiple ways. On the one hand, nitrogen and phosphorus are essential nutrients for the production of plant biomass. An over-application of commonly used organic or artificial fertilizers may negatively impact *groundwater quality* as well as surface water systems (Hallberg 1987; Wick et al. 2012). If the nitrogen and/or phosphorus concentrations rise above critical levels, groundwater may become undrinkable and eutrophication may affect surface water ecology. On the other hand, sufficient water availability is directly linked to crop productivity (Wagner et al. 2016). In fact, *irrigation* has existed for as long as humans have been cultivating plants, but more recently, the question of efficient resource usage has become more prominent. Due to its relatively temperate and relatively humid climate, Germany has sufficient water resources. Nevertheless, irrigation is sometimes meaningful due to the heterogeneous spatial and temporal distribution of rainfall—and particularly for the cultivation of more water-demanding crops. In total, an area of about 516,000 ha is equipped for irrigation in Germany (and thereof 120,000 ha in Lower Saxony), mainly to reduce a soil moisture deficit during the most important growth stages of crops (Riediger et al. 2016). Climate change in Germany is likely to increase soil water deficits at least temporally, while the availability of irrigation water is not expected to become critical in the near future even in the driest parts of Germany (Steidl et al. 2015). However, research is still needed to understand the impacts of water withdrawals for irrigation and changes in evapotranspiration at different spatial and temporal scales (Müller Schmied et al. 2016). Land-use change is another important driver of changes in the water cycle. While German history was dominated by the conversion of forest into agricultural land, a growing role of woody biomass in the emerging renewable energy sector might reverse this trend. Currently, almost 87% of renewable heat production in Germany is based on wood as a fuel. The implications of the increased biomass production by short rotation coppices are, however, discussed controversially, particularly with respect to potential negative impacts to the water balance (Wahren et al. 2015).

In this thematic issue (see Table 5), Hartwich et al. assessed the changes in the water balance by woody biomass production in the North German Plains by using a hydrological modeling approach. The authors used the Soil Water Assessment Tool (SWAT) and implemented a realistic (10% wood cover) and an extreme scenario (100% wood cover) on suitable sites. The results for both scenarios did not show a substantial impact on the investigated water balance components at the water basin level. At the local level, however, the effects of conversion were found to be more pronounced. The analysis and simulation of the water and energy balance of intense agriculture in the Upper Rhine valley, Southwest Germany, are at the focus of the manuscript by Stork et al. Their study aimed at measuring and simulating water and energy fluxes on farm level with respect to irrigation measures in a region where water supply is a limiting factor for crop yields. The authors combined an experimental and modeling approach and measured all components of the water and energy balance as well as the vegetation specific-parameters, such as LAI, crop height and phenological macrostages continuously during a period of 3 months. The observed dynamics were simulated with the physically based hydrological model TRAIN with good model efficiency. Current issues arising with irrigation measures are also addressed by the manuscripts of Herrmann et al. and Drastig et al., whereas Drastig et al. analyzed the history of irrigation water demand in Germany's federal states in relation to the yield of four crops (potato, spring barley, oat, winter wheat) during droughts between 1902 and 2010, Herrmann et al. focused on the impact of climate change on irrigation needs and groundwater resources in the metropolitan area of Hamburg. Looking at the other extreme, Klaus et al. investigated flood risks of agriculture in Germany. Based on the assumption that both agricultural crop losses and flood probability show a strongly seasonal variation, the authors analyzed this interrelation and provided a large-scale overview of agricultural flood risk in Germany. Core products of their work are risk maps, which provide guidance for the coordinated designation of retention areas at the state and federal levels. The manuscript by Kunkel et al. investigated the pathways of nitrogen from agricultural land in the state of Mecklenburg-

Table 5 Manuscripts in the section "Water in agriculture and forestry"

Drastig, K.; Libra, J.; Kraatz, S. & Koch, H. (2016): Relationship between irrigation water demand and yield of selected crops in Germany between 1902 and 2010: a modeling study. Environ Earth Sci. doi:10.1007/s12665-016-6235-8
Hartwich, J.; Schmidt, M.; Bölscher, J.; Reinhardt-Imjela, C.; Murach, D. & Schulte, A. (2016): Hydrological modelling of changes in the water balance due to the impact of woody biomass production in the North German Plain. Environ Earth Sci. doi:10.1007/s12665-016-5870-4
Herrmann, F.; Kunkel, R.; Ostermann, U.; Vereecken, H. & Wendland, F. (2016): Impact of climate change on irrigation needs and groundwater resources in the metropolitan area of Hamburg (Germany). Environ Earth Sci. doi:10.1007/s12665-016-5904-y
Klaus, S.; Kreibich, H.; Merz, B.; Kuhlmann, B. & Schröter, K. (2016): Large-scale, seasonal flood risk analysis for agricultural crops in Germany. Environ Earth Sci. doi:10.1007/s12665-016-6096-1
Kunkel, R.; Hermann, F.; Kape, H.E.; Keller, L.; Koch, F.; Tetzlaff, B. & Wendland, F. (2017): Simulation of terrestrial nitrogen fluxes in Mecklenburg-Vorpommern and scenario analyses how to reach N quality targets for groundwater and the coastal waters. Environ Earth Sci 76:146. doi:10.1007/s12665-017-6437-8
Stork, M. & Menzel, L. (2016): Analysis and simulation of the water and energy balance of intense agriculture in the Upper Rhine valley, southwest Germany. Environ Earth Sci. doi:10.1007/s12665-016-5980-z

Western Pomerania. The authors identified a predominance of diffuse nutrient sources and a high relevance of drainage systems as "collectors". They concluded that a general limit of 50 kg/ha of nitrogen application yearly would be sufficient to reach acceptable nutrient emissions to the Baltic Sea.

Water management and supply

In the course of its history, the socio-economic development of Germany was linked to water resources management in numerous ways. For example, in Roman and medieval times, many German cities were founded in the proximity of rivers which were used as water sources, transport pathways and for energy generation (Haasis-Berner 2009). At the beginning of the industrial age, hydrological modifications in Germany reached a new dimension, and frequently set the example for similar developments in other parts of the world. Some of the most drastic examples include the rectification of rivers such as that of the Rhine which started in 1817 (Cioc 2002), or the accelerated "hydromelioration" (i.e., drainage) of vast peatlands (Blackbourn 2007). However, industrialization and urbanization also prompted advances in urban water management such as improvements in drinking water supply and wastewater treatment—both for ecological and public health considerations (Schweikart and Kistemann 2017; Seeger 1999).

While water management from the beginnings of industrialization until the mid-twentieth century was typically technocratic and placed economic development and human health protection above environmental concerns, Germany was one of the first countries in the world to shift to the more holistic approach of *Integrated Water Resources Management* (IWRM), which was explicitly mentioned in water management directives of Hesse state in 1960 (Rahaman and Varis 2005). However, the concept was popularized much later by the World Summit in Rio de Janeiro in 1992 (Savenije and van der Zaag 2008) and the subsequent definition of IWRM by Global Water Partnership as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP-TAC 2000:22). In contrast to sectoral approaches, a key prerequisite for the operationalization of the IWRM concept is an interdisciplinary system understanding that takes into account both environmental and social developments in a regional context (Borchardt et al. 2013). The *food-water-energy-ecosystems nexus* can be seen as a successor (albeit not a replacement) of the IWRM concept. It was popularized much more recently, following the "The Water, Energy and Food Security Nexus" and "Water in the Anthropocene" conferences in Bonn, Germany, in 2011 and 2013, respectively (Ibisch et al. 2016a). One major difference is that water management is not the main focus of the nexus but that multiple sectors are considered concurrently to find sustainable solutions (de Strasser et al. 2016; Ibisch et al. 2016a). Even though the *European Water Framework Directive* (EU-WFD) is sometimes considered as an implementation tool for IWRM, the directive was adopted to unify the highly fragmented European water policies (Heldt et al. 2017; Rahaman et al. 2004) which focus on the ecosystem-based protection of European water resources. To this date, many surface water bodies in Germany do not yet reach the desired good ecological status, frequently due to hydromorphological alterations or elevated nutrient concentrations (Borchardt et al. 2012).

Capacity development at the individual, organizational and societal levels is a key prerequisite for sustainable water management at the local, national and international scale (Ibisch et al. 2016b). Nevertheless, for quite a long time the importance of a profound multilevel capacity development for sustainable water resources management has been neglected. The concepts of capacity and capacity development have come into wide usage in the context of international development cooperation since the 1980s (Alaerts et al. 1991), recognizing deficient governance structures and societal capacities rather than technical challenges, as the key constraints for enhanced water resources management (Alaerts 2009). However, today it is also widely acknowledged that water-related education at different educational levels ranging from schools to vocational training up to university level does not only confer theoretical and practical knowledge that may be necessary for certain professions, but that they can also facilitate environmental awareness and environmentally conscious behavior at the individual and societal levels (Karthe et al. 2012; Kasimov et al. 2013).

Even though ecological issues have received growing attention in recent years, ensuring a reliable and sustainable *water supply* for domestic, agricultural and industrial water remains a key objective for water resources management. Even though agriculture is the largest water consumer at the global scale, in Germany it ranks behind the energy sector consumption-wise. Urban water supply and sewage disposal is another key field for applied water research—not only because of their relevance for the general public, but also because of the complexity of related technical infrastructure systems. In the case of drinking water provision, for example, installations range from raw water abstraction facilities to water works and distribution networks which typically contain intermediate storage tanks, pumping stations and (often interconnected) pipelines (DIfU 2015). While municipal water and sewage systems in Germany are considered to be of very high technical standard, their significant age as well as developments outside the water supply sector such as climate change (Karthe 2015; Petry 2009) and demographic change (Karthe et al. 2016; Londong et al. 2011) constitute challenges that have only recently received a greater attention.

Several papers *in this thematic issue* (see Table 6) focus on the implementation of IWRM and the EU-WFD. The manuscript by *Evers* analyzes potential synergies between the EU-WFD and the EU Flood Directive at the river basin level. More theoretical considerations (literature, expert views) are further supported by experiential evidence from the Ilmenau River in Thuringia. Kirschke et al. propose a methodology for assessing the implementation of the WFD on the basis of management indicators related to policy formulation, implementation and evaluation. The authors argue that such an analysis can help to not only explain certain water management goals (e.g., achievement of a good ecological status), but that it can also be the basis for a more efficient approach in the future. Nevertheless, they note that the set of management indicators used in their study has to be carefully reviewed before application in different policy phases and on various regional and problem scales. Based on four case studies, the manuscript by Winker et al. discusses how integrated water research can help to overcome current challenges faced by Germany's municipal water sector. The focus of the case studies is on drinking water supply and wastewater treatment, particularly in urban areas. In particular, the authors emphasize that integrated research approaches are helpful to communicate results to stakeholders and practitioners. Heldt et al. analyzed the issue of public acceptance of water management measures at the example of a river restoration project at the example of the Emscher, which was once one of the most polluted streams in Germany and even throughout Europe. The authors point out that even the conversion of an industrial sewer into a close-to-natural river is not always easy to communicate to the general public as soon as this process conflicts with individual interests. Nevertheless, they argue that timely and transparent information is an important prerequisite for public acceptance (by at least a vast majority). Challenges for the implementation of innovative urban water technologies are discussed in the manuscript by Trapp et al., who emphasize the relevance of "mental" barriers, legal and institutional constraints, and complex structures of responsibilities. The authors conclude that innovative solutions require institutional and structural innovations in water management, including greater degrees of cross-sectoral integration and cooperation. The manuscript by Völker et al. is thematically linked by investigating the perception of "urban blue." The authors describe a large set of positive effects, ranging from the physical environment (e.g., noise reduction, creation of a specific microclimate) to more anthropocentric considerations (e.g., provision of recreational space, enhancement of mental well-being). They recommend considering "urban blue" as an elementary part of healthy cities and therefore a high priority in the context of urban landscape planning.

Another set of manuscripts deals more explicitly with technical water management options. Müller et al. propose a mathematical approach for optimizing the operation of multipurpose reservoir systems used for water supply (urban, agricultural and industrial), hydropower generation and flood protection. At the example of three linked reservoirs in the Eastern Ore Mountains near the German–Czech border, the authors show that modeling can help to develop long-term strategies that may not only further improve operational efficiency but also maximize the reliability. Gocht et al. investigated the impacts of climate and demographic changes on another reservoir system located in the Harz Mountains in North-Central Germany. Also based on a modeling approach, the authors conclude that multipurpose systems are relatively resilient to such changes because they allow tradeoffs between different

Table 6 Manuscripts in the section "Water management and supply"

Breuer, R.; Sewilam, H.; Nacken, H. & Pyka, C. (2017): Exploring the application of a flood risk management Serious Game platform. Environ Earth Sci 76:93. doi:10.1007/s12665-017-6387-1
Evers, M. (2016): Integrative river basin management: challenges and methodologies within the German planning system. Environ Earth Sci. doi:10.1007/s12665-016-5871-3
Gocht, M. & Meon, G. (2016): Modelling and assessment of the combined impacts of climatic and demographic change on a multipurpose reservoir system in the Harz mountains. Environ Earth Sci. doi:10.1007/s12665-016-6099-y
Heldt, S.; Budryte, P.; Ingensiep, H.W.; Teichgräber, B.; Schneider, U. & Denecke, M. (2016): Social Pitfalls for River Restoration: How Public Participation Uncovers Problems with Public Acceptance. Environ Earth Sci. doi:10.1007/s12665-016-5787-y
Kirschke, S.; Richter, S. & Völker, J. (2016): Evaluating water management processes in Germany: conceptual approach and practical applications. Environ Earth Sci. doi:10.1007/s12665-016-5900-2
Müller, R. & Schütze, N. (2016): Performance optimization of multi-purpose multi-reservoir systems under very high reliability constraints. Environ Earth Sci. doi:10.1007/s12665-016-6076-5
Sewilam, H.; Nacken, H.; Breuer, R. & Pyka, C. (2017): Competence-based and game-based capacity development for sustainable water management in Germany. Environ Earth Sci 76:131. doi:10.1007/s12665-017-6416-0
Sievers, J.C.; Wätzel, T.; Londong, J. & Kraft, E. (2016): Case Study-Characterization of source- separated blackwater and greywater in the ecological housing estate Lübeck "Flintenbreite" (Germany). Environ Earth Sci. doi:10.1007/s12665-016-6232-y
Trapp, J.; Kerber, H. & Schramm, E.: Implementation and diffusion of innovative water infrastructures-obstacles, stakeholder networks and strategic opportunities for utilities. Environ Earth Sci 76:154. doi:10.1007/s12665-017-6461-8
Völker, S.; Matros, J. & Claßen, T. (2016): Determining urban open spaces for health-related appropriations: a qualitative analysis on the significance of blue space. Environ Earth Sci. doi:10.1007/s12665-016-5839-3
Winker, M.; Schramm, E.; Schulz, O.; Zimmermann, M. & Liehr, S. (2016): Integrated water research and how it can help address the challenges faced by Germany's water sector. Environ Earth Sci. doi:10.1007/s12665-016-6029-z

purposes by adapting operation rules. Finally, the manuscript by Sievers et al. describes results of a research project on black- and graywater separation accompanying the development of a new housing estate in Lübeck, Germany. The authors show that household graywater is comparable to domestic wastewater in terms of organic parameters but not nutrients (significantly lower concentrations). The composition of blackwater was found to correspond well with the limited number of other studies that exists from similar settings. The results presented in this manuscript are therefore valuable planning tools for future wastewater separation projects, including adapted concepts for wastewater treatment and matter recycling.

The relevance of Capacity Development for water resources management is addressed by two thematically related manuscripts. Sewilam et al. provide a broad introduction into learning management systems in the context of technical water management, involving "conventional" competence-based approaches, "serious games" and a final assessment as principal components. In the manuscript by Breuer et al., the same authors discuss the design and first experiences with an educational serious game focusing on flood risk management.

Conclusions

Current water research in Germany covers a wide range of topics ranging from the investigation of fundamental principles governing hydrological cycles and aquatic systems to the management of water resources and water-related ecosystems. Even though Germany is a country with a sufficient (but not over-abundant) water supply, regional differences and climatic variability and changes are relevant for regional *hydrology*. Specifically, they result in challenges related to droughts and flow-flow situations on the one hand, and severe floods on the other hand. In particular since industrialization, changes in *hydromorphology* and the conversion of floodplains into agricultural land or urban areas have not only considerably increased flooding risks, but also desiccated significant areas of wetland. Current research in the field of hydrology and hydromorphology covers a multitude of topics, such as the reconstruction of historical hydrology and river courses; the investigation of soil water and groundwater resources; runoff generation and flow dynamics and their external drivers; and the assessment and improvement of river bed and floodplain morphology.

Regarding *water quality*, Germany's rivers have witnessed considerable improvements over the past few decades. Nevertheless, several water quality-related challenges remain. One key problem are elevated nutrient loads, which do not only affect inland surface water ecosystems but also threaten the receiving marine water bodies. In some regions, heavy metals continue to play a role as pollutants, often resulting from the legacies of mining and industrial waste disposal. The vast group of emerging pollutants is currently the subject of numerous research initiatives, and it is likely that additional substances will be added to this group of contaminants in the future.

Challenges related to emerging pollutants include the limited removal rates by the current generation of wastewater treatment facilities, and a limited understanding of their eco-toxicological relevance. A renewed interest can be stated for microbial pathogens, for which both basin-wide considerations and new monitoring techniques are currently on the scientific agenda.

Aquatic and riparian ecosystems do not only depend on sufficient water availability and water quality, but also on river and floodplain morphology. Riverine floodplains have undergone such a massive transformation that a very significant part of them were lost as integral parts of river ecosystems. Similarly, aquatic ecosystems in Germany have been modified to a degree that their restoration is very challenging—but also recognized as a priority for river basin management. Invasive aquatic species have not yet received much attention outside the scientific community in Germany, but may further contribute to the alteration of aquatic ecosystems. However, large-scale experiments such as the controlled flooding of degraded floodplain forests have shown that the restoration of river and riparian ecosystems to a near-natural state is possible to a certain extent.

Water usage and management in agriculture and forestry continue to be an important field for research for several reasons: both land uses cover vast parts of Germany and they significantly affect the regional hydrological cycle. Plant biomass production does not only require sufficient water supply, but in case of fertilizer and pesticide application threatens both ground and surface water quality. Both monitoring and modeling/simulation approaches are currently used to investigate the past, present and future water utilization in the agriculture and forestry sectors. *Water management and supply* is, however, a topic that goes far beyond the primary sector. On the one hand, urban and industrial water supply and wastewater disposal continue to be relevant research topics. On the other hand, holistic strategies such as IWRM or the water-food-energy nexus have in recent years received the attention of both water scientists and managers, with a specific focus on the implementation of the European Water Framework Directive. While the involvement of the public has been recognized as an important but sometimes challenging step in the implementation of new infrastructures, capacity development remains an important prerequisite for sustainable water management. One innovative approach discussed in this thematic issue consists of computer-aided learning based on computer games.

Despite all challenges addressed by this synthesis and the manuscripts in the thematic issue, the wide range of both fundamental and applied water research provides new answers and innovative solutions that can be the basis for a more sustainable water management in the future.

Acknowledgements The authors would like to thank Mrs. Michaela Walter-Rückel, Catholic University Eichstätt-Ingolstadt/Floodplain Institute Neuburg (Danube), for carefully proofreading the manuscript.

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