

The Bode hydrological observatory: a platform for integrated, interdisciplinary hydro-ecological research within the TERENO Harz/Central German Lowland Observatory

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Abstract This article provides an overview about the Bode River catchment that was selected as the hydrological observatory and main region for hydro-ecological research within the TERrestrial ENvironmental Observatories Harz/

Central German Lowland Observatory. It first provides information about the general characteristics of the catchment including climate, geology, soils, land use, water quality and aquatic ecology, followed by the description of the interdisciplinary research framework and the monitoring concept with the main components of the multi-scale and multi-temporal monitoring infrastructure. It also shows examples of interdisciplinary research projects aiming to advance the understanding of complex hydrological processes under natural and anthropogenic forcings and their interactions in a catchment context. The overview is complemented with research work conducted at a number of intensive research sites, each focusing on a particular functional zone or specific components and processes of the hydro-ecological system.

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Introduction

In most regions of the world, freshwater systems and biodiversity are affected by human activities and anthropogenic climate change at varying intensities. Hence, a science-based system understanding is necessary for appropriate management and conservation strategies are required (Vörösmarty et al. 2010). To this end, for example, predictions of biogeochemical behaviour of catchments in response to dynamic hydrological conditions at management relevant

scales are required (e.g. Krause et al. 2013). This is challenging since processes which control the functioning of catchments occur at various scales, and the relevant drivers, both natural and anthropogenic, need to be identified, and their impacts on the large-scale hydro-bio-geo-chemical behaviour of the catchment have to be assessed (e.g. Rode et al. 2010; Basu et al. 2011). Combining recent monitoring methods with advanced modelling techniques provides new opportunities to gain a more detailed understanding of catchment processes and to quantify and predict water and matter fluxes at the catchment scale as a function of and in feedback with changes in climate, land use and water usage (e.g. Grathwohl et al. 2013). Constraints to this endeavour are mainly imposed by a lack of longer-term (i.e. ideally several decades) observation of driving forces, time series of spatially and temporally resolved water quantity and quality measurements, and by a limited understanding of scaling of the highly dynamic and heterogeneous mobilization and transformation processes. In order to adequately characterize environmental processes at the catchment or river basin scale and to be able to cope with the complexity of the numerous involved processes, an adaptive and multi-scale mapping, monitoring, modelling and data exchange framework that allows to consider the processes from a systems perspective is recommended (e.g. Lin et al. 2006; Reed et al. 2006; Montgomery et al. 2007; Lin 2010; Rode et al. 2010). Monitoring environmental changes requires continuous time series of high-quality long-term data (e.g. Burt 2003; Parr et al. 2003), which are essential for making informed decisions, e.g. about how to manage catchments (e.g. Burt 2003; Jensen and Illangasekare 2011). Ideally, these time series data are complemented by information about spatial and temporal patterns of catchment properties and states which may be provided by geophysical and remote sensing measurements as well as catchment-scale models which carefully integrate these data (e.g. Schulz et al. 2006). Furthermore, combining this spatial information with high-resolution measurements of biogeochemical processes and states (e.g. by high-resolution sampling of water quality parameters or by running wireless soil moisture monitoring networks) at well-selected sampling locations may further assist to advance our understanding of the functioning of catchments and to optimize monitoring designs (e.g. Paola et al. 2006).

This strategy is also being followed within TERENO (TERrestrial ENvironmental Observatories), a network of Earth observatories in Germany (Bogena et al. 2012; Zacharias et al. 2011). TERENO is composed of four observatories—the Northeastern German Lowland Observatory, the Harz/Central German Lowland Observatory, the Eifel/Lower Rhine Valley Observatory and the Bavarian Alps/pre-Alps Observatory. Research within TERENO focuses on the terrestrial environment comprising the

subsurface environment, the land surface including the biosphere, the lower atmosphere and the anthroposphere (Bogena et al. 2006; Zacharias et al. 2011). It aims to provide long-term, multi-scale and multi-temporal data as well as experiments and modelling frameworks that help to derive a better understanding of the influence of climate and land use change on the terrestrial environment. All of them may be used to define possible adaptation strategies, e.g. with respect to land and water management, to react to the influences of climate and land use change on the terrestrial environment (Zacharias et al. 2011).

This article focuses on the Bode catchment (Fig. 1) that was selected as hydrological observatory (BHO) and the main region for hydrological research within the TERENO Harz/Central German Lowland Observatory operated by the Helmholtz Centre for Environmental Research—UFZ. Similar to the other hydrological observatories in TERENO, it aims to observe hydrological and hydro-ecological phenomena at several scales ranging from small, highly instrumented subcatchments to larger mesoscale catchments with a size of several 1000 km² (Zacharias et al. 2011). To this end, in the Bode catchment, an integrated, multi-scale monitoring and research framework linking hydrological, pedological, atmospheric and biodiversity-related research has been set up to investigate the influences of climate and land use change on the terrestrial system and on the hydrological system in particular. The aim of this article is to first provide a general overview of the Bode catchment including climate, geology, soils, land use, water quality and aquatic ecology. Second, it describes the general research concept and monitoring programme with the main components of the current infrastructure as part of a multi-scale and multi-temporal monitoring framework. This paper also highlights first examples of interdisciplinary research aiming to advance the understanding of complex hydrological processes and interactions within the catchment and provides an overview of the research conducted at the intensive research sites within the Bode catchment, each focusing on a particular functional zone of the catchment or specific components and processes of the hydrological system.

The Bode catchment

The Bode catchment is part of the TERENO Harz/Central German Lowland Observatory (Fig. 1; Zacharias et al. 2011). It is a mesoscale catchment within the Elbe river basin covering an area of approximately 3300 km². The catchment extends from the Harz Mountains, a low mountain range in the south-west across a part of the Central German Lowland to the Magdeburger Börde area in its north-eastern region. The topography of the

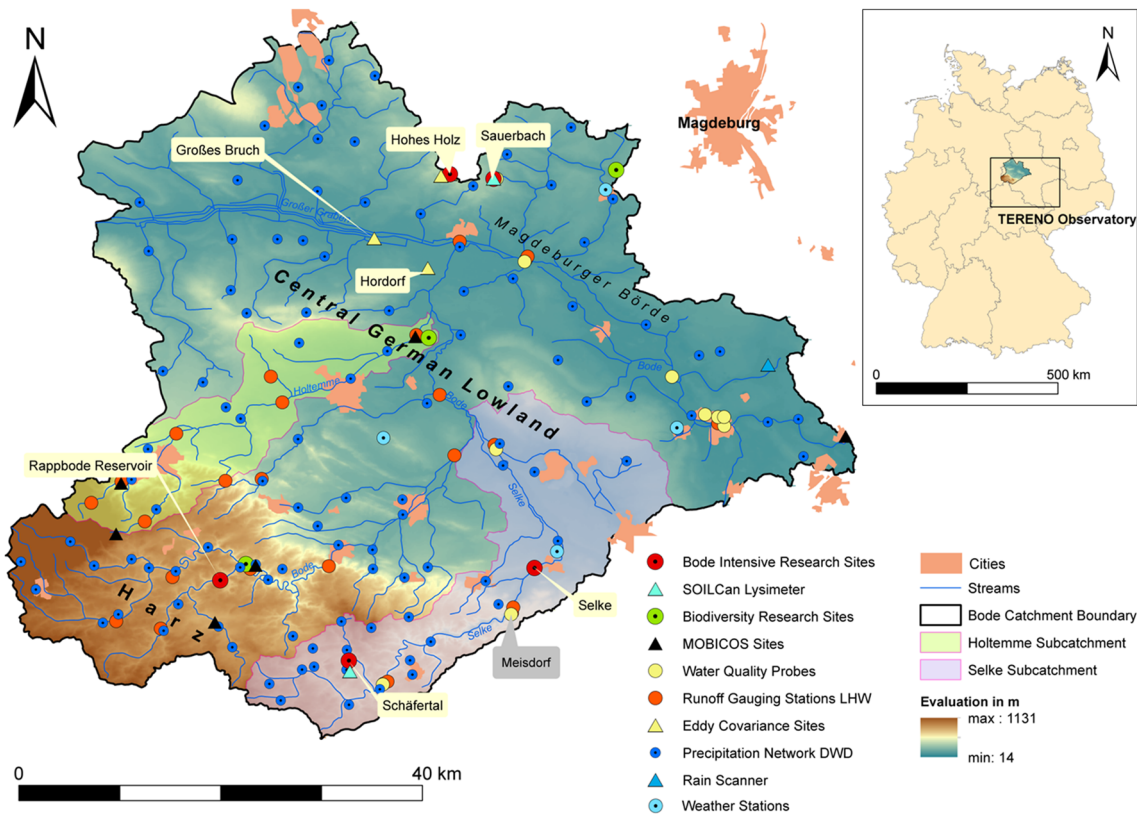


Fig. 1 Map of the Bode catchment within the TERENO Harz/Central German Lowland Observatory. The Selke catchment as one of the subcatchments of the Bode catchment is shaded in blue, and the Holtemme catchment is shaded in green; large red labels indicate the locations of intensive research sites. Topography is based on SRTM

data (Jarvis et al. 2008); catchment boundaries: description based on digital data provided by the State Office of Flood Protection and Water Management (LHW) Saxony-Anhalt, Gen.-Nr. LHW/5.1.3/14/2009

catchment shows a distinct zonation with respect to land surface elevations, with high elevations up to 1142 m a.s.l. at the Brocken, the highest peak in the Harz Mountains, and very low elevations, as low as about 50 m a.s.l., in the Central German Lowlands. This topographical zonation is also reflected in the spatial differences in climate, geology, soils, land use and water quality of the catchment.

The main tributaries of the Bode River are the Selke River at the southern boundary and the Holtemme River in the central part of the catchment. Both and the main Bode River itself have their headwaters in the Harz Mountains. In its northern part, the Bode catchment is crossed by the flat wetland Grosses Bruch, a former glacial valley extending by about 45 km in East–West direction.

The Bode catchment is one of the meteorologically and hydrologically best-instrumented catchments in Central Germany (Zacharias et al. 2011). Long-term precipitation and climate records are available from a large number of stations (Fig. 1) which are operated by the German Meteorological Service (DWD). Long-term time series on water quantity (i.e. streamflow) and quality are monitored at

various locations (Fig. 1) by the State Office of Flood Protection and Water Management (LHW) Saxony-Anhalt.

In the following, we provide an overview of the main characteristics of the Bode catchment including climate, geology, soils, land use and water quality.

Climate

Due to the large difference in elevation, the low mountain range of the Harz and the adjacent Central German Lowland regions show characteristic differences in climate. While the climate in the Harz Mountains is cold and moist, the Central German Lowland area is significantly warmer and dryer, which results in a negative climatic water balance for this region (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit 2003; Zebisch et al. 2005; Bernhofer et al. 2008). Consequently, the Central German Lowland has a high vulnerability to meteorological and agricultural droughts. The German Meteorological Service (DWD) provides station-based hourly meteorological data. For the time period 1951–2011, 465 precipitation and 29 climate stations are available. Annual

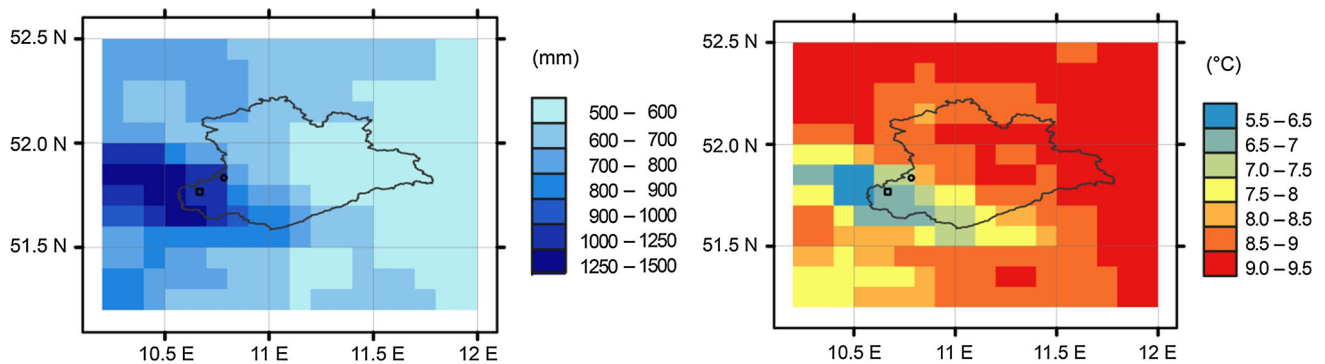


Fig. 2 Maps of mean annual precipitation (*left*) and mean annual air temperature (*right*) 1951–2011 for the Bode catchment. Data were interpolated on a 10-km grid from 532 (precipitation) and 70 (air temperature) stations with Kriging using elevation from Shuttle Radar Topography Mission (SRTM) 90 m digital elevation data as external

drift. Daily precipitation data have been corrected for systematic errors according to Richter (1995). The markings show the climate stations Brocken (*square*, 1142 m a.s.l.) and Wernigerode (*circle*, 234 m a.s.l.)

precipitation in the Bode catchment ranges from more than 1700 mm in the upper Harz Mountains to less than 500 mm on the extensive plains of the Central German Lowland area (Fig. 2). The low precipitation is primarily due to the continentality of the Central German Lowland combined with the flatness of the area with missing orographic effects and, partly, to its position in the rain shadow of the Harz Mountains. Mean annual air temperature ranges from 5 °C on the Brocken to 9.5 °C in the eastern part of the Magdeburger Börde. Comparing the 30-year time slices 1951–1980 with 1981–2010, mean annual air temperature shows a warming of 0.71 °C on the Brocken and 0.84 °C at Wernigerode.

A report published by the German Federal Environmental Agency (Zebisch et al. 2005) on Climate Change in Germany assesses the Eastern German lowland region including the Central German Lowland area of the Bode catchment to be highly vulnerable to Climate Change with a particular reference to the low water availability and the risk of summer droughts, both resulting from the actual negative climatic water balance (e.g. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit 2003). This is presumed to be further exacerbated by a future decrease in summer precipitation and increased evaporation due to increasing temperatures in this region. In contrast, the Harz Mountains are ranked to be less vulnerable to climate change because of their cold and moist climate. Nonetheless, a high vulnerability of the Harz Mountains to flooding was stated (Zebisch et al. 2005).

Geology

The Bode catchment can be subdivided into the Harz Mountains in the south-west and the Central German Lowland with the Magdeburger Börde region in the central and north-eastern part of the catchment (Fig. 3).

The geology of the Harz Mountains is predominantly characterized by Palaeozoic rocks (e.g. Frühauf and Schwab 2008), while the lowland areas are dominated by Mesozoic and late Palaeozoic rocks which, are largely covered by Tertiary and Quaternary sediments (Schuberth 2008).

Along with the uplift of the Harz Mountains during the Saxonian orogeny, the Mesozoic rocks situated eastwards were bent into a saddle and basin structure. They consist of Triassic and Cretaceous sandstones and limestones (Schuberth 2008) which occur as characteristic WNW-ESE-oriented ridges throughout the Central German Lowland area of the Bode catchment (Fig. 3). The surrounding areas are covered by Quaternary glacial and periglacial sediments that were deposited during three glaciations (Schuberth 2008). Most importantly, during the Weichsel glaciation, an almost area-wide loess cover was deposited up to the north-eastern rim of the Harz Mountains. It levels to a large extent the relief of the Central German Lowland and is the parent material of the highly fertile Chernozems of this area (Liedtke 1995; Schuberth 2008).

Soils

The soil map of the Bode catchment is depicted in Fig. 4. Soils in the area of the predominantly igneous and metamorphic rocks of the Harz Mountains are dominated by Cambisols and a smaller fraction of Leptosols, Luvisols and Gleysols. The north-eastern rim of the Harz Mountains which leads over to the Central German Lowland is characterized by non-metamorphic sedimentary rocks which are partly covered by loess. The dominating soils in this area are Luvisols, Leptosols, Cambisols and Gleysols.

The Central German Lowland in the loess and sandy loess regions of the Bode catchment is predominantly covered by Chernozems (Soil Map of the Federal Republic

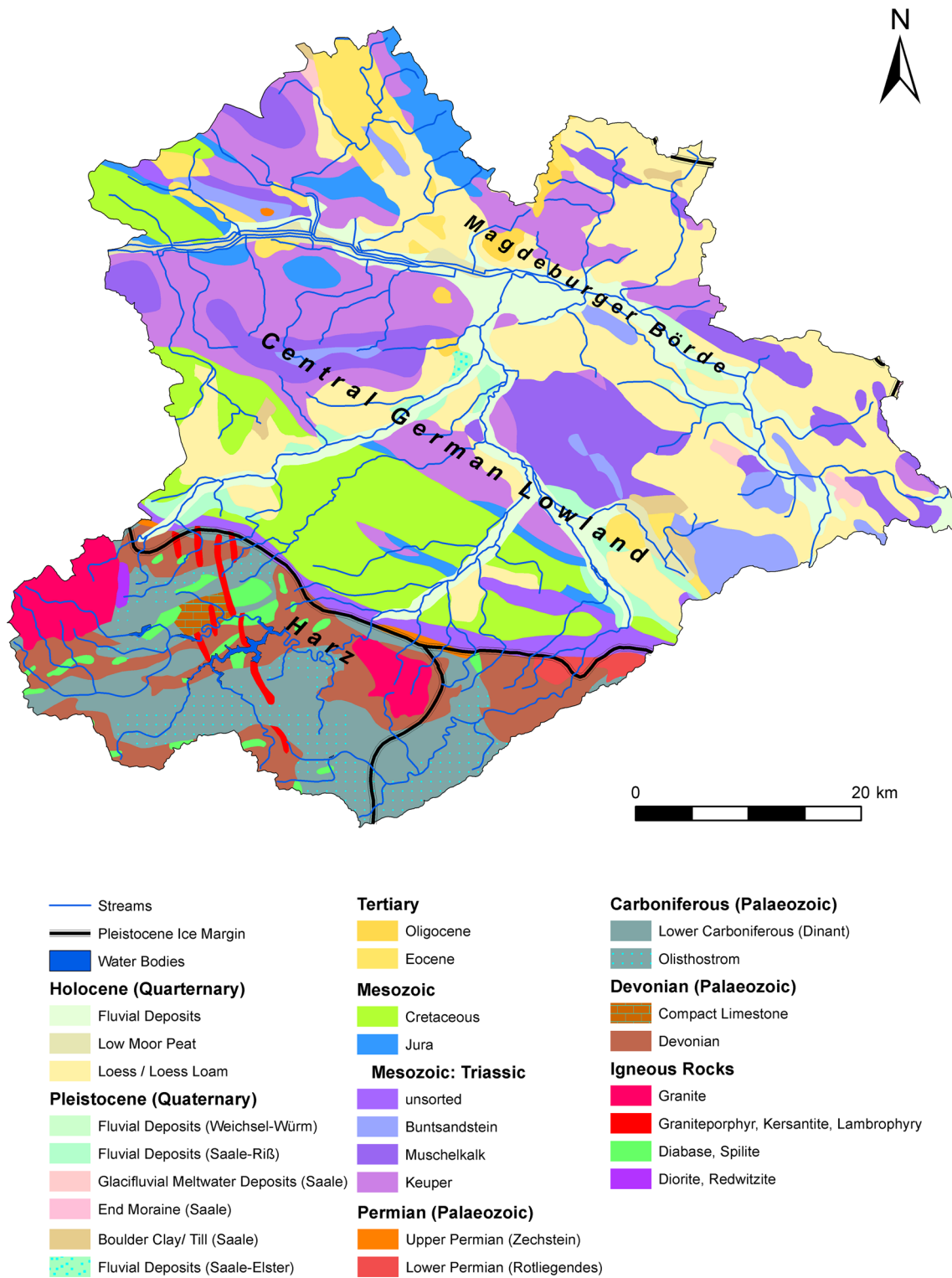
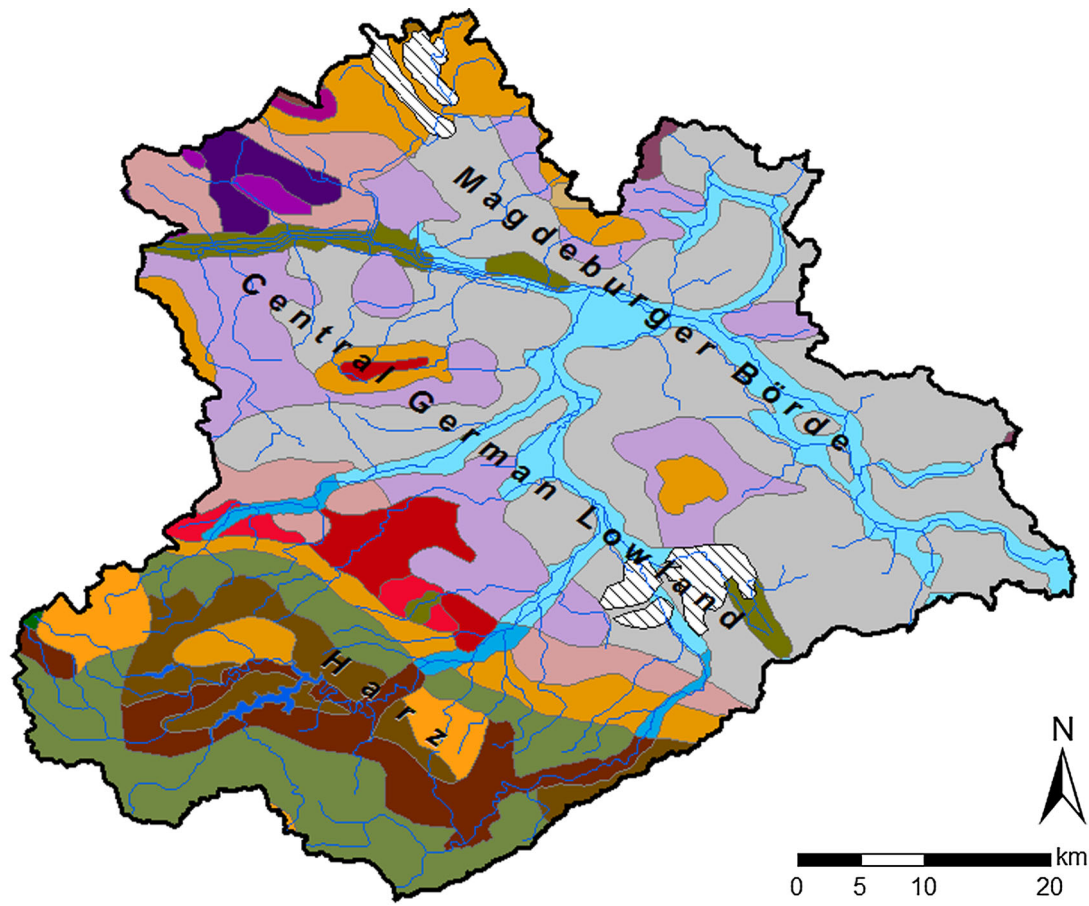


Fig. 3 Geology of the Bode catchment. In the Harz Mountains the geology is shown without Quaternary; map simplified after Geological Map 1:1,000,000 (GK 1000), source: BGR. Catchment

boundaries: description based on digital data provided by the State Office of Flood Protection and Water Management (LHW) Saxony-Anhalt, Gen.-Nr. LHW/5.1.3/14/2009

of Germany 1:1,000,000; Hydrologischer Atlas von Deutschland, 2000). These are the most widespread soils of the dry loess areas of the Central German Lowland

including the Magdeburger Börde region (Altermann et al. 2005). The Chernozem of the Magdeburger Börde is the most fertile soil within Germany (Schmidt 1995).



Legend

Streams



Soils

Water bodies

Eutric Histosols

Dystric Histosols

Fluvisols / Gleysols

Gleyic Chernozems

Cambic Podzols / Spodic Arenosols

Haplic Chernozems

Haplic Chernozems / Eutric Cambisols

Haplic and Stagnic Chernozems

Phaeozemic Luvisols / Luvic Phaeozems

Phaeozemic and Haplic Luvisols

Haplic Luvisols / Eutric Podzoluvisols / Stagnic Gleysols

Stagnic Gleysols

Haplic Luvisols / Eutric Podzoluvisols / Stagnic Gleysols

Eutric Cambisols / Haplic Luvisols / Eutric Podzoluvisols

Rendzic Leptosols, Chromic Cambisols, Chromic Luvisols

Vertic Cambisols / Stagnic Gleysols

Dystric Cambisols from acid igneous and metamorphic rocks

Dystric Cambisols / Stagnic Gleysols

Spodic Cambisols from acid igneous and metamorphic rocks

Spodic Cambisols from hard argillaceous and silty slates with greywacke, sandstone, quartzite, and phyllite

Dystric Cambisols from quartzitic sandstones and conglomerates with low base status

Dystric and Spodic Cambisols / Rendzic Leptosols / Haplic Luvisols

Rendzic and Umbric Leptosols / Spodic and Vertic Cambisols / Haplic Luvisol / Stagnic Gleysols

Soils redeposited by man and large open-cast mines (Cumulic Anthrosols)

Fig. 4 Soil map of the Bode catchment; data source: soil map of the Federal Republic of Germany 1:1,000,000 (BUEK 1000), source: BGR. Catchment boundaries: description based on digital data

provided by the State Office of Flood Protection and Water Management (LHW) Saxony-Anhalt, Gen.-Nr. LHW/5.1.3/14/2009

Land use

The zonation of the Harz Mountains and the Central German Lowland described previously is also apparent in the land use of the Bode catchment (Fig. 5). The mountainous region of the Harz with its steep slopes and shallow and less fertile soils is predominantly covered by forest, while agriculture is restricted to the plateau areas. In contrast, the highly fertile Chernozems of the Central German Lowland are intensively used for agriculture. According to the CORINE 2006 land cover map (CLC 2006; Umweltbundesamt, DLR-DFD 2009), approximately 66% of the Bode catchment area is in agricultural use while 26% are forested and seminatural areas. Artificial surfaces including cities, industrial areas and recent as well as former open-cast pits make up 7% of the total catchment area. Water

bodies and wetlands cover the remaining 1% of the Bode catchment.

Water quality and aquatic ecology

Surveys conducted in the course of the implementation of the Water Framework Directive (WFD) suggest that due to nutrient status, anthropogenic modifications of river morphology and other man-made stressors in about 80% of the river system it is unlikely or uncertain to reach a ‘good ecological status’ (e.g. FFG Elbe 2015). This is a common finding for water bodies throughout Germany and in other intensely used landscapes of Europe (Richter et al. 2013). While the headwaters in the Harz Mountains are nearly unaffected by anthropogenic pollution (e.g. Langheinrich et al. 2002; Reuter et al. 2003), several point sources in the

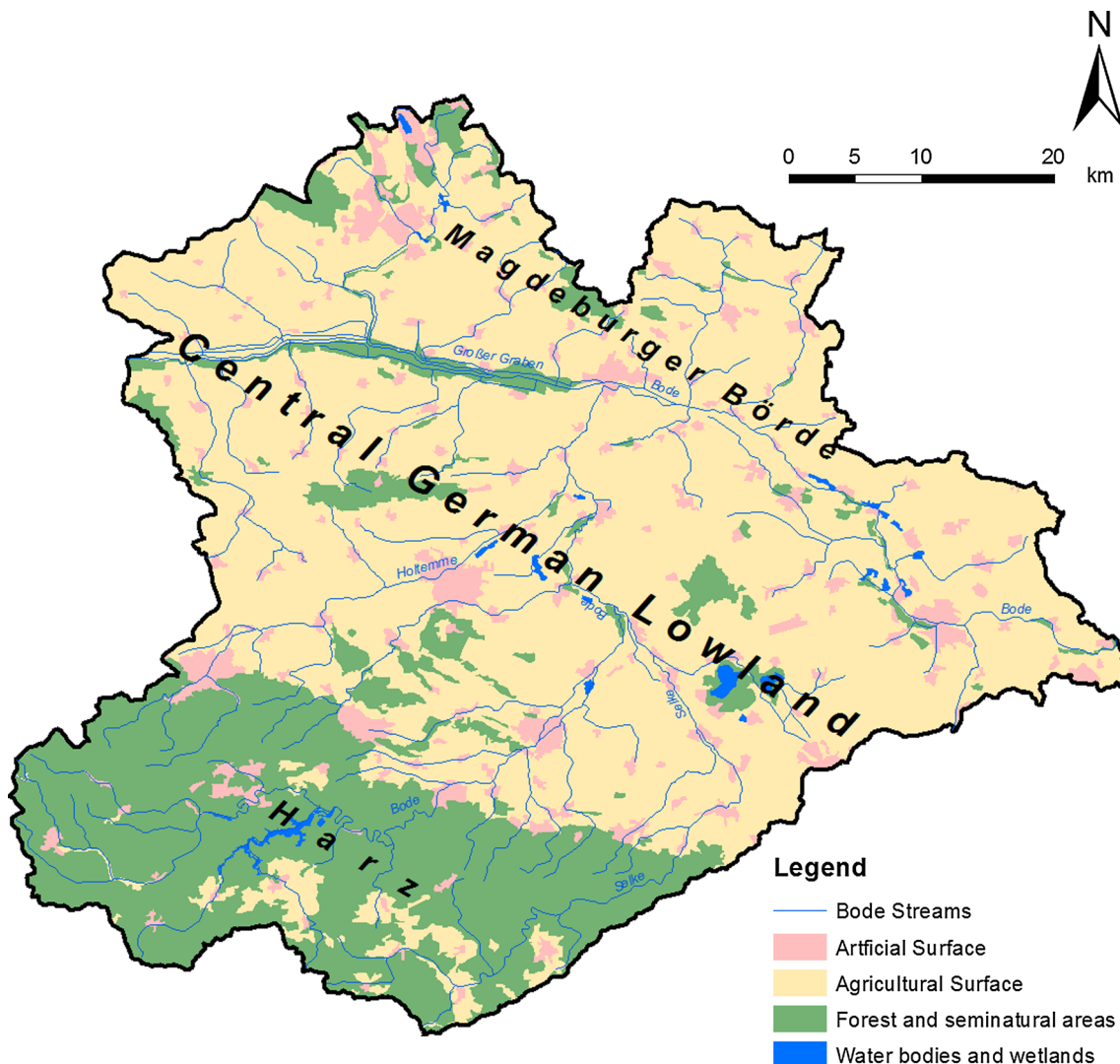


Fig. 5 Land surface classes of the Bode catchment; data source: CORINE Land Cover (CLC2006); Umweltbundesamt, DLR-DFD 2009. Catchment boundaries: description based on digital data

provided by the State Office of Flood Protection and Water Management (LHW) Saxony-Anhalt, Gen.-Nr. LHW/5.1.3/14/2009

lower part of the river system contribute to its poorer water quality (Hesse et al. 2012; Musolff et al. 2015; Reuter et al. 2003). Nevertheless, most of the headwater sections in the Bode catchment were—and to a certain extent are—subjected to acidification due to a combination of natural factors (siliceous bedrock (granite), peatland near to the springs) and anthropogenic ones caused by forestry with predominance of coniferous trees and acidic atmospheric depositions (e.g. Stöcker 1994; Langheinrich et al. 2002).

Among the most widespread problems within the catchment with regard to surface water and groundwater quality are eutrophication due to nutrient inputs (N, P) (e.g. Jiang et al. 2014, 2015) and also pesticide contamination (Ippolito et al. 2015; Munze et al. 2015) from agriculture. Future land use change (e.g. shifting to energy plants) may increase agricultural inputs of nutrients and pesticides (Kattwinkel et al. 2011) to surface waters (e.g. Jomaa et al. 2016). Climate change already altered and may further modify the hydrological regime due to (1) increase of winter precipitation, reduced snowmelt and soil freezing events (e.g. Anis and Rode 2015b), and decrease of summer precipitation, (2) effects on the ecohydrological boundary conditions of the river system and (3) changing effects on the interactions between groundwater and surface water, especially in the summer season (Kropp et al. 2010).

Hydrological research in the Bode catchment

The Bode basin was selected as a catchment for hydrological research in the TERENO Harz/Central German Lowland Observatory because of its strong gradients in topography, climate, geology, soils, water quality, land use and level of urbanization. It is located in a region in Germany that has been ranked highly vulnerable to climate change (e.g. Zebisch et al. 2005; Glaser 2008). Hence, the region provides excellent conditions for long-term studies of the effects of climate and land use changes on the terrestrial and—in case of the Bode catchment—the hydrological system in particular. The catchment comprises subcatchments of diverse hydrological characteristics and anthropogenic impacts: Hassel/Rappbode (flashy hydrology, predominantly good chemical status, extended forests, drinking water reservoir), Selke (flashy hydrology, low wastewater loading, moderate agricultural intensity), Holtemme (flashy hydrology, high wastewater loading, more intensive agriculture), Grosser Graben (monotonous, highly regulated hydrology, low wastewater load, highly intensive agriculture), Lower Bode (mixture of all other subcatchments). Of particular importance is the long history of hydro-ecological information (discharge time series >100 years) as well as significant shifts in catchment characteristics due to the demographic change after the

German reunification, e.g. wastewater loadings and agricultural intensities over the last three to four decades.

Hydrological research in the Bode catchment is based on an interdisciplinary approach aiming at the assessment and prediction of water and matter flux dynamics including in-stream processes as well as the structure and functioning of aquatic communities. Predictions are complicated by the need to quantify the water and mass fluxes as well as transformation processes in different compartments like the soil, vadose zone, hyporheic zones and groundwater as well as the surface water transport processes including stream–aquifer interactions. The goal of the research in the Bode Hydrological Observatory (BHO) is to generate an improved mechanistic understanding of matter mobilization and export under dynamic boundary conditions while acknowledging the important links between hydrological processes, biogeochemical transformations and ecological dynamics. Ecological research focuses on the contribution of microbial and macrofauna communities to the flux of matter as well as on the control of the structure and functioning of communities under impact of multiple stressors. To better account for the need of upscaling process knowledge, the adoption of combined process-oriented field and modelling studies at representative sites is advocated. To this end, data-driven and conceptual top-down analyses (e.g. Jiang et al. 2014, 2015; Musolff et al. 2015) are combined with detailed process-based bottom-up studies and modelling (e.g. Kamjunke et al. 2013; Vieweg et al. 2013; Trauth et al. 2015) in an integrated approach. This approach explicitly considers the links between structure and function including the heterogeneity of the catchment, processes in specific functional zones, and the dynamics of water fluxes and retention times. Biological processes are analysed at the patch scale, and those studies are combined with process studies suitable for upscaling such as the measurement of whole stream metabolism (e.g. Halbedel et al. 2013). Furthermore, in-stream nutrient metabolism studies at the entire range of stream and river scales will enable the improvement of the mathematical representation of these processes in coupled catchment-receiving water body models (Rode et al. 2010). Thorough evaluation of existing field data will further guide the development of new models of matter flux dynamics with enhanced predictive power for integrated catchment and water quality management. In addition, methods are being developed for the visualization of numerous types of complex data sets (Rink et al. 2014). These methods provide a better understanding of the acquired data and are useful instruments for preparing models for the simulation of interacting environmental processes. Visual analysis and validation algorithms allow for the syntheses of multiple data sets and the detection of potential problems during a subsequent simulation due to artefacts or inconsistencies between data sets.

Catchment instrumentation

The diversity of research objectives with regard to a holistic representation of the hydrological system across all relevant environmental domains and scales makes special demands on the monitoring design and the instrumentation. In the BHO, these demands are reflected by a comprehensive multi-scale measurement and monitoring network which has been set up as a basis for monitoring, modelling, analysing and predicting environmental processes and changes at different spatial scales within and across the different compartments of the terrestrial system (Fig. 1). Monitoring of various environmental state variables is conducted in an interdisciplinary effort at different scales encompassing the complete Bode catchment (3300 km²), the Selke (483 km²), Holtemme (278 km²) and Rappbode Reservoir subcatchments as well as at several intensive research sites, with scales of a few km² or even less (cf. “[Examples for research in the Bode hydrological observatory](#)” section).

To this end, the monitoring infrastructure has been set up as an extension to the already existing long-term monitoring programme of the federal state agencies (cf. “[The Bode catchment](#)” section). These data have been and are still being used for conducting top-down analysis as basis for understanding the general hydrological and chemical behaviour of the catchment and for selecting additional sampling and monitoring sites.

In addition to the precipitation sampling of the German Meteorological Service, a series of weather stations has been set up along a climate gradient (Fig. 1). These are complemented by three intensive research sites for monitoring soil atmosphere exchange processes which comprise a comprehensive infrastructure including eddy covariance station and monitoring of several additional ecohydrological parameters (cf. “[Intensive sites for investigating soil–vegetation–atmosphere transfer processes](#)” section for details).

In addition and in coordination with the regular sampling of river water quality carried out by the federal water authority, a network of high-temporal resolution water quality probes has been set up in the Selke catchment (Rode et al. 2016) and the catchments of the Holtemme and Rappbode Reservoir (Friese et al. 2014; Rinke et al. 2013) allowing for a more detailed investigation of catchment hydrological and chemical dynamics and river water quality (see “[High-resolution water quality monitoring in the Selke/Bode River System](#) and [The Rappbode Reservoir Observatory](#)” sections for details). Two of these probes are located at the outlet of the first-order catchments Schäfertal and Sauerbach.

Soil water dynamics is being monitored at a hierarchy of scales starting with very detailed measurements of the entire water balance with the TERENO SOILCan lysimeters (Hannes et al. 2015, 2016; Pütz et al. 2011, 2016) at the

intensive research sites Schäfertal and Sauerbach via field to hillslope-scale soil moisture monitoring networks under different land use at the Schäfertal (Martini et al. 2015), Hohes Holz and Grosses Bruch intensive sites (Fig. 1). These soil moisture monitoring networks allow a detailed analysis of spatio-temporal soil water dynamics and build the basis for modelling both soil water dynamics and soil–atmosphere exchange processes at this scale. At the even larger scale, a network of cosmic-ray neutron probes covering a footprint of about 10⁵ m² is under construction. These data may in future be complemented by the analysis of remotely sensed soil moisture at even larger scales.

The data from most of the permanently installed monitoring stations are transferred directly to a central server at UFZ via VPN Internet connection. The permanent monitoring is complemented by dedicated measurement campaigns such as catchment- or subcatchment-wide sampling for river water quality (e.g. Kamjunke et al. 2013), stable isotopes (e.g. Mueller et al. 2015), or soil moisture (e.g. Schröter et al. 2015), vegetation and soil sampling, geophysical exploration and remote sensing and by the analysis of long-term monitoring data from the Federal State Offices (e.g. Musolff et al. 2015).

Similar to the data from all TERENO catchments, the UFZ-monitoring data from the observatory will be made freely accessible via the TEODOOR data portal (<http://www.tereno.net>; Kunkel et al. 2013) according to the TERENO Data Policy (see <http://teodoor.icg.kfa-juelich.de/downloads-de/TERENO%20Data%20policy.pdf/view>). Prior to publication via TEODOOR, all data will be subjected to quality control following the TERENO Data Management Plan (see http://teodoor.icg.kfa-juelich.de/coordination-teams/CT_Data_Management/dokumente/TERENO%20DataManagementPlan.doc/download).

Examples for research in the Bode hydrological observatory

In the following, we provide an overview of the intensive research sites and the work conducted there. Furthermore, we present some examples of catchment-scale investigations which have helped to gain a first understanding of catchment status and behaviour with respect to water and matter dynamics and which will provide foundation for more comprehensive measurement campaigns and modelling approaches.

Intensive research sites

The Bode hydrological observatory includes several intensive research sites (Fig. 1) to study processes and functions in different ecosystem compartments in detail

and to later on build a knowledge base for analysing environmental processes at larger scales. The work in two small headwater catchments concentrates on the analysis of water and matter fluxes in agriculturally used catchments. The *Schäfertal* intensive research site is located in a small headwater catchment in the Lower Harz Mountains with Cambisols being the dominant soil types. It is contrasted by the *Sauerbach* catchment which lies in the Magdeburger Börde region with highly fertile Chernozems of the Central German lowland. Soil–vegetation–atmosphere exchange processes are studied at three intensive research sites. They are located in areas of different land use but close to each other: the *Hohes Holz* intensive research site is situated in a mixed beech forest, the *Grosses Bruch* is a grassland/meadow site, and the *Hordorf* site is in agricultural use. New methods, models and concepts to investigate groundwater–surface water interactions are explored at the *Selke* site. At the *Holtemme* site, research focuses on the structure and functioning of aquatic communities and the effects of both chemical and non-chemical stressors. The *Rappbode Reservoir Observatory* serves for detailed studies of the interactions between reservoirs and catchments with a focus on the quantification of exports of carbon and nutrients from the catchment, its driving processes in the catchment, as well as the consequences of matter fluxes on the ecological state of the reservoir. In the following, we provide a brief overview about the research conducted currently at the different intensive research sites.

The Schäfertal catchment

The Schäfertal catchment (51°39'N, 11°03'E, Figs. 1, 6) is a low mountain headwater catchment in the Lower Harz Mountains covering an area of 1.44 km² (e.g. Borchardt 1982). Hydrological research in the catchment started in 1968, when a runoff gauging station with subsurface barrage that collects the total surface and subsurface outflow from the catchment as well as a meteorological station was installed (Reinstorf et al. 2010). Since these early investigations, a main focus of research in the Schäfertal has been on the characteristics of the long-term water balance at the landscape scale including feedbacks and interactions with climatological, pedological, geological, topographical and ecological factors (Wenk 2004, unpublished report). Currently, the infrastructure in the catchment is operated by the University of Applied Sciences Magdeburg-Stendal, which continuously extended and modernized the research infrastructure. Today, it comprises a modern climate station, a dense groundwater observation network, a multi-parameter water quality probe and automated sampler at the catchment outlet, and several plots to measure soil water content, soil water potential as well as snow water equivalent (Reinstorf et al. 2010). For numerous variables,

records dating back to the 1960s are available. Due to more than 40 years of research in the Schäfertal, the geological and pedological as well as the hydrological (e.g. Borchardt 1982; Becker and McDonnell 1998; Lindenschmidt et al. 2004, Ollesch et al. 2005; Graeff et al. 2009; Ollesch et al. 2010; Reinstorf et al. 2010; Kistner et al. 2013) characteristics of the catchment are very well known. This provides excellent conditions for testing novel measurement and modelling approaches for understanding the hydrological functioning of the catchment.

To this end, the already existing research infrastructure of the Schäfertal catchment has recently been extended by a number of new state-of-the-art measurement technologies with a focus on the monitoring of soil moisture content at different scales. At the point scale, the SOILCan lysimeters (Pütz et al. 2011, 2016) allow for a detailed monitoring of soil moisture dynamics and the separation of the different water balance components (e.g. Hannes et al. 2015). In addition, a VAdose Zone MOnitoring System (VAMOS) consisting of a lysimeter and a similarly instrumented measurement chamber at the position of lysimeter excavation allows for the identification of lateral flow processes in the undisturbed field soil, a process which cannot be determined using standard lysimeters. At the hillslope scale, a wireless monitoring network (Bogena et al. 2010; Martini et al. 2015; Qu et al. 2013) provides spatially distributed information about soil moisture and soil temperature dynamics from three different depths and helps to identify dominant hillslope hydrological processes (Martini et al. 2015). In addition, at the same hillslope, a time-lapse digital snow camera allows for the quantification of snow accumulation and melt and, in combination with the wireless sensor network, the analysis of near-surface freeze/thaw processes. At the larger scale, four cosmic-ray neutron soil moisture probes (Zreda et al. 2012) are being employed for a few years to continuously and non-invasively monitor integral values of soil moisture content within a footprint radius of up to 240 m and down to 80 cm depth (Köhli et al. 2015). This continuous monitoring is complemented by campaign-based measurements of soil moisture content or soil moisture proxies using traditional (e.g. TDR; Schröter et al. 2015), geophysical (e.g. electromagnetic induction (EMI), e.g. Martini et al. 2016; gamma spectroscopy, e.g. Dierke and Werban 2013), mobile cosmic-ray neutron surveys (e.g. Chrisman and Zreda 2013) as well as airborne and space borne remote sensing techniques, i.e. predominantly hyperspectral (e.g. Lausch et al. 2013a, b; Pause et al. 2014; Paz-Kagan et al. 2015) and active radar (SAR) measurements (e.g. Jagdhuber et al. 2013). With this, a research infrastructure is available which provides on the one hand static spatial information about soil properties and soil quality and, on the other hand, temporally dynamic information about state

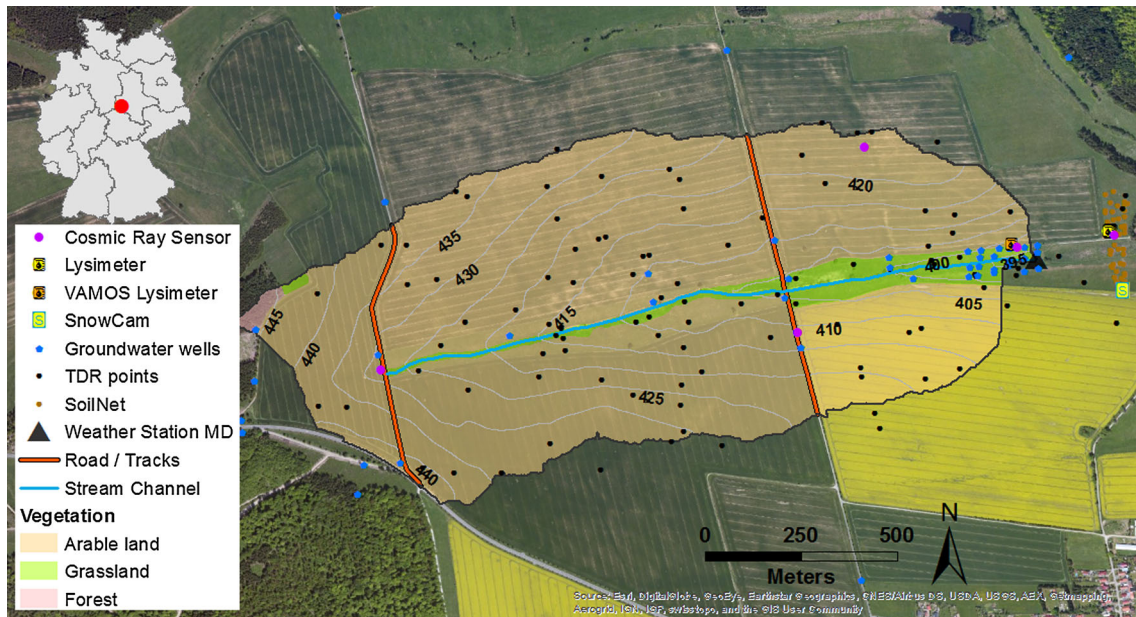


Fig. 6 Instrumentation of the Schäferfalter intensive research site around the Schäferbach creek flowing west-to-east. The map shows permanent installations as well as TDR measurement points being sampled in a time series of measurement campaigns (Schröter et al. 2015). SoilNet indicates positions of the soil moisture and soil temperature monitoring network nodes (Martini et al. 2015). Map of

the study site superimposed over an aerial image (2012) (source: ESRI, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP and the GIS User Community), topographical data: DGM1 © GeoBasis-DE / LVerGeo LSA [2012, 6015798/16]

variables. Both assist in the identification of hydrological processes within the catchment at different spatial and temporal scales.

The main difficulty in hydrological modelling at the catchment scale is the consideration of subsurface heterogeneity of hydraulic properties that follows the structure of the underlying geology and soil formation. In addition, rainfall, evapotranspiration and snowmelt lead to strong temporal dynamics of the system (e.g. Martini et al. 2015; Schröter et al. 2015; Anis and Rode 2015a, b). The combination of heterogeneity and temporal forcing results in dynamic flow networks which determine transport velocities and residence times within the different parts of the catchment.

So far, research in the Schäferfalter catchment has been conducted to identify the hydrologically relevant structural patterns by continuous or campaign-based monitoring of soil moisture at various scales (e.g. Martini et al. 2015; Schröter et al. 2015). These measurements are complemented by time-lapse geophysical (EMI, gamma spectroscopy) and remote sensing measurements [multi-, hyperspectral, thermal, active radar (SAR)] and, prospectively, by estimating the spatial distribution of soil types and soil depths based on modelling of soil formation. The joint evaluation of the various data sets leads to an estimation of the explicit spatial pattern of regions having similar hydraulic properties. Based on these patterns, the

local hydraulic properties can be estimated from the continuous or campaign-based monitoring of soil moisture at different scales. The ultimate goal is to evaluate to what detail the hydrological structure needs to be known to arrive at a consistent hydraulic description of the catchment. This structural information will be an essential part for modelling catchment-scale water dynamics. These types of models and subsequent particle tracking algorithms will allow for a sound estimation of water travel times within the entire catchment. The time water needs to travel through the catchment’s subsurface is a fundamental variable modulating catchment solute export. Its probability distribution can be used to model catchment-scale solute export in a spatially integrated way (e.g. van der Velde et al. 2010). The goal is to reveal the dominant controls of travel time distribution in catchments. Using process-based catchment-scale numerical models of surface as well as subsurface water flows (unsaturated zone and groundwater), the spatial and temporal characteristics of travel time distribution within the catchment can be evaluated. We hypothesize that the probability distribution of travel times (i.e. the age distribution) of water leaving the catchment and of water residing in the catchment storage significantly deviates from each other as a result of climatic forcing. By the numerical models, the level of detail needed to adequately characterize dynamic travel time distributions as proxy for solute dynamics to

ultimately develop parsimonious modelling tools which can be transferred to less data-rich catchments and to larger scales will be assessed.

The Sauerbach catchment

The Sauerbach headwater catchment (52°04'N, 11°16'E; Figs. 1, 7), located in the Magdeburger Börde region, which in contrast to the Schäfertal catchment (“The Schäfertal catchment” section) is a fertile and intensively used agricultural lowland area where decades of intensive agricultural activity have led to a significant deterioration of groundwater and surface water quality. From the spring to the gauging station at the catchment outlet, the Sauerbach drains a surface area of 1.4 km² and has a length of 1.1 km. Mean runoff is 13.9 l s⁻¹ (01.07.2010–30.06.2013).

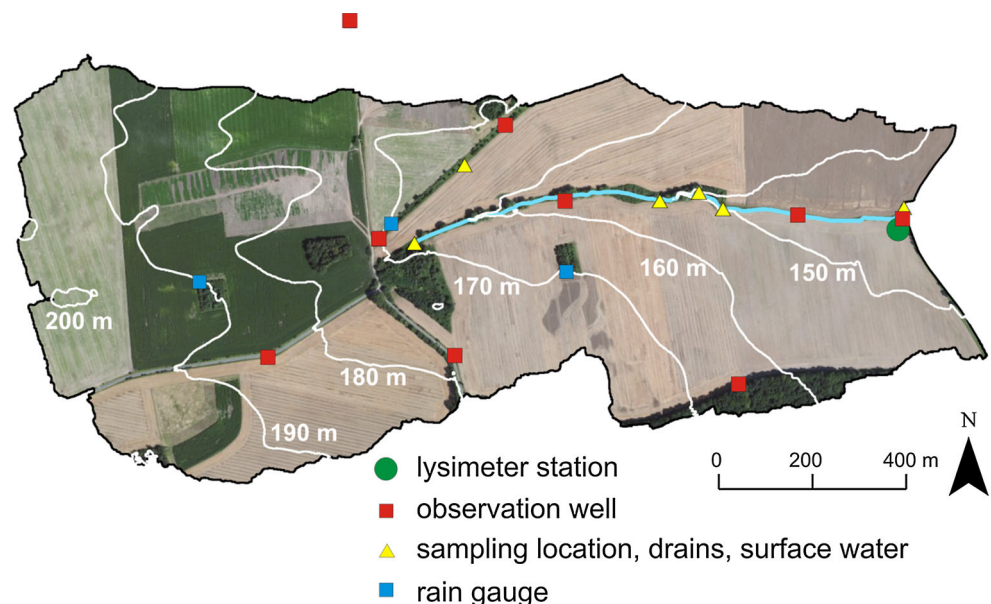
The general goal of research at the Sauerbach is the assessment of water and solute fluxes in a lowland headwater catchment. To this end, activities focus on the spatial and temporal dynamics of these fluxes in all terrestrial compartments: the unsaturated and saturated zones, the transition zone between ground- and surface water and the stream itself with a specific focus on agricultural chemicals. The river bed is seen as an important reactor, mediating the flux of agricultural chemicals. Hence, an additional objective of the work at the Sauerbach is the quantification of solute turnover in the river bed and to evaluate the relative importance of geologically controlled groundwater–surface water interactions versus hyporheic exchange.

The Sauerbach catchment is equipped with a climate station and three additional rain gauges to determine the climatic forcing of water and solute fluxes. At the

catchment outlet the streamflow and the integral flux-signal concentrations are measured by a stream gauge in combination with a multi-parameter probe (NO₃-N, turbidity, temperature, electrical conductivity, pH and SAK₂₅₄). Groundwater levels, temperature and electrical conductivity within the Sauerbach catchment are monitored by observation wells and data loggers. Groundwater recharge quantity, quality and its dynamics can be estimated from a SOILCan lysimeter station. Finally, stream and streambed temperature along the Sauerbach are monitored by multi-level temperature probes.

The Sauerbach stream exhibits high concentrations of nitrate (mean 45.73 mg L⁻¹, $n = 79$, Musolff et al. 2016), which raises questions on the origin and future trend of nutrient exports from the catchment. Nitrate concentrations at the catchment outlet exhibit an accretion pattern of increasing concentration with increasing discharge. This export behaviour is very typical for all parts in the Bode catchment where agriculture is the dominant land use (Musolff et al. 2015). A statistical evaluation of hydrological time series revealed that the variance in discharge is largely controlled by groundwater head variance ($R^2 = 0.90$) (Musolff et al. 2016). Moreover, a distinct steady pattern of nitrate concentration decrease with depth was found in the upper aquifer that feeds baseflow to the stream. These two simple groundwater level-discharge and depth-concentration relations can be integrated to model the accretion pattern of nitrate concentration in the receiving stream adapting the concentration-discharge-integration approach of Seibert et al. (2009) developed for riparian solute mobilization ($R^2 = 0.64$, Nash–Sutcliffe efficiency = 0.59). This shows that stream discharge is generated from different spatial units of the catchment as a

Fig. 7 Instrumentation of the Sauerbach intensive research site. Map of the study site superimposed over an aerial image (2012) (source: ESRI, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP and the GIS User Community)



function of groundwater levels. Even though there are local-scale heterogeneities of hydraulic and chemical properties, the catchment-scale integrated solute flux signal can thus be effectively modelled with this parsimonious data-driven approach (Musolff et al. 2016).

Finally, the river bed is seen as an important reactor, mediating the flux of agricultural chemicals. An additional objective of the work at the Sauerbach is the quantification of solute turnover in the river bed and to evaluate the relative importance of geologically controlled groundwater–surface water interactions versus hyporheic exchange.

The Selke intensive research site

The river Selke is a tributary to the Bode River and drains a catchment of 483 km² (Figs. 1, 8). Along an approximately 1-km-long river section, 3 km downstream of the Meisdorf gauging station a test site for studying stream–groundwater interactions was developed (Schmidt et al. 2012). The long-term mean discharge at the Meisdorf gauge is 1.5 m³ s⁻¹. The reach is characterized by a nearly natural morphology with meanders, pool-riffle sequences, point bars and mid-channel bars. Hydraulic conductivities of the streambed are in a range between 2.7 10⁻⁴ and 6.0 10⁻³ m s⁻¹ as obtained from slug tests.

Research activities at the Selke test site focus on the spatio-temporal patterns and dynamics of water flow and solute transport within these morphological features. It is of particular interest how varying discharge and alternating hydraulic gradients with the ambient groundwater level influence pathways and residence times in the streambed. It is hypothesized that the residence time of stream water in the streambed significantly influences solute turnover and stream metabolism. Reactions in the streambed are essentially controlled by the redox conditions, which are in turn strongly influenced by hydraulically governed flows and water residence times. For instance, denitrification can only occur when oxygen concentrations have declined below a certain threshold (e.g. 1 mg/l), which is a function of residence time in the hyporheic zone. One other key parameter is streambed temperature. Temperature controls microbially mediated reactions and is a crucial parameter for reactive transport modelling. The key objective at the Selke test site is to better understand which hydraulic and morphological factors control the metabolic activity of the hyporheic zone.

The Selke intensive research site is specifically equipped for monitoring hyporheic zone processes (Fig. 8). Stream and streambed temperatures are continuously monitored with multi-level temperature probes to estimate spatial and temporal variability of streambed water fluxes (Munz et al. 2016). Hydraulic heads and gradients, water chemistry and isotopic data are monitored in a network of in-stream and

riparian piezometers. Those data are used to parameterize reactive transport models of the hyporheic zone (e.g. Trauth et al. 2013, 2014, 2015). Monitored diurnal temperature oscillations also serve as natural tracer to estimate direction and magnitude of water flow in the streambed. This information is used as additional constraints for calibrating flow models. Electrical conductivity is continuously monitored in the stream and the streambed and is also used as natural tracer to derive travel times in the streambed. Vertical profiles of dissolved oxygen are measured between the streambed surface down to a depth of 0.4 m applying a newly developed optical oxygen profiling method (Vieweg et al. 2013). The investigations are supplemented by an adaptive approach of time-lapse geophysical (e.g. geoelectrical tomography) and direct push-based measurements for characterization of morphological structures.

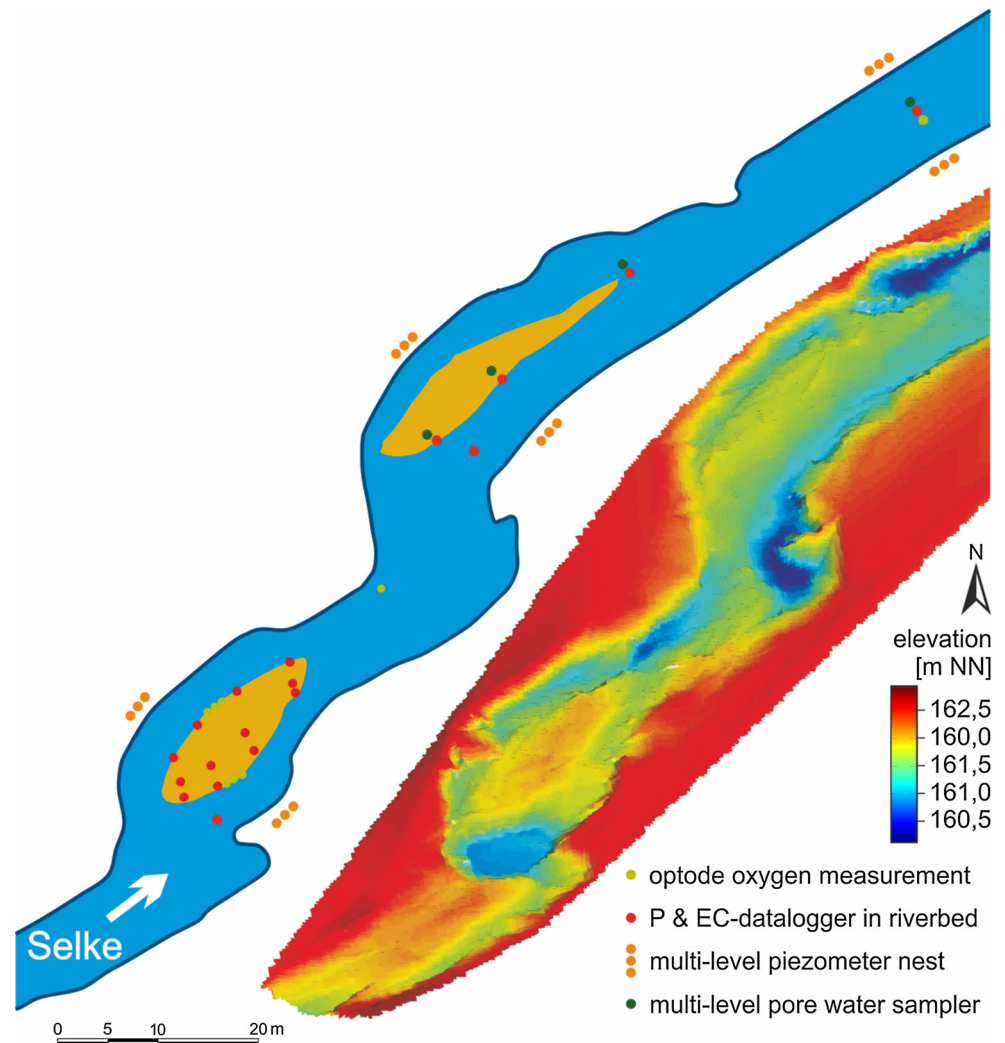
The Holtemme intensive research site

The Holtemme River is a third order river that originates in the Harz National Park at 862 m a.s.l. and flows into the Bode River. It has a length of 47 km and long-term mean annual discharge of 1.34 m³ s⁻¹ (gauging station Mahndorf). Land use in the catchment is dominated by agriculture (60%), followed by forests (30%) and urban (10%) areas (Figs. 1, 5). The distribution of land use types is reflected in the hydromorphology that is natural in the upstream sections but highly impacted due to channelization, riparian clearcutting and incision in urban and agricultural areas. Moreover, the river receives substantial inputs of nutrients as well as a large range of urban chemicals from two wastewater treatment facilities having a population equivalent of more than 40,000 each and from tributaries draining agricultural areas. With its incremental increase of human stressors, the Holtemme River is a typical example of a multiple stressed ecosystem.

Research activities at this intensive site focus on the interdisciplinary study (including the fields of aquatic ecology, biogeochemistry and ecotoxicology as well as hydrology) of the effects of the longitudinal increase of human stressors on ecosystem structure and functioning. Taxonomically grounded ecological research is linked with concepts rooted in ecosystem ecology like organic matter cycling, productivity and ecosystem stability to identify causal relationships between stressors and their effects.

In order to characterize temporal variation in the longitudinal development of water quality, the Holtemme River has several automated measurement stations equipped with multi-parameter probes (cf. MOBICOS sites in Fig. 1 and “Linking monitoring and experiment: the mobile aquatic mesocosms MOBICOS within TERENO” section). Two of these stations are equipped with large

Fig. 8 Instrumentation of the Selke intensive research site. Map of the river reach and measurement locations (*left*); topographical map of the river and surrounding (*right*)



volume solid-phase extraction devices for automated high-resolution sampling of organic pollutants including pesticides. In order to reveal a mechanistic understanding on the ecological processes and the interactive effects of multiple stressors, the observations in the Holtemme are linked with experimental process studies in mobile field mesocosms placed next to the river (see “[Linking monitoring and experiment: the mobile aquatic mesocosms MOBICOS within TERENO](#)” section).

The Rappbode Reservoir Observatory

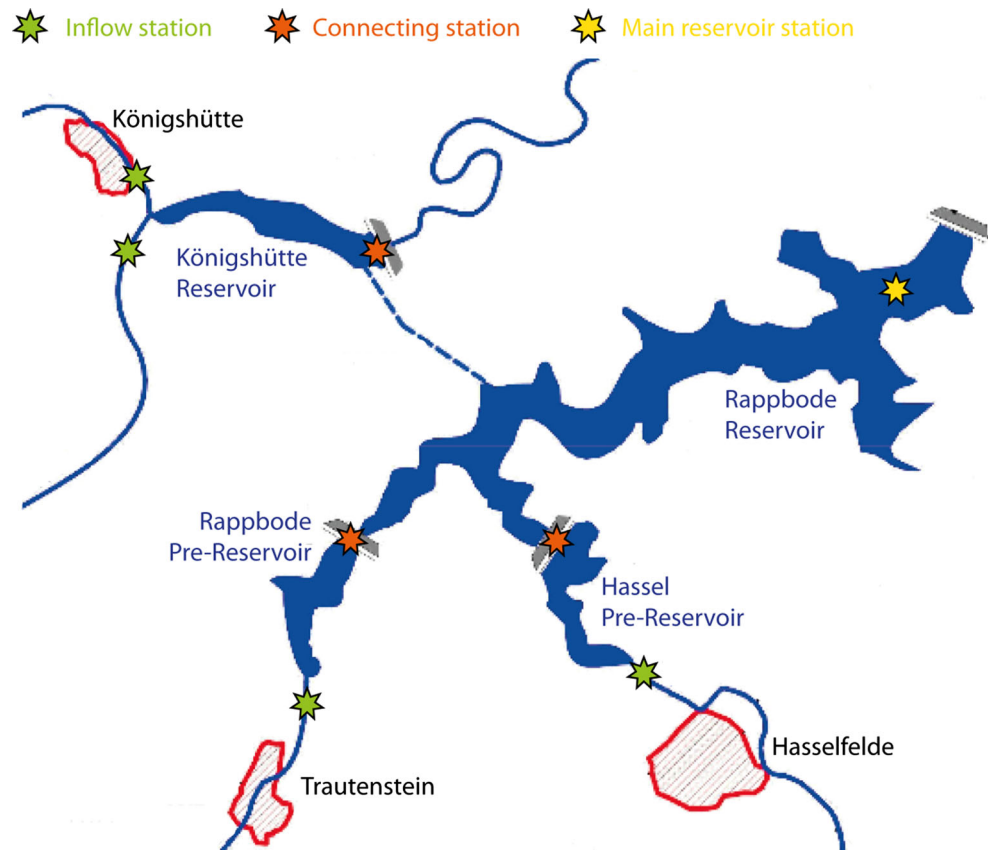
The Rappbode Reservoir system (Figs. 1, 9) is located in the Harz Mountains. Its catchment has an area of 520 km² and provides drinking water to more than 1 Mio people in central East Germany. Having a maximum depth of almost 90 m and a maximum volume of about 100 × 10⁶ m³, the Rappbode Reservoir is the largest drinking water reservoir in Germany. The catchments of the three major tributaries (Bode, Hassel and Rappbode) into the reservoir, each of

them being separately dammed by smaller pre-dams, are contrasted by different land use characteristics with large differences in nutrient loading and exports of dissolved organic carbon (DOC; Friese et al. 2014).

The aim of the work within this intensive research site is to study the interactions between reservoirs and their catchment. The dynamics of reservoirs are conceptually viewed as being simultaneously driven by external inputs from the catchments (e.g. import of organic carbon) and internal processes within the reservoir (e.g. production of organic carbon by algal photosynthesis). This importance of external and internal processes changes over time, for instance, due to inflow dynamics or plankton community dynamics.

The main research focus at the Rappbode Reservoir Observatory is on the quantification of exports of carbon and nutrients from the catchment, its driving processes in the catchment, as well as the consequences of these matter fluxes for the ecological state of the reservoir. Particular attention is paid to the dynamics of DOC, which showed a

Fig. 9 Map of the Rappbode Reservoir Observatory. Coloured stars indicate the position of monitoring stations



consistently increasing trend over the past 20 years in the Rappbode Reservoir leading to a degrading water quality and more demanding efforts in the drinking water preparation of the raw water.

To this end, physical, chemical and biological parameters are continuously monitored by automated measurement stations at nine locations in and around the reservoir system (Fig. 9; Rinke et al. 2013). This includes stations at all tributaries, at the connecting infrastructures in between the pre-dams and the main reservoir, as well as within the main reservoir. Besides automated sampling stations also a detailed limnological monitoring programme in the water bodies is conducted on a fortnightly sampling regime.

Intensive sites for investigating soil–vegetation–atmosphere transfer processes

Soil–vegetation–atmosphere transfer processes are investigated at the intensive research sites *Hohes Holz*, *Grosses Bruch* and *Hordorf* (Figs. 1, 10). The main research goal at these sites is the understanding of the energy, water and carbon cycles of the ecosystem. Thus, intensive monitoring of energy, water, and trace gas stocks and fluxes between the ecosystem and the atmosphere in addition to extensive meteorological observations is performed. It aims to characterize the processes and their driving forces and

wants to partition the trace gas exchanges into their individual components. Energy fluxes measured at the site include short- and long-wave radiation, sensible and latent heat fluxes, as well as the ground heat flux.

The measurements at *Hohes Holz*, *Grosses Bruch* and *Hordorf* will be complemented by soil–vegetation–atmosphere transfer (SVAT) modelling (Ogée et al. 2003). The detailed observations of, for example, ecohydrological variables will be mirrored in a detailed modelling of the individual flux components. The comparison between the three sites will allow testing hypotheses, for example, about different water use strategies of the different plants or ecosystems and will therefore allow a transfer of modelling strategies to other sites. In addition, the connection with remote sensing products from air planes as well as satellites will improve the possibility to upscale fluxes up to larger regions.

Intensive research site ‘Hohes Holz’ The research site *Hohes Holz* (Figs. 1, 10) is a mixed beech forest at the northern border of the Bode catchment (52°05’N, 11°13’E, 210 m a.s.l.). At this site, individual incoming and outgoing water fluxes are partitioned in detail. Precipitation is measured above and below canopy. Precipitation below canopy is determined as stemflow, throughfall and open land precipitation. Total evapotranspiration is measured

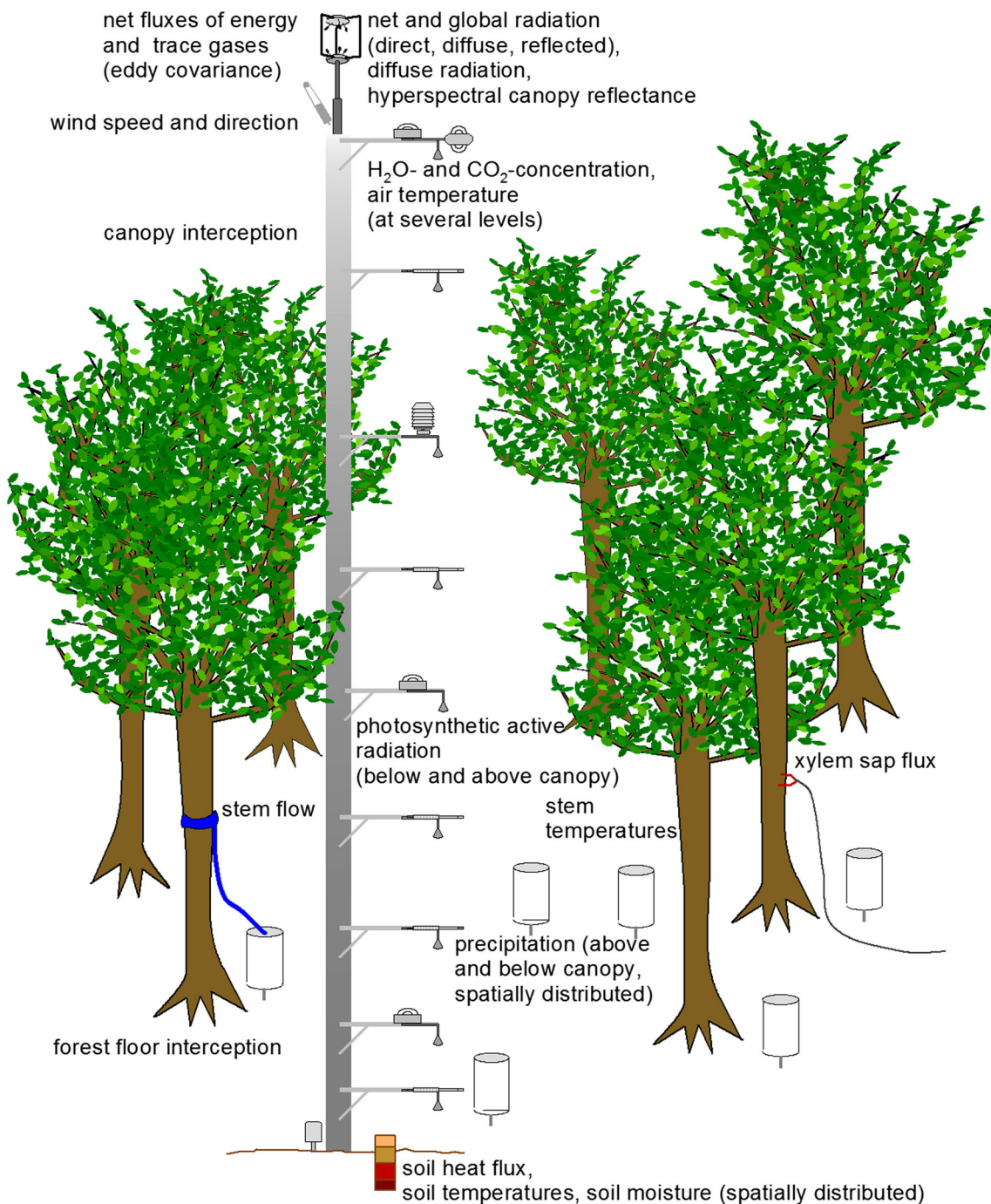


Fig. 10 Exemplary instrumentation of the Hohes Holz forest site

with the eddy covariance technique on a tower at 49 m height. Transpiration of the trees is ascertained with sap flux measurements on selected trees, forest floor interception is determined with gauges, and soil moisture changes are determined with the help of a distributed soil moisture network. Additionally, soil moisture profiles facilitate derivation of vertical water flow. The carbon fluxes are net ecosystem exchange (NEE, from eddy covariance), soil and aboveground biomass increments and continuous soil

respiration with bi-weekly spatially extended surveys as well as continuous measurements on selected plots. The instrumentation consists of standard techniques such as Eddy covariance (Baldocchi et al. 1996; Mauder et al. 2013) and meteorological variables according to the standard of the ICOS network, individual solutions such as trough-type collectors for throughfall (Crockford and Richardson 2000; Staelens et al. 2008) and experimental set-ups such as forest floor interception devices (Gerrits

et al. 2007). A sweep of additional variables is measured including soil moisture at high spatial and temporal resolution with a wireless sensor network (Bogena et al. 2010; Qu et al. 2013) as well as tree characteristics (Van Stan et al. 2015), bi-weekly leaf area index with digital images, phenology, fluorescence and hyperspectral reflectance. The forest site *Hohes Holz* is a class 1 site of the ICOS ecosystem component (<http://www.icos-infrastructure.eu>).

Intensive research site ‘Grosses Bruch’ The research site *Grosses Bruch* (Fig. 1) is a mesophilic grassland used as meadow, within a nature protection site surrounding the water channel Grosser Graben (52.01°N, 11.06°E, 78 m a.s.l.). The grassland is usually flooded naturally once or twice a year and is thus prone to produce methane fluxes. Eddy covariance measurements of energy, water, carbon dioxide as well as methane are conducted at the site *Grosses Bruch*. Meteorological conditions as well as spatially distributed soil moisture and soil temperature in several depths are observed continuously, accompanied by bi-weekly acquisition of soil respiration. In general, all measurements are performed in the same way as described for the forest site above, besides the partitioning of the water fluxes. The research site *Grosses Bruch* is an associated site within ICOS.

Intensive research site ‘Hordorf’ An agricultural site close to the village Hordorf (52.00°N, 11.10°E, 80 m a.s.l., Fig. 1) is equipped almost equally to the grassland site except for methane fluxes. Fluxes of energy, water and carbon dioxide are measured with the eddy covariance technique, and meteorological variables are determined as well. The site is managed on a rotational basis so that the installation of spatially distributed soil sensors is not possible due to management activities such as harrowing or sowing. The surrounding of the Eddy covariance tower is managed separately, and soil temperatures and moisture are measured in one profile down to a depth of 0.7 m.

Linking monitoring and experiment: the mobile aquatic mesocosms MOBICOS within TERENO

In addition to the observational studies within TERENO, targeted experiments that facilitate detection of causalities between anthropogenic stressors and ecological status of surface waters constitute an important pillar of water research. In this respect, the experimental mesocosm platform MOBICOS was placed at representative sites within the Bode River network (Fig. 1) according to the results of preceding large-scale hydrochemical and biological field studies (cf. Kamjunke et al. 2013, 2015a). MOBICOS are container-based laboratories operated as bypasses to surface water bodies, thereby establishing a hybrid between

laboratory and field studies. This approach allows a targeted experimental manipulation of selected environmental variables, whereas the physicochemical background of the water remains unchanged (Liess and Schulz 1999). Briefly, unaltered surface water is continually pumped into MOBICOS and subsequently distributed to different experimental facilities such as monitoring devices, laminar flow channels, rotating reactors of sediment–water compartments, which mimic the conditions in different compartments of the aquatic ecosystem. Within these experimental devices the ecological effects of selected stressors including nutrients, particulate and dissolved organic matter, chemicals or water temperature as well as their interactions can be tested. Currently, eight MOBICOS containers are positioned along the typical land use gradient that characterizes the TERENO observatory, ranging from very pristine sites in the Harz Mountains to moderately and highly imprinted sites in the lowland (Fig. 1). Due to its compact design MOBICOS can be shifted to sites of interest such as the Holtemme intensive site. In this arrangement, MOBICOS provides a hand-in-hand tool together with the ecological observations within TERENO as well as ecological modelling, which supports the mechanistic understanding of the ecological processes.

Examples for catchment-scale investigations

Biogeochemical characterization of the Bode River network

A biogeochemical characterization of the Bode River network was conducted in 2011 (Kamjunke et al. 2013). It focused on the detection of longitudinal gradients from the headwaters to the lowlands along the gradient of land use. A sampling field campaign was conducted where measurements were done nearly simultaneously at 31 measurement sites. Many of the measured parameters increased in concentration from unimpaired upstream reaches in the Harz National Park (predominantly forest) to highly affected downstream reaches (intensive agriculture and industrial land use) reflecting anthropogenically induced environmental gradients. Particularly, nutrients (ammonium, nitrate, phosphorus) were discharged from agricultural and urbanized areas into the rivers. As an example, the concentration of soluble reactive phosphorus (SRP; Fig. 11), which is the limiting nutrient for the autotrophic growth of planktonic algae, and chlorophyll *a* and total phosphorus concentrations were positively correlated. In contrast, the concentration of dissolved organic carbon (DOC) as a basis for heterotrophic growth of bacteria was higher in some headwaters than in downstream reaches (Fig. 11), whereas the specific UV absorption (SUVA) as a measure of humic content was higher in headwater regions

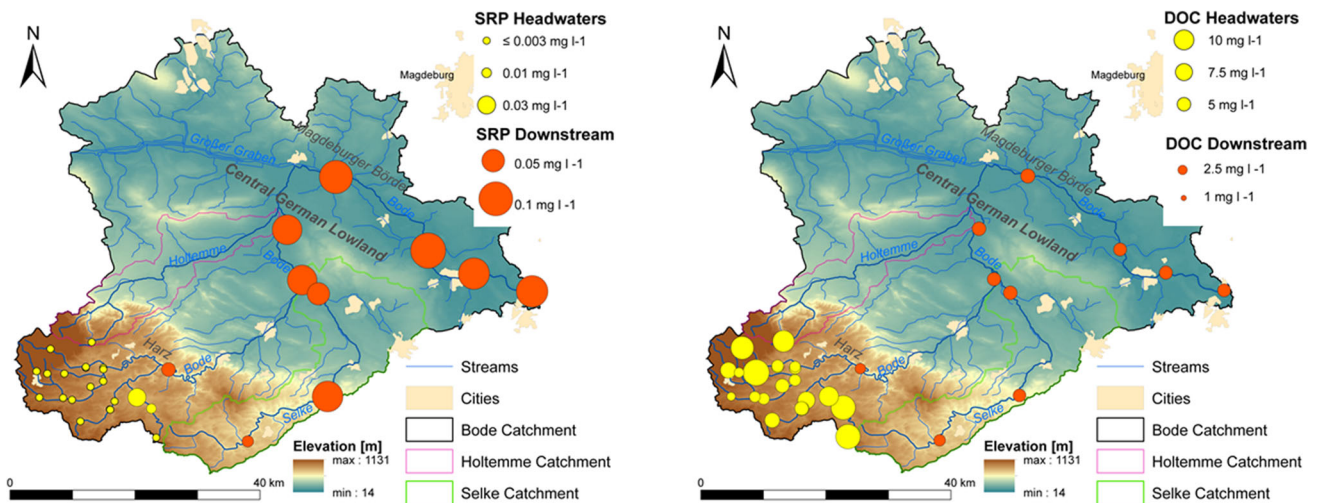


Fig. 11 Spatial distribution of (left) soluble reactive phosphorus (SRP) and (right) dissolved organic carbon (DOC) in the surface water of the Bode River and its tributaries in September 2011

draining the forests. Some indicator parameters were suitable for the characterization of different land use such as dissolved copper for urbanized areas, aluminium in the sediments for soil erosion, carbon parameters for biological metabolism and dissolved arsenic for point sources of former mining activities.

In a second field campaign, the catchment-wide investigation was extended to stream biofilms which are a central part of the research. Regarding the elemental composition, biofilms were enriched in metals compared to their concentrations in water, and manganese and arsenic were negatively related to the biomasses of biofilm diatoms and cyanobacteria (Kamjunke et al. 2015). The biogeochemical characterization of the catchment allowed focusing on functional traits of the streams afterwards, e.g. the measurement of microbial production or degradation rates. The biomass production of heterotrophic bacteria clearly depended on the quality of dissolved organic matter which in turn was affected by land use in the catchment (Kamjunke et al. 2015). Further detailed research, e.g. flume experiments in mobile mesocosms, might be performed at suitable sites detected by the catchment characterization.

High-resolution water quality monitoring in the Selke/Bode River system

In the mesoscale catchments of the Selke (Jiang 2014; Jiang et al. 2014, 2015) and Bode River, six high-frequency water quality measurement stations have been implemented at the river discharge gauge stations Silberhütte, Meisdorf, Hausneindorf and Hadmersleben as well as in Athensleben and at the discharge gauge station in the town Stassfurt (Fig. 1). These stations are supplemented by the

already existing long-term water quality investigation in the small Selke headwater stream Schäferbach (see “The Schäfertal catchment” section). These high-frequency online measurements open up new opportunities to understand the links between catchment hydrology and stream water chemistry (e.g. Kirchner et al. 2004; Kirchner and Neal 2013). High-frequency monitoring has the potential to greatly increase the accuracy of river load estimates. This is especially true for sediment bound nutrients and contaminants, which change their concentrations rapidly in time and are transported to downstream waters during brief intensive episodes (e.g. heavy metals, PAH) (Horowitz 2013; Meybeck and Moatar 2012; Rode and Suhr 2007). The implementation of the water quality gauge stations has been conducted in close cooperation with the State Office of Flood Protection and Water Management (LHW) Saxony-Anhalt. Automatic samplers and water quality sensors (TRIOS optical and YSI sensors) allow event-based temporally high-resolution sampling with flexible sampling frequencies (15–180 min). Soluble variables like phosphorus, potassium, DOC as well as suspended particulate matter are currently sampled during high flow events. Remote data transfer ensures online control of the measurement devices. The new monitoring system is coordinated with already existing water quality measurements conducted in the Bode catchment. Figure 12 shows an example of continuous measurements (10-min frequency) of the selected water quality variables discharge, electrical conductivity, pH, soluble oxygen and nitrate-N. Nitrate-N concentrations show a clear relationship to the discharge with highest concentrations in the first autumn discharge peak. Electrical conductivity shows the opposite behaviour with decreasing values during elevated discharge. Oxygen concentration and pH show maximum

diurnal variability in spring, which indicates increased primary production by phytoplankton during low flow conditions. These continuous sensor measurements are also used to estimate assimilatory NO_3^- uptake and to compare these estimates with metabolic rates at daily and yearly timescale. Using this new high-frequency water quality data type allows to calculate NO_3^- uptake rates on a daily basis and to identify typical yearly patterns of in-stream assimilatory NO_3^- uptake. Recently, daily assimilatory NO_3^- uptake of the whole stream network as a percentage of the total stream NO_3^- input load was calculated (Rode et al. 2016). Furthermore, high-resolution monitoring can greatly support identification and modelling of nutrient transport processes at the catchment scale (Hesser et al. 2010; Shrestha et al. 2007, 2013). Recent studies suggest that the new type of water quality data can also considerably reduce the uncertainties of catchment water quality models (Jiang 2014).

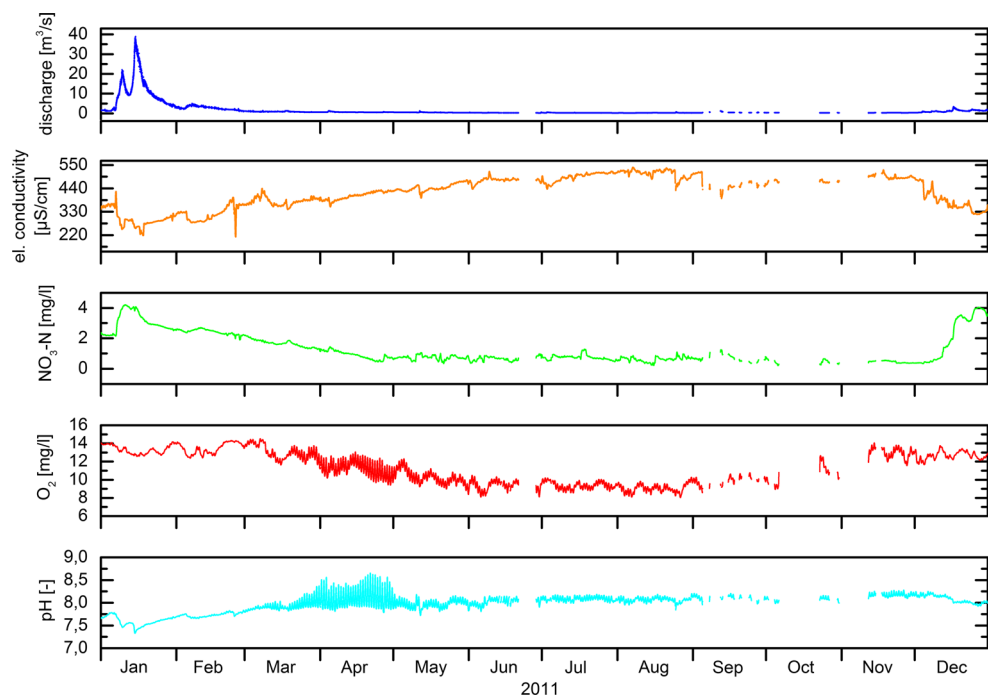
Multi-isotope monitoring approach using modelled discharge time series

Isotope studies conducted on large spatial and temporal scales can provide powerful insights into natural ecosystem processes and the effects of anthropogenic influences. Therefore, the Bode River catchment was intensively investigated by a two-year monitoring approach with 133 sampling locations representing the same number of subcatchments. Besides a seasonal measurement conducted at all sites, 25 intensive

observation points spread over the entire catchment have been sampled monthly (Fig. 13). Laboratory analyses on stream water were conducted for stable isotope signatures of water ($\delta^{18}\text{O}$, $\delta^2\text{H}$), sulphate ($\delta^{34}\text{S}$ and $\delta^{18}\text{O}$), dissolved inorganic/organic carbon ($\delta^{13}\text{C}_{\text{DIC/DOC}}$) and nitrate ($\delta^{15}\text{N}$ and $\delta^{18}\text{O}$). The concentration of major anions and cations was analysed as well as the amount of dissolved organic, inorganic and total carbon.

Because discharge observations have not been available at all 133 sampling points, the mesoscale Hydrological Model (mHM; www.ufz.de/mhm/) was used for estimating runoff at those locations. mHM is a process-based, spatially explicit, multi-scale hydrological model that explicitly accounts for the subgrid variability of essential basin physical characteristics using the Multiscale Parameter Regionalization scheme proposed by Samaniego et al. (2010) and further developed by Kumar et al. (2013). The water balance of many tributaries in the Bode River is influenced by water management activities or industrial water extraction. The model was fed with observed discharge time series at locations downstream major reservoirs (e.g. the Rappbode dam) to minimize the effects of these anthropogenic activities. mHM represented the streamflow observed at the (Bode) basin outlet with a Nash–Sutcliffe efficiency (NSE) of 0.75 during the validation period 1980–1999. The evaluation at other 19 gauging stations further confirmed the capability of the model to make reliable discharge predictions for all sampling points. Using simulated discharge time series, a load-based interpretation of hydrochemical and isotope

Fig. 12 High-resolution time series of runoff and water quality data measured at the Meisdorf gauging station in the Selke River catchment. The high daily amplitudes of O_2 concentrations and pH values are caused by in-stream primary production primarily in spring when leaf cover is still low



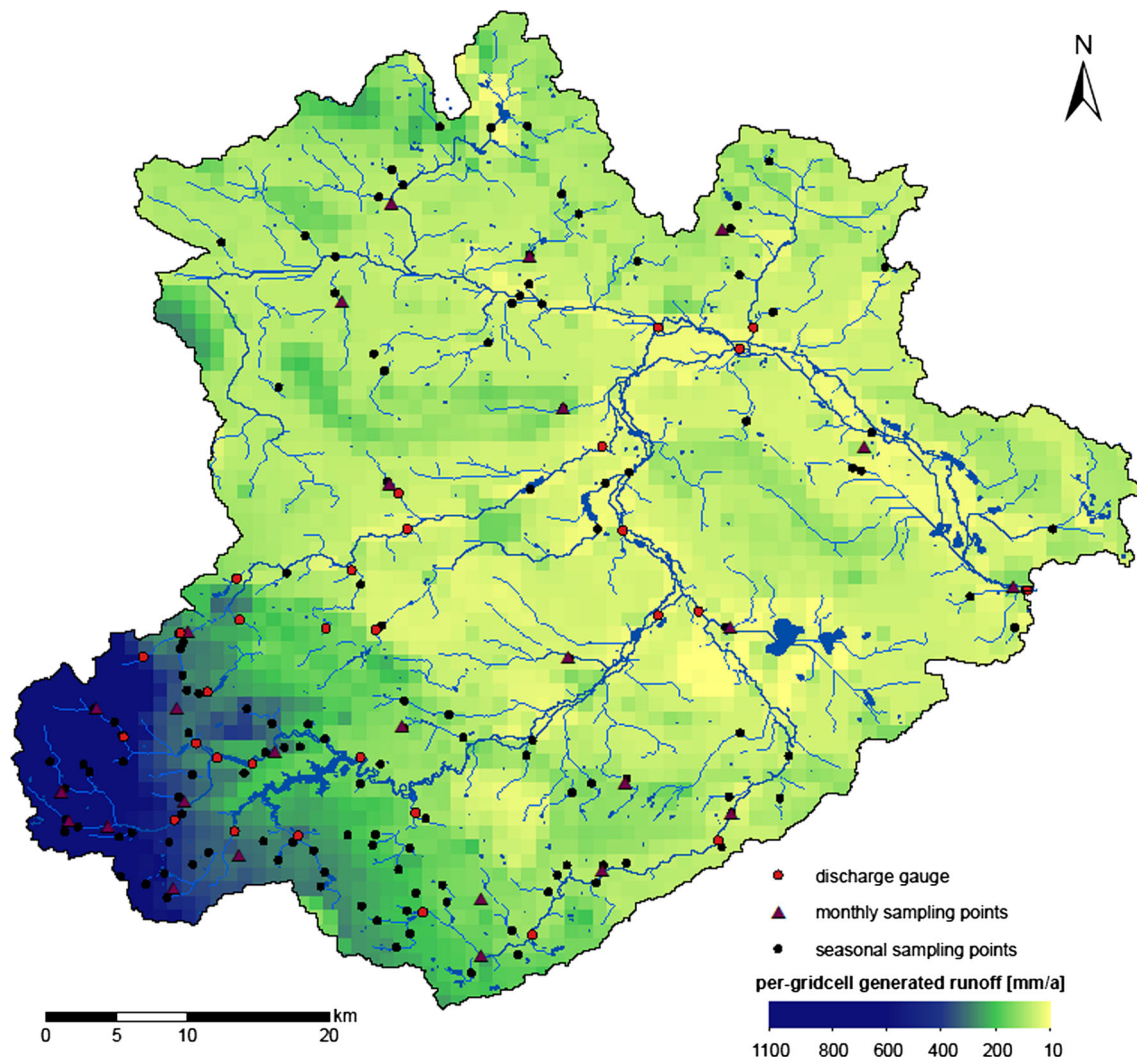


Fig. 13 Bode catchment with its main tributaries, discharge stations, monthly and seasonal sampling stations for isotope monitoring and mHM-grid cell simulated mean annual runoff (1980–2013)

observations is conducted, to evaluate the impact of anthropogenic, climatic and topographical factors.

Mueller et al. (2015, 2016) found that anthropogenic influence from agriculture and wastewater governs the original isotope signature within the stream, increasing along a gradient from the mountains towards the lowlands. They concluded that nitrate loads in the Bode catchment could only be controlled by preventive measures, especially through an optimized land use/cover management plan.

Summary, conclusions and future work

This article provides an overview of the Bode catchment which is part of the TERENO Harz/Central German Lowland Observatory, accompanied by examples and first

results of the interdisciplinary and integrated research on the functioning of the catchment. The Bode catchment serves as an integral platform for research that addresses complex environmental problems by merging expertise from different disciplines such as hydrology, pedology, biology, biogeochemistry, atmospheric sciences, geophysics and remote sensing, with a focus on hydrology (a summary of the activities presented in this paper is provided in Table 1). Although TERENO research in the Bode catchment is still in its initial phase and the measurement infrastructures have been built up only a few years ago, the first few years of research have already demonstrated how multi- and interdisciplinary research conducted at joint sites (or in the same area) can provide comprehensive, rich data sets which allow new insights into and interpretations of the functioning of catchments. In addition, it facilitates both, the development of new approaches in monitoring

Table 1 Summary of interdisciplinary activities in the Bode catchment based on the examples provided in “Examples for research in the Bode hydrological observatory” section

Site	Objective	Involved disciplines
Schäferfalter catchment	Landscape-scale water balance including feedbacks and interactions with climatological, pedological, geological, topographical and ecological factors	Water management, soil physics, (hydro-)geophysics, remote sensing, hydrogeology, community ecology, hydrological modelling
Sauerbach catchment	Assessment of water and solute fluxes in a lowland catchment	Hydrogeology, aquatic ecology
Selke intensive research site	Stream–groundwater interactions	Hydrogeology, environmental modelling, geophysics, aquatic ecology, fluvial ecology
Holtemme intensive research site	Relative effects of multiple human stressors on ecosystem structure and functioning	Aquatic ecology, biogeochemistry, ecotoxicology, hydrology
MOBICOS research facilities	Experimental testing of hypotheses on multiple stressor effects on aquatic biota and processes	Aquatic ecology, biogeochemistry, ecotoxicology, food webs, hydrodynamics
Rappbode Reservoir Observatory	Reservoir–catchment interactions with focus on exports of carbon and nutrients from the catchment and influence on the ecological state of the reservoir	Lake research, hydrogeology, hydrogeochemistry
Hohes Holz, Großes Bruch, Hordorf	Soil–vegetation–atmosphere transfer processes	Micrometeorology, ecohydrology, environmental modelling, soil physics
Bode catchment	Biogeochemical characterization of the Bode River network	Aquatic ecology, biogeochemistry
Selke/Bode river system	High-resolution water quality monitoring	Aquatic ecology, hydrological modelling
Bode catchment	Multi-isotope monitoring	Catchment hydrology, hydrological modelling

and modelling to address specific environmental questions as well as the integration of new measurement technologies, into catchment research.

Monitoring infrastructures in the different compartments (surface waters, vadose zone, groundwater and lower atmosphere) have started to provide the urgently required high-resolution long-term time series of environmental data, which can now be employed to set up and run models which help to understand the functioning of catchments at different scales. This will in turn support the ultimate goal, which is to assess and to predict the influence of climate and land use change as well as current and future human activities on catchment functioning.

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