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Special Section: Hydrological Observatories

Core Ideas

- Awareness of hydrological observatories needs to be increased.
- These 23 papers document hydrological observatories on four continents.
- Hydrological observatories can help to solve relevant and important scientific questions.

Toward Better Understanding of Terrestrial Processes through Long-Term Hydrological Observatories

H.R. Bogena,* T. White, O. Bour, X. Li, and K.H. Jensen

Observation of hydrological processes has a long-standing tradition covering various climatic, hydrologic, geologic, and geomorphologic conditions. Hydrological observations are either organized in dedicated observatories focused on hydrology or within larger environmental observatories that address processes from the atmosphere to the groundwater. In this special section, we document hydrological observations currently conducted in long-term hydrological observatories and other multidisciplinary observatories across the world. Besides monitoring basic climatic and hydrological variables, dedicated experiments are performed in many of these observatories. Hydrological observatories have proven to be crucial for the advance of the hydrological and greater Earth surface and environmental sciences. The accrued benefits include the development of integrated hydrological models that consider complex feedbacks between hydrological compartments. It is of utmost importance to increase awareness and knowledge of these infrastructures to optimize exploration of new hypotheses in hydrology and neighboring and allied disciplines. This special section consists of 23 papers documenting hydrological observatories on four continents covering diverse environmental conditions and research aspects of catchment science. We expect that the use of worldwide long-term hydrological observatories across multiple compartments will help to solve important relevant scientific and societal questions.

In the coming decades, anticipated changes in the water cycle will be a major driver in shaping our environment and ecosystems. Access to clean water is vital for humanity and it is a key factor for sustaining food and biomass for energy production in today's bio-based economies. The water cycle has been strongly affected by anthropogenic impacts such as climate and land use change, but the extent and impact on ecosystem functioning and services are only beginning to be known. Hydrological extremes, such as floods and droughts, are expected to occur more frequently and with more severity, leading to critical ecological, economic, and societal impacts.

Sustainable water management as well as prediction of the hydrological consequences of climate and land use change require a solid scientific understanding of Earth surface processes at the catchment scale. The fluxes of water, energy, and matter within and between hydrological compartments occur across a variety of spatial and temporal scales as a consequence of the complexity and heterogeneity of catchment characteristics. In recent years, new developments in ground-based (in situ), airborne, and satellite-borne instrumentation have made it possible to measure states and fluxes at unprecedented spatial and temporal resolutions. This has enabled the creation of databases of long-term time series of states and fluxes, providing a basis for improving our understanding of integrated hydrological behavior and for testing of crucial scientific questions.

With this special section, we hope to give a representative overview of existing hydrological observatories and to increase the awareness and knowledge of these infrastructures and their associated databases. The compilation is not exhaustive but instead provides a good overview of hydrological observatories that are presently operated worldwide. This special section aims to increase the visibility and to communicate the scientific value of hydrological observatories in operation worldwide by providing information on (i) catchment characteristics and available data, (ii) research questions being addressed, (iii) new insights and novel scientific findings, and (iv) future perspectives.

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What Are Hydrological Observatories?

The use of catchments as hydrological observatories dates back to the 1900s. For instance, one of the longest continuous runoff records (1903–2015) derives from long-term hydrological monitoring in the Sperbel- and Rappengraben experimental paired catchments in Emmental, Switzerland (Engler, 1919; Stähli et al., 2016). A few years later, the first experimental paired catchments were established in the United States, including the Wagon Wheel Gap experiment in Colorado (Van Haveren, 1988) and the Coweeta Hydrological Laboratory in North Carolina (Swank and Crossley, 1988). In the 1950s and 1960s the number of experimental catchments increased with the aim to empirically determine the influence of human intervention on hydrological systems (Brantley et al., 2017). The Hubbard Brook catchments established in 1955 were one of the first interdisciplinary experimental sites enabling the detailed study of hydrogeochemical balances (Likens et al., 1977), and soon after the USGS initiated the Hydrologic Benchmark Network of 57 basins (Cobb and Biesecker, 1971). In the 1980s, the US National Science Foundation created the Long-Term Ecological Research (LTER) program to carry out observation-based research across a network of sites that spanned the major biotic regions of North America (Knapp et al., 2012). The LTER network was later expanded to worldwide coverage (Haase et al., 2018).

Long-term historical hydrological data sets are useful in various ways, e.g., for analysis of the generalized extreme value distributions of catchments, of the mechanisms governing runoff, as well as for testing stochastic and deterministic models. These long-term hydrological data are often complemented with geophysical and remote sensing measurements, providing spatial and temporal patterns of catchment properties and states (Robinson et al., 2008; Bogena et al., 2015). Today the concept of the experimental catchment is more and more relevant to a diversity of environmental issues beyond hydrology (Tetzlaff et al., 2017). Well-monitored catchments with multidisciplinary approaches have been included in national and international networks including the Critical Zone Observatories (Brantley et al., 2017; White et al., 2015) and the National Ecological Observatory Network (NEON) (Loescher et al., 2017) in the United States, the German Terrestrial Environmental Observatories (TERENO) network (Zacharias et al., 2011; Bogena et al., 2012), the Terrestrial Ecosystem Research Network (TERN) in Australia (Thurgate et al., 2017), and experimental river basins for integrated watershed study in China such as the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) (Li et al., 2013) and the Chinese critical zone observatories (CZOs). Recently, the European Network of Hydrological Observatories (ENOHA, www.enoha.eu) initiative was established as a European data platform for hydrological observatories (Blöschl et al., 2017). Besides making hydrological data available to the research community, ENOHA aims to also include hydrological models for improved data analysis, for model-driven design of catchment experiments, and to perform hydrological forecasts at the European scale. Such environmental observatory networks and data platforms can also help to answer key questions related to ecosystems and terrestrial research from the continental to the global scale, for example, how ecosystems are changing or adapting to global change stressors, identification of determinants of ecosystem resilience, and threshold interactions resulting in system shifts (Bogena et al., 2017).

Overview of These Hydrological Observatories

This special section consists of 24 papers that present hydrological observatories covering four continents with diverse environmental conditions (Fig. 1) and research aspects of catchment science. The presented hydrological observatories and networks of research sites cover plains, highlands, and mountainous environments as well as various climate zones and geological conditions (Table 1).

This special section covers classical long-term hydrological observatories, e.g., the Hupsel Brook catchment (Brauer et al., 2018; Fig. 1, no. 15) and the Strengbach catchment (Pierret et al., 2018; Fig. 1, no. 16) as well as more recently established multidisciplinary terrestrial observatories, e.g., the TERENO (Bogena et al., 2018; Fig. 1, no. 13) and Critical Zone Observatories (Guo and Lin, 2016). The data available from these observatories can be used to answer research questions of varying complexity. For instance, classical long-term observatories are suitable for analyzing the long-term effects of climate and land-use change on the amount of runoff or its dynamics.

On the other hand, modern hydrological observatories are typically able to monitor the major hydrological and atmospheric fluxes and dynamics of the storage reservoirs (e.g., vegetation, soil, groundwater, rivers) at various temporal and spatial scales using state-of-the-art measurement technologies (Tauro et al., 2018). The major fluxes include precipitation, infiltration, evapotranspiration, groundwater recharge, capillary rise, river runoff, snowmelt and glacier melt, frozen soil runoff, and drainage to river systems, lakes, and oceans. In addition to quantifying the major components of the surface hydrological cycle, observatories often monitor groundwater as well as river water quality. In this respect, the quantification of residence and travel times of soil and ground and surface waters is of great importance (Hrachowitz et al., 2016). For this purpose, tracer experiments are used to quantify residence and travel times of water in different compartments of the hydrological system, as well as to delineate flow paths at the catchment scale (e.g., Stockinger et al., 2016). In addition, recent developments in the measurement of the isotopic composition of water and greenhouse gases open new perspectives in better understanding hydrological processes at the field and catchment scales (Stumpp et al., 2018). Remote sensing technologies (e.g., airborne and satellite-based optical and microwave sensors), meteorological measurement techniques (e.g., eddy-covariance towers, weather radars, scintillometers), novel wireless sensor technologies embedded in networks, and hydrogeophysical measurement techniques are now widely used in hydrological observatories and

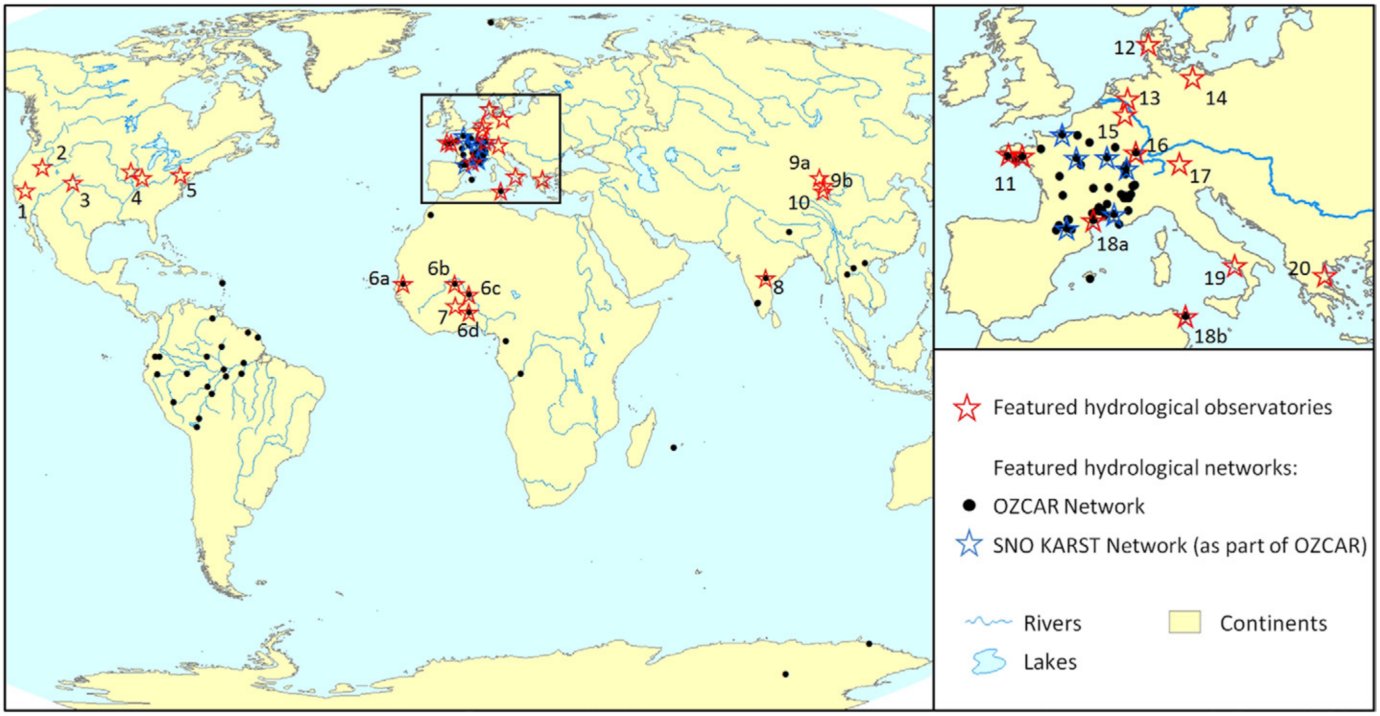

Fig. 1. World map showing the locations of the hydrological observatories featured in this special section: Southern Sierra CZO (1), Reynolds Creek Experimental Watershed and CZO (2), East River, Colorado, watershed (3), Intensively Managed Landscape CZO (4), Susquehanna Shale Hills CZO (5), AMMA-CATCH observatory network (6a,6b), WASCAL observatory (7), Hyderabad observatory (8), Heihe Observatory Network (9a), CHOICE observatory (9b), Qinghai Lake Basin CZO (10), AgrHyS Observatory (11), HOBE Hydrological Observatory (12), TERENO-Rur Hydrological Observatory (13), TERENO-NE Observatory (14), Hupsel Brook catchment (15), Strengbach catchment (16), TERENO Pre-Alpine Observatory (17), OMERE observatory (18a,18b), Alento Hydrological Observatory (19), and Pinios Hydrological Observatory (20). Research sites belonging to the OZCAR CZO network, including some featured hydrological observatories and the SNO KARST network, are also located on the world map.

for process-oriented and hypothesis-driven experiments (Bogena et al., 2017). With the aid of these measurement capabilities, modern hydrological observatories also facilitate the investigation of more complex research questions, e.g., what are the key drivers for biogeochemical processes related to nutrient transport in ground and stream water and greenhouse gas emissions.

The presented hydrological observatories often consist of a nested hierarchy of catchments such that upscaling from the local to the largest scale is possible using scale-appropriate measurement techniques (e.g., multiscale multi-temporal remote sensing methods) and models (Vereecken et al., 2018). At the same time, the nested organization allows testing and validating upscaling theories as well as the development and validation of integrated hydrological models (e.g., Baatz et al., 2017; Stisen et al., 2018). The selection of catchments within existing networks often accounts for the existence of already well-monitored systems having long-term databases on both environmental and socioeconomic information, e.g., population and agricultural and industrial activities affecting water resources (Mollenhauer et al., 2018).

An important aspect of hydrological observatories is the accessibility of data for the research community. Often the observatory data are disseminated through common information and exchange platforms, e.g., the TEODOOR portal of the TERENO network (www.tereno.net) or the ENOHA data portal (www.enoha.eu). In addition, some hydrological observatories have implemented individual solutions for publishing their measurement data. The data management and data dissemination solutions of each hydrological observatory are described in detail in this special section.

Main Research Questions Addressed in the Hydrological Observatories

The overall goals of the Southern Sierra Critical Zone Observatory (O'Geen et al., 2018; Fig. 1, no. 1) are to: (i) expand process-based understanding of the critical zone within a landscape that is crucial to California's social and environmental well-being; (ii) provide a platform for long-term physical, biogeochemical, and ecological studies; and (iii) develop a framework for improving Earth system models. Kings River Experimental Watersheds (O'Geen et al., 2018) has the following complementary goals: (i) to quantify the natural variability in physical, biological, and biogeochemical states and processes of headwater stream ecosystems relevant to California; and (ii) to evaluate the effects of forest restoration techniques including prescribed fire and mechanical thinning.

Reynolds Creek Experimental Watershed and Critical Zone Observatory (RCEW-CZO) was established in 1960 to investigate hydrological processes of interest in the interior northwestern part of the United States (Seyfried et al., 2018; Fig. 1, no. 2). The

Table 1. Overview of the hydrological observatories presented this special **section** and their basic characteristics. Please note that some contributions to the special section present networks of many observatories (i.e., Gaillardet et al., 2018; Jourde et al., 2018), which are not included in this table.

No.	Observatory	Location	Operation period	Size	Climate†	Land cover	Subsurface	Hydrology
1	Southern Sierra CZO	USA	2002–present	multiple sites along an ~84 km transect	Mediterranean *P*: 1000–2000 mm *T*: 13.8–4.2°C	mainly forest	initial, shallow soils, alluvium from granitic rocks	delayed snowmelt, direct runoff
2	Reynolds Creek CZO	USA	1967–present	239 km^2	cold arid *P*: 230–1100 mm *T*: 4.7–8.9°C	semi-arid shrubs, coniferous forests	granitic and vulcanite rocks, alluvium	delayed snowmelt, direct runoff
3	East River, CO, watershed	USA	2014–present	300 km^2	cold continental *P*: 1200 mm *T*: ~0°C	mainly montane shrub	Paleozoic and Mesozoic sedimentary rocks	direct runoff dominated
4	Intensively Managed Landscape CZO	USA	1984‡–present	two catchments (270 and 3690 km^2)	humid continental *P*: 889–1000 mm *T*: ~11°C	intensive agricultural	loess, glacial deposits	diverse
5	Susquehanna Shale Hills CZO	USA	2013–present	nested approach, up to 163 km^2	humid continental *P*: 1070 mm *T*: ~10°C	mainly temperate forest	fractured weathered rock	direct runoff dominated
6a–d	AMMA-CATCH	West Africa	1990–present	4 sites, up to 30,000 km^2	semiarid, tropical monsoon *P*: 200–1300 mm E_{pot}: ~1500 mm	Mali/Senegal: pastoral Niger: pastoral, crops Benin: crops, woodland	Mali/Senegal: saprolite Niger/Benin: aeolian deposits	Mali/Senegal: endorheic basin Niger/Benin: groundwater dominated
7	WASCAL Hydro-Meteorological Observatory	West Africa	2012–present	two catchments (12,800 and 300 km^2)	tropical monsoon *P*: 800–1100 mm	pastoral, crops	(missing information)	(missing information)
8	Hyderabad Observatory	India	2000–present	two sites (4 and 55 km^2)	tropical *P*: 750 mm E_{pot}: ~1800 mm	intensive agricultural	saprolite (from granite rock)	groundwater dominated
9a	Heihe River Basin Observatory	China	2012–present	143,000 km^2	cold, arid continental *P*: 50–500 mm *T*: 2.3–9.4°C	glaciers, alpine meadow, forests, crops, shrubs, deserts, water bodies	metamorphic, volcanic and sedimentary rocks, glacial, alluvial conglomerate, desert	snowmelt runoff, glacier melt, frozen soil hydrological processes, surface water–groundwater interaction
9b	CHOICE Observatory	China	2009–present	23.1 km^2	continental *P*: 734 mm *T*: −0.3°C	grassland, shrub, forest	metamorphic and volcanic rocks, moraine deposits	snowmelt runoff, glacial runoff
10	Qingkai Lake Basin	China	2008–present	nested approach, up to 30,000 km^2	cold desert *P*: 29–579 mm E_{pot}: 1300–2000 mm	alpine meadow, montane shrub, grassland	metamorphic and acidic igneous rocks	endorheic basin, saline lake
11	AGRHYS Observatory	France	1990–present	nested approach, up to 5 km^2	temperate oceanic *P*: 837–1114 mm E_{pot}: 680–699 mm *Q*: 227–325 mm	mainly agriculture	low permeability crystalline rocks	groundwater dominated
12	HOBE: Danish Hydrological Observatory	Denmark	2007–present	nested approach, up to 2500 km^2	temperate oceanic *P*: 1000 mm E_{pot}: 500 mm	mainly agriculture	sandy alluvial	groundwater dominated
13	TERENO-Rur Hydrological Observatory	Germany	2008–present	nested approach, up to 2500 km^2	temperate oceanic *P*: 650–1200 mm E_{pot}: 500–600 mm	north: mainly agriculture; south: mainly grassland and forest	north: loess and sandy alluvial; south: Paleozoic solid rocks	Upper Rur: direct runoff dominated Lower Rur: groundwater dominated
14	TERENO-NE German Lowland Observatory	Germany	2009–present	7 sites, up to 900 km^2	sub-maritime to subcontinental temperate *P*: ~600 mm *T*: ~8°C	agriculture, peatland and forest	sandy and loamy glacial	groundwater dominated
15	Hupsel Brook catchment	Netherlands	1964–present	6.5 km^2	temperate oceanic *P*: 772 mm E_{pot}: 560 mm *T*: ~10°C	mainly agriculture	sandy alluvial	groundwater dominated

Continued on next page.

Table 1. (cont.)

No.	Observatory	Location	Operation period	Size	Climate†	Land cover	Subsurface	Hydrology
16	Strengbach catchment	France	1985–present	0.8 km^2	temperate oceanic P: 1380 mm E_{pot}: 571 mm T: 6°C	forest	granite, gneiss	direct runoff dominated
17	TERENO Pre-Alpine Observatory	Germany	2009–present	nested approach, up to 655 km^2	humid continental P: 980–2460 mm T: 7.1°C Q: 775 mm	mainly grassland	low permeable solid rocks, alluvial aquifers	Upper Ammer: direct runoff dominated Lower Ammer: groundwater dominated
18a,b	OMERE Observatory	France	2002–present	two sites (0.92 and 2.63 km^2)	Mediterranean P: 628–645 mm E_{pot}: 1109–1366 mm T: ~15°C	mainly agriculture	limestones and marls	direct runoff dominated
19	Alento Hydrological Observatory	Italy	1965‡–present	nested approach, up to 411 km^2	Mediterranean P: 1100–1200 mm E_{pot}: ~700–800 mm T: ~15°C	mainly forest and permanent crops	complex sequence of flysch sediments, karstic limestone	Upper Alento: seasonal direct runoff Lower Alento: groundwater dominated
20	Pinios Hydrological Observatory	Greece	2017–present	45 km^2	Mediterranean P: 500–1200 mm E_{pot}: ~1100 mm T: ~15°C	agriculture (orchards, cropland), Mediterranean scrubland and mixed forest	metamorphic rocks, alluvial deposits	seasonal (winter) direct runoff

† P, annual precipitation; E_{pot}, annual potential evapotranspiration; T, annual air temperature; Q, annual runoff.
‡ Governmental river gauging station.

emphasis of the RCEW-CZO is on the investigation of how interactions among geologic, topographic, and climatic gradients across the landscape control hydrologic processes, carbon cycling, soil genesis, and other ecosystem processes over time. Although hydrology continues to be a focus of the observatory, related ecological and biogeochemical processes are increasingly incorporated into its research themes. The data from RCEW-CZO are also used for the validation and testing of distributed models.

The East River, CO, watershed is part of the Upper Colorado River Basin and was specifically designed to improve predictions of hydrology-driven watershed biogeochemical behavior (Hubbard et al., 2018; Fig. 1, no. 3). Research includes the identification of key controls on hydrology-driven biogeochemistry and testing new approaches for characterizing and simulating multiscale behavior—up to the floodplain scale. A particular emphasis has been placed on exploring the value of fine space or time scale information for informing reactive transport models and improving the prediction of floodplain-scale exports of carbon to the Colorado River. Research includes consideration of the floodplain microbial community diversity and metabolic potential, the contribution of vadose zone microbial respiration to the floodplain carbon cycle, the identification of hotspots and hot moments using geophysical approaches, and the impact of hotspots and hot moments on floodplain reactive transport predictions of floodplain exports to the Colorado River.

The Intensively Managed Landscape Critical Zone Observatory (IML-CZO) is a network of three well instrumented and highly managed catchments in the United States, i.e., Clear Creek in Iowa, Upper Sangamon River in Illinois, and the Minnesota River in Minnesota (Wilson et al., 2018; Fig. 1, no. 4). The main goal of the IML-CZO is to quantify the heterogeneity in structure and dynamic response of critical zone processes to human activities in the context of the glacial and management (anthropogenic) legacies. Observations at IML-CZO focus on water, sediment, and nutrients at nested points of the landscape during and between storm events. The overarching research question of the IML-CZO is: How have the interactions between weather/climate dynamics and management restructured landscape heterogeneity in agroecosystems and thus affected system response through changes in transport and residence times of water, sediment, and nutrients across scales?

The Garner Run and Cole Farm observatories (Li et al., 2018) and the Shaver's Creek Hydrological Observatory are part of the Susquehanna Shale Hills Critical Zone Observatory (Brantley et al., 2018; Fig. 1, no. 5). The satellite sites were added to the Susquehanna Shale Hills Critical Zone Observatory to learn how to upscale understanding from small footprints like the original Shale Hills catchment to larger, more regional footprints (Brantley et al., 2018). The upscaling involves: (i) continued investigation of the original Shale Hills subcatchment; (ii) monitoring the two small subcatchments in addition to Shale Hills (i.e., Garner Run and Cole Farm observatories) and monitoring several sites along the mainstream of Shaver's Creek for chemistry and discharge; and (iii) using topographic and geophysical measurements to link the observations from the various sites.

The African Monsoon Multidisciplinary Analysis (AMMA)–Couplage de l'Atmosphère Tropicale et du Cycle eco-Hydrologique

(CATCH) long-term regional observatory network has been developed to monitor the impacts of global change on the critical zone of West Africa and to better understand its current and future dynamics (Galle et al., 2018; Fig. 1, no. 6a–6d). It is comprised of a Sudanian site in Benin, a Sahelian site in Niger, and two pastoral Sahelian sites in Mali and Senegal. Research in the AMMA-CATCH observatory focuses on: (i) analysis of the long-term evolution of eco-hydro-systems from a regional perspective; (ii) better understanding of critical zone processes and their variability; and (iii) developing methods to better meet socioeconomic and development needs in West Africa based on proper mastering of environmental conditions.

The WASCAL (West African Science Service Centre on Climate Change and Adapted Land Use) Hydro-Meteorological Observatory is comprised of the Sissili River catchment in the Sudan savanna of southern Burkina Faso and the Vea River catchment in northern Ghana (Bliefernicht et al., 2018; Fig. 1, no. 7). In the framework of the WASCAL program, the following research questions are addressed:

1. How are climate-relevant land surface properties, such as albedo, changed by land conversion?
2. What is the impact of land cover changes on the partitioning of water and energy fluxes at the land surface?
3. Can near-natural savanna ecosystems lose their function as a carbon sink when used for agriculture?
4. How are components of the water balance changed when savanna ecosystems are converted to agricultural land?

The Hyderabad Observatory in India is comprised of two sites (Maheswaram and Choutuppal) and was created to improve understanding of hydrogeological processes in crystalline-rock aquifers under global climate change, including transfer processes and hydrochemical cycles to improve a regional conceptual model (Maréchal et al., 2018; Fig. 1, no. 8). Research at the Hyderabad observatory focuses on: (i) characterization of hydrodynamic properties of the crystalline aquifer; (ii) improving understanding of various hydrological components of the water cycle in irrigated areas at the watershed scale; (iii) identification of the impact of fractures on recharge processes; and (iv) investigation of the influence of cropping pattern changes on groundwater.

The Heihe Integrated Observatory Network comprises the Heihe River catchment, the second largest inland river in China (Liu et al., 2018; Fig. 1, no. 9a). The Heihe observatory network was first established in 2007 and completed in 2013 during the HiWATER experiment, which has included at most 23 observation sites and 11 operational observation sites at present, is used to investigate land surface processes involving diverse landscapes and the coexistence of cold and arid regions. More specifically, the following research topics are addressed: (i) water efficiency of plants under drought conditions and their adaptation mechanisms to water stress; (ii) groundwater–surface water interaction and their eco-hydrological effects; (iii) eco-hydrological processes across scales and involved scaling issues; (iv) response of watershed eco-hydrological processes under climate change and human activities; and (v) integration of the comprehensive observational data into models.

The Cryospheric Hydrometeorology Observation System (CHOICE) is a satellite site of the Heihe observatory and was established in 2008 in the Hulu River catchment (Han et al., 2018; Fig. 1, no. 9b). The CHOICE observatory is located upstream of the Heihe observatory and focuses on cryospheric hydrometeorology observation. Research topics include: (i) the spatial and temporal distribution of precipitation in the complex terrain of alpine mountains; (ii) the effects of cryospheric changes on streamflow; (iii) the effects of changes in the vegetation pattern in mountainous landscapes on water balance and river runoff; and (iv) development of a distributed hydrological model that accounts for cryospheric processes.

Research in the Qinghai Lake Basin Critical Zone Observatory focuses on how climate and anthropogenic activities influence the water cycle and ecological degradation in this particular area (Li et al., 2018; Fig. 1, no. 10). More specifically, the following research questions are addressed:

1. What was the inherent hydrological mechanism for the degradation of different ecosystems along precipitation and temperature gradients, and how does the water cycle couple with ecological process?
2. What are water flux and surface energy budgets in various terrestrial ecosystems and the Qinghai Lake?
3. How do precipitation, surface water, groundwater and lake water interact with each other?
4. How should water resources be allocated for sustainable development in the Qinghai Lake Basin?

The catchments of the AgrHyS Observatory were first instrumented to assess the effects of agriculture in France and Europe on altering water and soil quality, and the first studies in the 1970s showed a rapid increase of nitrate concentrations in streams and rivers (Fovet et al., 2018; Fig. 1, no. 11). Thus, the catchment scale was recognized as relevant for developing a systemic approach to evaluating the impacts of agricultural systems on the environment. Consequently, the exploration of environmental parameters was extended to the whole catchment to understand the spatial organization of landscapes (soil maps, spatial rainfall variability) and intensified in specific hotspots (wetlands, groundwater), moving from the rainfall–discharge relation as an in–out approach to a landscape hydrology–hydrochemistry approach using a wide range of chemical species as geochemical tracers.

The Danish HOBE hydrological observatory was initiated in 2007 (Jensen and Refsgaard, 2018; Fig. 1, no. 12) and aims to: (i) establish an observatory for detailed measurements and experiments in a catchment representing temperate climate conditions and with groundwater-dominated streamflow; (ii) establish scientific datasets to support fundamental research of hydrological processes at various scales; (iii) test new innovative field instrumentation and observation techniques from ground-based as well as air- and satellite-borne platforms; (iv) investigate the interaction between hydrological compartments; and (v) integrate monitoring, measurements, and experiments in complex integrated hydrological models to address the primary research question, which is water balance closure at different scales.

The Rur Hydrological Observatory is part of the German TERENO network and was established in 2008 (Bogena et al., 2018; Fig. 1, no. 13). It was specifically designed to determine complex patterns of state variables and parameters of the hydrological system influenced by the heterogeneous inter- and intra-compartmental fluxes of heat, energy, water, carbon, nitrogen, and momentum at different spatiotemporal scales. More specific hydrological research questions include:

1. How do soil moisture patterns impact runoff, evapotranspiration and water storage processes?
2. What are the key drivers for biogeochemical processes?
3. What are the key controls on travel time distributions?
4. What is the information content of spatially and temporally, highly resolved soil moisture data?
5. How do patterns in crop development and yield relate to soil water dynamics during droughts?
6. How can data assimilation and cloud computing support the real-time water management?

The Northeast German Lowland Observatory is also part of the German TERENO network and was established to investigate the regional impact of climate and land use change (Heinrich et al., 2018; Fig. 1, no. 14). The goal of the observatory is to investigate a broad variety of processes in river catchments and in different subsystems including lake and peat systems, soils, and trees, with different degrees of human interferences ranging from near-natural landscapes to intensive agricultural land use, and at different spatial and temporal scales. To this end, the observatory consists of a network of sites (i.e., the peatland Hütelmoor, the Polder Zarnekow, the DEMMIN test site representing a typical agricultural landscape, the lakes Tiefer See and Fürstenseer See located in the Müritz National Park, and the Quillow River catchment).

The Dutch Hupsel Brook catchment is a long-term hydrological observatory for research and education first established in 1964 (Brauer et al., 2018; Fig. 1, no. 15). The original motivation for initiating this hydrological observatory was the improvement of agricultural water management during times of both water shortage and excess. This work laid the foundation for a thorough understanding of the hydrological functioning of freely draining lowland catchments in general. The Hupsel Brook catchment has been used for research and education by generations of Dutch hydrologists and hydrology students.

The Strengbach catchment is the observation and experimental site of the Observatoire Hydro-Géochimique de l'Environnement (OHGE) as part of the French OZCAR (Observatoires de la Zone Critique Applications et Recherches) network (Pierret et al., 2018; Fig. 1, no. 16). Research at Strengbach catchment addresses key questions of the Millennium Ecosystem Assessment concerning the evolution of ecosystems under plausible scenarios, as well as the knowledge of time scales, inertia, and risks of nonlinear changes occurring in ecosystems. Research conducted on the Strengbach catchment targets two key questions related to major societal challenges: hydrology patterns and solute transport through the critical zone.

The main long-term objectives of the German TERENO Pre-Alpine Observatory focus on the characterization and quantification of climate change and land cover and management effects on terrestrial hydrology and biogeochemical processes at site and regional scales (Kiese et al., 2018; Fig. 1, no. 17). Hydrological research focuses on (i) quantification of the spatiotemporal variability of precipitation in complex terrain; (ii) investigation of soil moisture response to precipitation; and (iii) closure of the regional interlinked water and energy cycles. The biosphere–atmosphere exchange research focuses on (i) improving understanding of atmospheric exchange processes in complex terrain; (ii) investigation of the energy balance closure problem; and (iii) the response of net ecosystem exchange to transient climatic events. Biogeochemical research focuses on (i) greenhouse gas emissions; (ii) nutrient export by seepage water; and (iii) vegetation and microbial productivity and diversity effects on ecosystem carbon and nitrogen transformations and losses.

The OMERE (Observatoire Méditerranéen de l'Environnement Rural et de l'Eau) observatory consists of two sites (Roujan in France and Kamech in Tunisia) and aims to monitor and analyze the impacts of agricultural and land management on mass fluxes in typical farmed headwater catchments of the Mediterranean Basin and to support integrative multidisciplinary research for improved soil and water management and delivery of ecosystem services (Molénat et al., 2018; Fig. 1, no. 18a–18b). The research objectives include: (i) estimation of fluxes of water, eroded sediment, and contaminants and identification of their natural and anthropogenic drivers on short- and long-term scales (e.g., the influence of runoff events and of long periods of drought on the hydrological cycle and pesticide transport); (ii) elucidation of the aggregate effects of farming and land management activities (e.g., soil tillage, water harvesting, ditch networks, and terraces) on mass fluxes from the plot to catchment and landscape scales; and (iii) derivation of scenarios for sustainable agricultural management (e.g., agricultural biomass production, water production, erosion prevention, flood regulation, and water contamination regulation).

The main focus of the Alento Hydrological Observatory in Italy is to provide high-quality data sets for hydrological modeling to evaluate the impact of land-use and land-cover changes and variations in climatic seasonality on hydrologic ecosystem functions under different environmental and socioeconomic conditions (Romano et al., 2018; Fig. 1, no. 19). More specifically, future research in the Alento Hydrological Observatory aims to couple near-real-time monitoring of hydro-meteorological variables and fluxes with catchment-scale modeling tools of different complexities to evaluate the impact of anthropogenic disturbance.

The results will be used to propose appropriate supply-side and demand-side adaptation options with the main aim of developing innovative solutions for cost-efficient management of land and water resources in a typical Mediterranean ecosystem.

The recent establishment of the Pinios Hydrological Observatory in Greece was motivated by the following research questions (Pisinaras et al., 2018; Fig. 1, no. 20):

1. Will there be enough water reserves to sustain demands including agricultural production?
2. How will drought episodes affect water reserves and what are the best management scenarios to sustain both soil and water resources?
3. To what extent will natural recharge decreases affect groundwater reserves in terms of quantity and quality, and will there be irreversible damage of soil resources?
4. Can water governance be supported through a decision support system only on the basis of existing monitoring data?

The OZCAR (Critical Zone Observatories–Application and Research) research infrastructure is a network of critical zone observatories launched in 2015 in France (Gaillardet et al., 2018). OZCAR gathers and organizes more than 60 research sites in 21 preexisting observatories that are operated by diverse research institutions and was initially created to address environmental questions of societal relevance (Fig. 1). The main common research focus is about monitoring, understanding, and predicting fluxes of water, solutes, gases, and sediments at the Earth's near surface and how they will change in response to the "new climatic regime." The OZCAR network contains the catchment network RBV, the network of hydrogeological sites H^+, the CRYOBS-CLIM observatory (cryosphere), the Tourbières (peatland) observatory network, the OSR (Regional Spatial Observatory), the ROSES Observatory network, and the OPE long-lasting environmental observatory. From this large network, a few observatories and research sites are featured in this special section (AGRHYS, OMERE, Hyderabad, AMMA-CATCH, SNO KARST, and Strengbach catchment).

The French Karst National Observatory Service (SNO KARST) is a long-term critical zone observatory network in Europe as part of the OZCAR network (Jourde et al., 2018). It is designed to provide a better understanding of flow and transport in karst aquifers and watersheds via a multidisciplinary approach. SNO KARST gathers nine observation sites located within various regions of France with different climatic, geologic, geomorphologic, and physiographic contexts (Fig. 1). This diversity allows several research questions to be addressed:

1. What is the hydrological and geochemical response of karst aquifers and the respective catchments to climate variability and anthropogenic pressure changes?
2. What is the biogeochemical functioning of the critical zone with respect to the vulnerability of the groundwater resource?
3. How does karst geometry influence the hydrological functioning of catchments?

Outlook

Overall, the new insights and novel scientific findings presented in this special section illustrate that long-term integrated hydrological monitoring essential for expanding our understanding of hydrological processes at various temporal and spatial scales (i.e., from the field to the catchment). For instance, Zhang et al. (2017) examined about 312 small and large catchments worldwide to provide a generalized framework to evaluate hydrological responses to forest cover change and to identify the contributions of spatial scale, climate, forest type, and hydrological regime. They found a general tendency for runoff responses to be more sensitive to forest change in water-limited watersheds than in energy-limited watersheds. Clearly, such studies are only possible if data from a large number of hydrological observatories with a wide range of different environmental conditions are available.

The ongoing long-term monitoring of a large number of hydrological variables across multiple compartments in many experimental catchments around the world representing a variety of climatic and hydrological conditions will help solve important scientific questions such as:

- How will climate change affect the major hydrological fluxes (including the fluxes of solutes, gases and sediments) in the long-term?
- How will land-use change influence the hydrological cycle and especially the quality of surface water and groundwater?
- How can local information (e.g., from in situ sensors) be used to predict large scale hydrological processes?
- What will be the impact of an improved understanding of interface processes and feedback mechanisms between the different compartments of the terrestrial system (soil, plant, atmosphere, and groundwater) on long-term predictions of hydrological and atmospheric processes under changing climate conditions?
- What will be the effect of climate and human-induced changes on physical, chemical and biological indicators used to assess the status of water bodies?

The high number of contributions to this special section demonstrates that the hydrological community is very active. However, one of the challenges in the coming years will be to better coordinate these efforts (e.g., Blöschl et al., 2017; Bogena et al., 2017). This is required not only for improving data analysis and model-driven design of catchment experiments, but also to perform hydrological forecasts at larger, perhaps global scales, to develop interdisciplinary research at all scales, and to better address the pressing societally relevant environmental problems related to the impacts of climate and land use change on the hydrologic cycle. The presented hydrological observatories and their associated databases are crucial for the advancement of integrated hydrological models that consider complex feedback mechanisms between the hydrological compartments. Thus, in our view, it is essential to increase the awareness and knowledge of these infrastructures in the international hydrological community to increase their utilization for the exploration of new hypotheses in hydrology and related disciplines.

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