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Discussions

The Hydrological Open Air Laboratory (HOAL) in Petzenkirchen: a hypotheses driven observatory

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Abstract

Hydrological observatories bear a lot of resemblance to the more traditional research catchment concept but tend to differ in providing more long term facilities that transcend the lifetime of individual projects, are more strongly geared towards performing interdisciplinary research, and are often designed as networks to assist in performing collaborative science. This paper illustrates how the experimental and monitoring setup of an observatory, the 66 ha Hydrological Open Air Laboratory (HOAL) in Petzenkirchen, Lower Austria, has been established in a way that allows meaningful hypothesis testing. The overarching science questions guided site selection, identifying dissertation topics and the base monitoring. The specific hypotheses guided the dedicated monitoring and sampling, individual experiments, and repeated experiments with controlled boundary conditions. The purpose of the HOAL is to advance the understanding of water related flow and transport processes involving sediments, nutrients and microbes in small catchments. The HOAL catchment is ideally suited for this purpose, because it features a range of different runoff generation processes (surface runoff, springs, tile drains, wetlands), the nutrient inputs are known, and it is convenient from a logistic point of view as all instruments can be connected to the power grid and a high speed glassfibre Local Area Network. The multitude of runoff generation mechanisms in the catchment provide a genuine laboratory where hypotheses of flow and transport can be tested, either by controlled experiments or by contrasting sub-regions of different characteristics. This diversity also ensures that the HOAL is representative of a range of catchments around the world and the specific process findings from the HOAL are applicable to a variety of agricultural catchment settings. The HOAL is operated jointly by the Vienna University of Technology and the Federal Agency for Water Management and takes advantage of the Vienna Doctoral Programme on Water Resource Systems funded by the Austrian Science Funds. The paper presents the science strategy of the setup of the observatory, discusses the implementation of the HOAL, gives examples

of the hypothesis testing and summarises the lessons learned. The paper concludes with an outlook on future developments.

1 Introduction

Understanding water related flow and transport processes in catchments and their interactions with other environmental processes across space and time scales are essential research issues in the context of environmental technology, planning and management. From a water quantity perspective, understanding runoff generation mechanisms is very important for better estimating floods that may occur in small catchments, in particular if one is interested in extrapolating from small to large floods (Merz and Blöschl, 2008). Water yield under different management options as well as land–atmosphere feedbacks are particularly relevant when addressing issues of climate change. From chemical and sediment perspectives, understanding the relevant mechanisms is important in the context of land management practices that aim at reducing sediment production (e.g. Yeshaneh et al., 2015), and for water resources management where the interest resides in understanding the fate of nutrients and designing relevant management practices (Schilling et al., 2005; Zessner et al., 2005; Strauß and Klaghofer, 2006; Kovacs et al., 2012). From a human health related perspective, characterising microbial faecal hazards in water and identifying contamination sources contribute to more reliable hazard characterisation and risk estimation in the context of water safety management, for example by allowing target-oriented protection measures in the catchment and delineating effective and site specific protection zones (Reischer et al., 2011; Farnleiter et al., 2011). While these research issues are relevant in their own right, they are also closely connected to each other through process interactions. Integrated research into these processes is therefore needed to shed light on the interactions and fully explore the causal relationships of the catchment system.

Experimental research addressing these issues differs from experiments in many other fields of science in at least two ways. First, the processes related to water flow in the landscape are strongly controlled by the forcing of the weather. It is therefore difficult, if not impossible, to conduct controlled experiments where one varies the boundary conditions in a prescribed way. As a consequence, the processes associated with water flow are intrinsically non-repeatable and require particular care when hypothesis testing (Blöschl et al., 2014). Second, the processes occur at the catchment scale (where much of the interesting process interactions occur) and may not be present at the small laboratory scale. As a result, the experimental setup must be designed at the catchment scale which, again, involves a number of scientific and logistic challenges.

Experimental catchments have a long tradition in hydrology. Some corner stones include the Coweeta hydrologic laboratory (Southern Appalachians) in the early 1930s where the focus was on forest management practices (Swank and Crossley, 1988; Elliott and Vose, 2011), the Plynlimon catchment (Wales) in the late 1960s where pollution was the main interest (Kirby et al., 1991; Robinson et al., 2013), the Weiherbach (Germany) and Löhnersbach (Austria) catchments in the 1990s where a broader, interdisciplinary approach was taken (Plate and Zehe, 2008; Zehe et al., 2011; Kirnbauer et al., 2005); and the Tarrawarra catchment (Australia) in the 1990s where the focus was specifically on spatial process patterns (Western et al., 1998, 1999; 2001). An overview of some of the European experimental catchments is given in Schumann et al. (2010) and Holko et al. (2015).

More recently, the concept of *environmental observatories* has been developed and implemented. Examples are the Critical Zone Observatories (CZO) in the US where the starting point was geochemical processes (e.g. Anderson et al., 2008; Lin and Hopmans, 2011), and the Terrestrial Environmental Observatories (TERENO) in Germany where the starting point was processes at the hydrological–ecological interface (Zacharias et al., 2011). While these observatories bear a lot of resemblance to the more traditional research catchments they differ in three important ways. (a) Similar to astronomical and meteorological observatories their objective is to provide long term facilities that transcend the lifetime of individual projects. (b) Even more so than their more traditional counterparts they are geared towards performing interdisciplinary research. (c) Often they are designed as networks to assist in performing collaborative science within the research community. Indeed, long-term, interdisciplinary research in networks may be the hallmark of catchment-scale experimental research in an era where "Humans may no longer be treated as boundary conditions but should be seen as an integral part of the coupled human-nature system . . . [and] the coupling between the geoscience disciplines . . . gets more important." (Blöschl et al., 2015, p. 17).

Establishment of research catchments or hydrological observatories may be either driven by management questions as was the case with much of the early experimental work, or by fundamental research questions, and the two aims may feed into each other. In both instances, the experimental or monitoring setup must be designed in a way that enables the critical research questions to be tested. The classical example are paired catchment studies (e.g. Brown et al., 2005) where the effects of forest management on the hydrological cycle are studied with a similar, untreated catchment used as a control. Differences in the observations between these two catchments are then used to test hypotheses on, e.g. the effects of forest on water yield. Again, a classical hypothesis to be tested by this setup is that forest cutting will increase water yield from the catchment. In the Coweeta, for example, "the largest water yield increases occurred the first year after cutting when evapotranspiration (Et) was most reduced due to minimal leaf area index (LAI). As vegetation regrew, LAI and Et increased and streamflow declined logarithmically, until it returned to the pre-treatment level by five to six years." (Elliott and Vose, 2011; p. 906). For more complex hypotheses, the experimental or monitoring setup must be more elaborate in order to allow the hypothesis testing in a meaningful way.

The purpose of this paper is to illustrate how the experimental or monitoring setup of an observatory can be established in a way that allows meaningful hypothesis testing, and to communicate the lessons learned from the experiences with the Hydrology Open Air Laboratory (HOAL) in Petzenkirchen, Austria. We will first present the science strategy of the setup of such an observatory, discuss the implementation of the HOAL, give examples of the hypothesis testing and summarise the lessons learned.

2 Science strategy of the HOAL

The success of a research programme hinges on whether new, cutting-edge scientific findings are achieved. The HOAL observatory is designed to facilitate cutting-edge research by providing long-term experimental infrastructure, fostering interdisciplinary collaboration and encouraging networking within the science community. All three aspects are considered through the prism of the hypotheses to be addressed.

2.1 Long-term experimental infrastructure

Some of the most interesting science questions require long term observation. These include questions related to hydrological change where one aims at detecting differences of hydrological fluxes and/or processes between decades. Another such question relates to hydrological extremes, since the likelihood of observing extreme events increases with the observation period. At the same time, long term infrastructure can most efficiently be used if a range of complementary research questions are addressed that all build on that infrastructure, i.e. where the synergies of different questions are exploited. To cater for a range of questions a nested approach was therefore adopted for the HOAL related to overarching science questions and specific hypotheses (Fig. 1).

2.1.1 Overarching science questions

At a first layer overarching science questions were identified that were relevant for advancing the fundamental understanding of water related flow and transport processes at the catchment scale. These were defined in a broad way and included the following.

- What are the space–time patterns of flow paths and evaporation in a small agricultural catchment?
- What are the space–time patterns of erosion and sediment transport processes in the catchment and what are their driving forces?

- What are the processes controlling nutrient and faecal pollution dynamics in the catchment?

These questions are aligned with the interests of the individuals and institutions involved in the context of prior experience, societal relevance and funding opportunities. The site location, the research student dissertation topics, and the base monitoring were selected based on the overarching questions.

Site location: selection of the site was guided by the ability to address the overarching science questions. Importantly, much of the research is related to runoff generation. It was therefore deemed important to select an area with many different runoff generation mechanisms in the same catchment to make the scientific findings applicable to a wide spectrum of catchments around the world. Questions such as erosion and nutrient dynamics are usually associated with agricultural practices which was another criterion for selecting the site.

Dissertation topics: the topics of the dissertations were chosen in a way that a number of generations of research students can build on each other. The topics of the first generation students (2009–2013) were geared towards the more fundamental processes of water and matter flow in the catchment as well as soil moisture. The second generation (2012–2016) had more elaborate topics such as microbial processes, land–atmosphere interactions and linkages to the deep subsurface. The third generation of students will, again, build on these findings and address upscaling and hydrological change more explicitly. The fourth generation of students will be concerned with how all of these findings can be generalised to other climatic and management conditions around the world.

Base monitoring: all overarching research questions require an understanding of the hydrological fluxes with high spatial and temporal detail. Consequently, a substantial number of high resolution raingauges and stream gauges were chosen as the base monitoring setup. Locations of runoff related measurements were carefully considered to sample different runoff mechanisms. At the catchment outlet basic chemical and physical parameters were monitored by online sensors and regular grab sampling. To complement these, a weather station was set up to monitor the energy fluxes at the land–atmosphere interface. Spatial sampling to characterise the catchment included Lidar for high definition topography, soil mapping and sampling.

2.1.2 Specific hypotheses

Nested into the overarching science questions, specific hypotheses were defined, dedicated monitoring and sampling was performed, individual experiments were conducted, some of which were repeated with controlled boundary conditions.

Dedicated monitoring and sampling: a soil moisture network within the catchment was set up to understand the spatial soil moisture distribution and link it to remotely sensed soil moisture. Three eddy correlation stations were set up to understand the spatial distribution of land–atmosphere interactions. Faecal indicators were monitored to test alternative measurement methods and understand the dynamics of faecal contamination, and water quality characteristics were monitored at a number of locations to understand nutrient fluxes (Exner-Kittridge et al., 2013).

Individual experiments: field campaigns were conducted over limited periods of time to obtain more in-depth understanding of the processes at the field scale. Examples include tracer tests in the stream to elucidate stream aquifer interactions and a field campaign dedicated to measuring transpiration and bare soil evaporation separately in a field of maize.

Repeated experiments with controlled boundary conditions: a small number of experiments were conducted with controlled boundary conditions. Examples include resuspension experiments were sediment-free water was pumped into the stream to understand the sources of suspended sediments at the beginning of events (Eder et al., 2014) and an experiment where soil plots were prepared to a prescribed roughness and moisture which were then measured by Lidar to understand the controls on Lidar response.

More detailed examples of how instrumentation and experimental setup were selected on the basis of the specific hypotheses are given in Sect. 4 of this paper.

2.2 Interdisciplinary collaboration

One of the hallmarks of an observatory is its ability for fostering cooperation across the disciplinary boundaries. In the case of the HOAL much of the research is conducted within the frame of the Vienna Doctoral Programme on Water Resource Systems (Blöschl et al., 2012). The programme is funded by the Austrian Science Funds and aims at producing top graduates capable of conducting advanced, independent research of the highest international standards which cuts across multiple disciplines. The HOAL is therefore a natural platform for the Programme and benefits from its integration strategy. The Programme enables integration between disciplines that ensures that students can address more complex science questions than is possible through individual dissertations. The main strategy for achieving this consists of organising the research through joint groups, joint research questions, and joint study sites. One of the joint study sites is the HOAL.

As an example, the concept of integration between the research of the nine doctoral students currently working in the HOAL is illustrated for one of the overarching science questions, i.e. “Space time patterns of flow paths and evaporation”. Atmospheric scientist Patrick Hogan is investigating the soil moisture and land use controls on spatial evaporation patterns within the catchment. One specific hypothesis Patrick Hogan is testing is that the relative importance of soil moisture controls exceeds that of topographic controls at all times of the year. As evaporation is an important flux in the HOAL it will directly affect soil moisture (of interest to remote sensing specialist Mariette Vreugdenhil) and indirectly affect the flow paths (of interest to hydrogeologist Michael Exner-Kittridge who deals with nutrient fluxes). Structural engineer Abbas Kazemi Amiri is taking advantage of the eddy correlation systems and conducts measurements of the dynamic wind loading of the mast structure to understand the interactions of water resource structures with wind, and specifically the role of fatigue. Conversely, Patrick Hogan can make use of the expertise and research progress of other students by testing the spatial distribution of evaporation obtained by his eddy-correlation instrumentation against observed runoff volumes in different parts of the catchment. Hydrologist Rasmiaditya Silasari's thesis quantifies the spatial organization of the flow patterns. One specific hypothesis she is testing is that spatial connectivity is a major determinant of the flow rates and flow dynamics. The numerical hydrological simulations she conducts for testing her hypotheses are directly relevant to Mariette Vreugdenhil for interpreting spatial soil moisture.

2.3 Networking within the science community and beyond

Another key characteristic of observatories is that they are embedded into a network of scientists to maximise the opportunities of producing novel and societally relevant research. Networking of the HOAL has therefore been designed at a number of levels.

The TU Wien – IKT collaboration: at the centre of the HOAL stands the collaboration between a number of institutes and centres of the Vienna University of Technology (TU Wien) and the Institute for Land and Water Management Research (IKT) of the Federal Agency for Water Management. The expertise of a number of TU Wien institutes is brought together through their affiliation with the Centre for Water Resource Systems at TU Wien, involving professors from structural mechanics, remote sensing, hydrology, hydrogeology and water quality. Each institute operates their own in-house laboratories in their area of specialisation. In addition, the IKT has a long standing expertise in measuring and modelling soil water, sediments and nutrients with a focus on field work. They have operated experimental sites for decades and also operate a physical and chemical soil laboratory and workshop.

Collaborations with instrument companies: a second level of networking and collaboration takes place with some of the providers of the instrumentation. Although most of the instrumentation has been simply purchased from the vendors, for a number of providers a joint venture has been embarked upon to test new instrumentation and methods. One of such collaboration is with the company Microtronics regarding telemetering data from the catchment to the central server and data management. Another is with company VWM (Vienna Water Monitoring) regarding testing novel devices for automated measurements of proxy-parameter of microbial faecal pollution in the stream of the HOAL under field conditions (Farnleitner et al., 2002; Ryzinska-Paier et al., 2014).

Collaborations with other research institutions: a range of collaboration with both national and international research institutes and agencies are under way most of which focus on testing a particular hypothesis. A collaboration with the Austrian Institute of Technology (AIT) focuses on stable isotope analyses to understand water age, a collaboration with the International Atomic Energy Agency (IAEA) is geared to testing a cosmic ray soil moisture sensor against the soil moisture network, and a collaboration with the Helmholtz Centre for Environmental Research (UFZ) deals with understanding water isotopic signatures in a regional context. HOAL is one of the ground truthing sites of the NASA's SMAP (soil moisture active passive satellite) mission. Collaborations with additional institutes are being planned. The doctoral students working in the HOAL are entitled to spend a semester abroad with a research institution of their choice. This provides further opportunity to knit a strong network of collaborations with leading groups around the world in their field of expertise.

Communication and outreach: visibility of the research output hinges on suitable dissemination of the research results at a range of scales. Dissemination has therefore been designed as a multi-scale process involving the university (e.g. workshops and seminars within the university, email and website communication), the national and international scientific communities (through journal papers, conference presentations, and a guest scientist programme) and the general public through a range of outreach activities (e.g. newspaper, television and radio interviews with scientists working in the HOAL, as well as regular meetings with the local community).

3 Implementation

3.1 Site selection and hydrological characteristics

3.1.1 Site selection

Since many of the questions are related to runoff generation it was considered important to select an area with many different runoff generation mechanisms in the same catchment. A small catchment near Petzenkirchen, Lower Austria, was found to be ideally suited. In this catchment a wide range of runoff generation mechanisms occurs, including infiltration excess overland flow, re-infiltration of overland flow, saturation excess runoff from wetlands, tile drainage flow, shallow aquifer seepage flow and groundwater discharge from springs. The multitude of runoff generation mechanisms in the catchment provides a genuine laboratory where hypotheses of flow and transport can be tested, either by controlled experiments or by contrasting sub-regions of contrasting characteristics. This diversity also ensures that the HOAL is representative of a range of catchments around the world and the specific process findings from the HOAL are applicable to a variety of agricultural catchment settings.

As many of the overarching science questions are related to erosion and nutrients, it was considered an advantage that most of the catchment is used for agricultural purposes where sediment and nutrient fluxes tend to be bigger than for forested or urban settings. The crops include winter wheat and maize which allows examining the effect of different crops on the hydrological processes. Manure and fertilizer application are accurately known from farmers' book keeping which are useful for estimating nutrient and faecal pollution inputs. Part of the catchment is pasture and part of it is forested which opens up more comparative research opportunities.

The catchment selected also had other, more practical, advantages over other catchments. Importantly, it is very convenient from a logistic point of view. It is located within walking distance of the premises of the Institute for Land and Water Management Research which vastly facilitates the day-to-day maintenance of the instruments and experimental setups. Because of the proximity to the institute, the instruments can be connected to the power grid which, again, has major advantages as it avoids battery failures – a frequent cause of data loss. Finally, the instruments can be connected to a high speed glassfibre Local Area Network which is very useful for data management and remote monitoring of the functioning of the instruments and the short term planning of experiments.

An additional bonus for the selection of the site is that runoff measurements at the catchment outlet started in 1945 (Blümel und Klaghofer, 1977; Turpin et al., 2006; Strauß et al., 2007) which helps put the recent observations into a longer term context.

3.1.2 Catchment description

The Petzenkirchen HOAL (Hydrology Open Air Laboratory) catchment is situated in the western part of Lower Austria (48°9′ N, 15°9′ E) (Fig. 2). The catchment area at the outlet (termed MW) is 66 ha. The elevation of the catchment ranges from 268 to 323 m a.s.l. with a mean slope of 8 %. At present, 87 % of the catchment area is arable land, 5 % is used as pasture, 6 % is forested and 2 % is paved. The crops are mainly winter wheat and maize.

The climate can be characterised as humid with a mean annual temperature of 9.5 °C and a mean annual precipitation of 823 mm yr^{-1} from 1990 to 2014. Precipitation tends to be higher in summer than in winter (Fig. 3, Table A1). Crop evapotranspiration ($\mathrm{ET_c}$) estimated by the FAO (1998) method using local climate data and crop growth information for this period was 471 mm yr^{-1}. Annual evaporation estimated by the water balance ranged from 435 to 841 with a mean of 628 mm yr^{-1} (1990–2014). The natural surface water outlet of the catchment is known as the Seitengraben stream. Mean annual flow from the catchment in this stream is 4.1 L s^{-1} (or 195 mm yr^{-1}) (1990–2014). Mean flows tend to peak in the spring (Fig. 3). The largest flood events on record occurred in 1949 and 2002 with estimated peak discharges of 2.8 and 2.0 $\mathrm{m}^3\,\mathrm{s}^{-1}$, respectively. The highest discharge in recent times occurred in summer 2013 with 0.66 $\mathrm{m}^3\,\mathrm{s}^{-1}$. The subsurface consists of Tertiary sediments of the Molasse zone and fractured siltstone. The dominant soil types are Cambisols and Planosols with medium to poor infiltration capacities. Gleysols occur close to the stream (Fig. 4).

The HOAL is special in that many runoff generation mechanisms can be observed simultaneously in different parts of the catchment (Fig. 5). Due to shallow, low permeable soils and the use of the catchment area as agricultural land, the concave part of the catchment was tile drained in the 1950s in an effort to reduce water logging. The estimated drainage area from the tile drains is about 15 % of the total catchment and can be divided into two bigger systems in the south-western part of the catchment and four smaller drainage systems in the north-eastern part. The pipes drain into the main stream at four locations. Two tile drain systems (Sys1, Sys2) do not dry out during the year while two are ephemeral (Frau1, Frau2) (see Fig. 7). The uppermost 25 % of the stream was piped in the 1950s to enlarge the agricultural production area. The pipe enters the main stream at inlet Sys4. Its flow dynamics and chemistry are similar to those of the permanent tile drains as it drains the surrounding soil.

There are two clearly visible springs that directly discharge into the stream. These are Q1 and K1. The water from Q1 originates from a fractured siltstone aquifer with distinct hydrologic and chemical characteristic from those of other point sources along the stream. The hydrologic dynamics and chemical characteristics of K1 are more similar to the perennial tile drainages. Q1 is perennial, while K1 is not.

In the south-eastern part of the catchment is a small wetland close to the stream which permanently seeps into the stream via two rivulets (A1, A2). The wetland is fed by springs at the upper part of the wetland and usually responds very quickly to all types of rainfall due to its high saturation state.

During low intensity events in summer, the flow in the main stream responds to rainfall with substantial delay as the soil usually offers a lot of storage capacity, depending on soil moisture. A mixture of tile drainage water, diffusive inflow from the shallow aquifer, spring water, and surface water from the wetland tends to feed the stream. During major storms, saturation overland flow occurs across the fields (mainly in the depression areas along the talweg and close to the stream) which enters the stream at two (E1, E2) or three locations, depending on the magnitude of the event. The overland flow causes gully erosion.

During high intensity thunderstorms in summer and spring, infiltration excess overland flow tends to occur with a very substantial, fast contribution from the tile drainage system. During infiltration excess overland flow events, splash and gully erosion may occur on the fields that are poorly covered by crops (such as bare soil after harvest or the adolescence state of maize), but sedimentation immediately occurs when the sediment laden water enters a field with better cover (such as wheat). During very dry periods in summer, the high clay contents will cause shrinking cracks which act as macropores for re-infiltration during subsequent events.

In winter rain-on-snow runoff may occur as saturation overland flow during large events leading to gully erosion. In fact, this is when most of the overland flow occurs during the year. However, the main runoff generation mechanism in winter is through lateral subsurface pathways (shallow subsurface preferential flowpaths, drainage pipes). Even minor events (of, say, 5 mm) will lead to a significant increase of stream flow due to high soil moisture during the winter. After freezing periods, when the soil is still frozen, infiltration excess overland flow may occur.

3.2 Setting up the HOAL and instrumentation

Setting up the base monitoring and the dedicated monitoring and sampling was guided by the overarching science questions and the specific hypotheses.

3.2.1 Basic infrastructure and monitoring

Planning of the HOAL started in 2008. In September 2009 the Vienna Doctoral Programme on Water Resource Systems started and the financial resources for the base instrumentation were made available through the TU Wien. In line with the overarching science questions the instrumentation was designed for high spatial and temporal resolution which involves substantial power consumption. Consequently, a mains cable was run from the nearest connector a few hundred meters outside the catchment along the stream to the weather station to enable 380 V electric power supply to the instruments. To facilitate maintenance of the instruments, data storage and the short term planning of experiments, a high speed glassfibre cable was run from the premises of the Institute for Land and Water Management Research into the HOAL to provide a Local Area Network (LAN) for data transmission. The glassfibre network allows fast streaming of the data and is less susceptible to damage due to lightening than electrical transmission lines. Subsequently, a range of instruments was installed as the basic monitoring setup to measure dynamic data. All are operated at a temporal resolution of 1 min with the exception of the piezometers where groundwater levels are recorded at temporal resolutions of 5 to 30 min.

- Atmospheric processes: four raingauges were installed to monitor spatial rainfall patterns. Three of the raingauges are distributed within the catchment and one is located close to its boundary.
- Atmospheric and soil processes: monitoring at the weather station located approximately in the centre of gravity of the catchment includes air temperature, air humidity, wind speed and direction (all at three heights), incoming and outgoing solar and long wave radiation, wind load on the construction, rain drop size distribution, snow depths, soil heat flux and soil temperatures at different depths.
- Surface water: a total of 12 flumes were installed within the catchment to monitor discharge at 1 min resolution from the inlet piped stream, tile drains, erosion gullies, springs and tributaries from wetlands. These flumes are the backbone of the HOAL. All flumes were calibrated in the Hydraulic Laboratory of the TU Wien to obtain a reliable stage–discharge relationship.
- Surface water: at the catchment outlet, the existing H-flume (dating from 1945 with a number of changes since) was upgraded in 2009. The maximum discharge capacity was increased and a number of additional sensors were installed including water temperature, electrical conductivity, turbidity (two probes from different

makes), chloride, pH, nitrate. Grab samples are taken weekly for a range of chemical analyses including suspended solids and various compounds of nutrients. Additionally, autosamplers take water samples during events. A video camera was installed to monitor the water level in the flume and the functioning of the instruments.

- Groundwater: 23 piezometers were installed within the catchment where groundwater level and water temperature are monitored. Most of the piezometers are located along transects perpendicular to the stream to help understand stream–aquifer interactions. Two additional air pressure sensors were needed to correct the readings of the pressure transducers for the air pressure fluctuations.

Tables 1 and B1 give more details of the instruments. All of these instruments are connected to data loggers (some of them through interfaces) where the data are stored temporarily. Most of the data loggers are then directly connected to a computer at IKT through the glassfibre LAN. These include the loggers of the discharge pressure transducers, the turbidity measurements, the water chemical parameters and the instruments at the weather station. The rain gauges are connected through a GSM (mobile phone) module. The data of the piezometers and the movable eddy correlation stations are stored locally and read out manually at regular intervals.

To complement the base monitoring of the dynamics of the hydrological flow and transport processes at specific locations, a number of spatial surveys were conducted after setting up the HOAL which included a Lidar survey, aerial photographs, soil mapping and sampling, and collection of agricultural data (Table 2). Further details are given in Tables B1 and B2, Figs. 6 and 7.

3.2.2 Dedicated monitoring and experiments

Three eddy correlation stations were set up in 2012 and 2013 to understand the spatial distribution of land–atmosphere interactions. As evaporation is an important flux in the HOAL it will directly affect soil moisture and flow paths of interest to other HOAL

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research questions. One set of instruments has been set up at the weather station location, using a closed path device. Additionally, two mobile stations are deployed (using open path devices) based on a site rotation plan to optimise the locations for each sensor relating to the factors of interest; topography, soil type and moisture and vegetation. The devices measure at a frequency of 10 Hz and are processed offline using TK3 software (Mauder and Foken, 2011) to provide 30 min values for the sensible, latent heat and CO_2 fluxes. The height at which the devices are installed varies depending on the height of the surrounding vegetation to try to ensure the footprint contains only one particular land use. Soil heat flux and net radiation sensors are also installed to complete the energy balance. Scintillometer measurements of aggregated fluxes over a line of about 150 m are made for comparison to obtain momentum flux, sensible heat flux and information on the turbulent parameters of the air. The evapotranspiration can also be calculated using energy balance measurements from the mobile eddy stations.

Acceleration sensors (Accelerometers) are installed on the guyed mast of the weather station to evaluate the fatigue of water related structures caused by the fluctuating components of wind. For the elements of steel structures (such as poles of water supply towers) fatigue damages due to the high cyclic wind-induced vibration is a relevant failure mechanism. To this end, a finite element model of the structure is verified by dynamic system identification and the measured structural responses are used to extract the stress/strain time histories at critical points. The measurement duration of the capacitive accelerometers was set to 30 min at a 100 Hz sampling rate that repeats every 18 h. Another step is to identify the wind loads inversely from the measured structural response and correlate them to the wind statistics from eddy correlation measurements. The wind load identification follows the general lines of the experiments already accomplished at the TU Wien Laboratory of structural model dynamics (Kazemi and Bucher, 2015).

A soil moisture monitoring network was set up to understand the effect of small scale variability of landscape characteristics on the microwave response of satellite sensors. Since soil moisture is such a key parameter, a better understanding of its space–time patterns will also be useful to other processes in the HOAL including evapotranspiration and runoff generation. The network uses wireless transmission technology based on the ZigBee protocol (Bogena et al., 2010) where the local data are telemetered to hubs which connect to the LAN. Time Domain Transmission sensors are used which measure the dielectric conductivity from the propagation velocity of an electromagnetic wave, similar to TDR (Bogena et al., 2010). All sensors are installed at four depths below ground surface (two stations at five depths). One of the difficulties with measuring soil moisture in agricultural catchments is that it is not possible to install the sensors permanently in the field. As a consequence, 20 stations were installed permanently on pasture, while 11 stations were temporary, which were removed and replaced once or twice a year in accordance with the agricultural manipulations on the fields.

Monitoring of saturation patterns within the catchment is conducted using video camera to understand the space–time patterns and connectivity of surface flow following the pattern comparison paradigm of Blöschl et al. (1991) and Parajka et al. (2012). This is complementary to the soil moisture network by providing visual observation with better spatial resolution. For these observations, a two megapixels HD camera was installed on the weather station mast 7 m above the ground, overlooking a hillslope area of about 2 ha. The camera captures one 1280 × 720 resolution picture per minute and records 720P video by motion-trigger during rainfall events. The camera exterior orientation was determined based on 15 ground targets for georeferencing. Pictures of overland flow generation provide a visual assessment of saturation patterns and are useful for validating distributed models of surface runoff (Grayson et al., 2002; Horvath et al., 2015).

To understand the dynamics of nutrients such as phosphorus and nitrogen and their compounds a water quality monitoring network was installed at the tributaries within the HOAL to complement the base monitoring at the catchment outlet. Flumes for overland flow from the fields (erosion gullies), the wetland, tile drains and the springs were equipped with in situ sensors for electrical conductivity, temperature, turbidity, pH, nitrate and chloride sampling at 1 min intervals. While the high sediment concentrations in the HOAL facilitated the sediment process analyses, they turned out to be a challenge for monitoring the water quality parameters, as the stilling wells in which sensors are usually placed tended to silt up quickly. A new device was developed, termed Water Monitoring Enclosure (WME), that allows in-situ monitoring of water quality parameters for highly dynamic, sediment laden streams (Exner-Kittridge et al., 2013). The WME ensures a minimum internal water level which keeps the monitoring equipment submerged even when there is no flow into the enclosure. Four WME and six autosamplers were installed throughout the catchment for event sampling. Grab sampling is performed monthly at the tributaries, in addition to the weekly sampling at the catchment outlet, and analysed for a range of parameters including stable isotopes.

Four enzymatic analysers have been set up at the catchment outlet to understand the dynamics and pathways of faecal pollution and to test the instruments for real-time surface water monitoring. The devices have two different designs (BACTcontrol and ColiMinder) both of which detect the enzymatic activity of β-D-glucuronidase (GLUC) occurring in faecal associated microbes. The measurement principle is based on the enzymatic hydrolyses of a non-fluorescent substrate that leads, depending on the concentration and activity of the target GLUC enzymes, to the accumulation of a fluorescent product which is detected optically. The devices sample stream water at intervals of 1 or 3 h. The results from the devices are compared for different setups with laboratory analyses of water samples to understand the strengths and limitations of the instruments in an on-line mode, and interpreted in the context of a range of physical and chemical parameters for events with contrasting characteristics (e.g. fast and short response times, dry and wet antecedent soil moisture) to shed light on the processes of microbial pollution.

Sediment monitoring and experimentation was conducted to understand the sources and pathways of sediments within the catchment. Turbidity is monitored at both erosion gullies along with autosamplers to be able to calibrate the sediment–turbidity relationships for each event separately (Eder et al., 2010). Further autosamplers are located at the inlet of the piped stream and some of the tile drains on the right bank to investigate subsurface sediment transport. Aerial photographs are taken to identify erosion patterns and calculate eroded soil volumes after erosive rainfall events. To understand sediment deposition and resuspension in the stream, flushing experiments were conducted, where sediment-free water was pumped into the source of the stream and flow rates, sediment and solute concentrations as well as grain size distributions were measured (Eder et al., 2014).

To understand the stream–aquifer interactions several stream tracer tests were performed in the main stream. One set of tracer experiments was performed during winter baseflow conditions (where evaporation can be assumed to be negligible). Bromide was injected as a tracer and bromide concentrations and flow were measured for five locations along the stream. This allowed the estimation of stream bank fluxes (Exner-Kittridge et al., 2014). An infrared camera was used to identify hotspots of groundwater recharge into the stream. Similar tracer tests were performed during summer with the additional focus on evaporation. Mass balances over sections of the stream were used to determine the role of near-stream riparian trees on the daily fluctuations of the stream flow during low flow conditions.

A number of geophysical surveys were conducted to improve the delineation of hydrogeological heterogeneities and processes in the subsurface. Initially, a series of measurements using ground penetrating radar (GPR) were performed in 2010 for the characterisation of drainage pipes. However, the resolution of these results was limited due to the high attenuation in the signatures due to the high clay content. To improve the characterisation of the HOAL site at different spatial scales, imaging surveys are being started with the Induced Polarization (IP) method for delineating the aquifer geometry and hydrogeological structures such as preferential flow paths. Application of the spectral IP method (SIP) at different frequencies is planned to gain information on hydraulic conductivity and changes in the subsurface associated with microbial activity (e.g., Flores Orozco et al., 2011, 2013; 2015). Low-induction number electromagnetic induction (EMI) methods that do not require contact between the sensors and the ground will permit the collection of data at extensive areas with reduced acquisition times.

3.3 Managing the HOAL

Meaningful hypothesis testing in an observatory not only requires careful planning of installation of instruments and conducting the monitoring and the experimentation, but also coordination of the research between the groups involved, maintenance of the instruments, dealing with land owners, and data management.

3.3.1 Coordination of research

One of the main strengths of this kind of observatory comes from the synergies between a critical group of people conducting related research. In the HOAL, currently more than 20 researchers are involved plus support staff. Nine dissertation projects focussed on the HOAL are being conducted. While observatories sometimes adopt a top-down approach where the individual research activities are subsidiary to the main goal, a slightly different approach has been adopted in the HOAL. A general master plan for the research to be conducted was defined as the overarching sciences questions. These were specified in the research proposals of the Doctoral Programme on Water Resource Systems that were submitted to the Austrian Science Funds (Blöschl et al., 2012). The research proposals also included more specific hypotheses. When actually implementing the research, the individual doctoral students were given considerable freedom in specifying their own hypotheses and their experimental/monitoring setups. This then led to an iterative network structure of the interactions between the research of the students. Figure 8 illustrates the general concept of implementation. For each hypothesis, the individual steps of implementation consisted of (i) planning of the dedicated monitoring and experiments, (ii) conducting monitoring and experiments, (iii) data analysis and hypothesis testing, and (iv) research write up. Depending on the outcomes of the experiments, these steps would be repeated in an iterative way. At the same time other hypotheses are tested in the HOAL (by the same or other students). These interact, as indicated by the double arrows in Fig. 8. The interactions occur at all four steps of the research, from the planning to the write up. The main advantages of this iterative, network-based process of conducting hypothesis testing are its flexibility and the encouragement of creative thinking by the students.

The Doctoral Programme on Water Resource Systems is an ideal setting for this exchange as it is specifically geared towards fostering collaboration between students, including from different disciplines. As part of the Doctoral Programme, each student is encouraged to develop collaborations through joint supervision (each student has two supervisors), regular research cluster meetings focusing on research themes, and annual and six-monthly symposia that bring all research students and supervisors together for one or two days for research presentations, posters and discussion sessions.

3.3.2 Maintenance of instruments

The overall responsibility of coordinating the maintenance of the instruments lies with the HOAL manager who draws the maintenance plans and coordinates or supports any repairs and replacements. The manager also coordinates the installation of new instrumentation and the setup of experiments. An important part of the maintenance work relates to the base monitoring, and in particular the cleaning of the H-flumes at the stream tributaries. Some of the water quality sensors need regular cleaning to avoid biofilm formation and calcification. The sensors on the weather station are checked regularly for level position and cleanliness. The soil moisture sensors and the other sensors that are not connected to the power grid are checked regularly for power supply (change of batteries, cutting out grass to prevent solar panels from being overgrown). A regular schedule of checking the instrumentation is operated. In these tasks, the HOAL manager is assisted by a number of local technicians with diverse expertises, including electronics.

Generally, each student is responsible for the proper set up and operation of any dedicated monitoring and experimentation for their PhD research. There is, again, a set maintenance schedule. Maintenance and regular checking of the stations are coordinated with the HOAL manager and carried out by the students and the local technicians.

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One of the main advantages of the HOAL is its location within walking distance of the premises of the Institute for Land and Water Management Research which vastly facilitates the day-to-day maintenance of the instruments and experimental setups. Both the HOAL manager and the local technicians are based at the Institute. Heavy rainfall events can be observed live and reference measurements can be taken during events. The operation of the auto samplers can be checked during events, to maximise the number of water samples from an event. After events associated with lightening the entire system is checked for operation (e.g. power outages).

To facilitate the exchange of information between the team members, a web-logbook has been specifically created for the HOAL. All activities within the HOAL are entered into the logbook including installation and maintenance of instrumentation, all sampling and surveying activities, and any other activities that are relevant to the operation of the HOAL. The web-logbook is a web application that allows access anywhere anytime by simply using a web browser. The main advantage of the logbook is that it sets a minimum standard protocol for all the information relevant to operating the HOAL and its easy, instantaneous accessibility to all team members. The logbook is often accessed in the field during manual measurements. The software also features user management, search and import/export facilities.

3.3.3 Land owners

Observatories in most other geoscience disciplines, such as astronomy and meteorology, require relatively modest space on the land. Typically, the land is purchased by the operators of the observatory. In contrast, hydrology is about water and matter fluxes at the landscape scale, so the requirements regarding space are invariably more extensive and purchasing the entire catchment of interest is rarely an option. Arrangements have therefore to be made between the operators of the observatories and the land owners. The arrangements in the HOAL involve:

- Permissions to use the land,

- Information on agricultural management practices and, where applicable, changes to these practices.

Permissions to use land are needed for the permanent instrumentation (such as the weather station) as well as to access the fields for sampling and for the temporary sensors of the soil moisture network. Information on agricultural management practices is particularly important for estimating nutrient input and it is also very relevant for estimating other fluxes such as transpiration. In a number of instances specific tillage practices are part of hillslope experiments.

Agreements have been drawn up between the HOAL management and the landowners to make arrangements for both aspects. About half the land is privately owned by a total of nine farmers. The remaining land is state owned and management by the Austrian agricultural research agency, which facilitates the collaboration with the HOAL team due to similar objectives. A small fee is paid as part of the agreement but, more importantly, a good working relationship is always sought. Any maintenance or experimentation activities in the field are planned in agreement with the land owners, in order to avoid obstructions of the daily agricultural routines. The HOAL manager makes an effort to introduce the doctoral students and their research to the farmers on site, e.g. when they meet by chance during sensor installations or field work. The farmers are given access to the weather data, which is generally appreciated. They also get Christmas presents and there is an annual open day where the students explain their recent research to the local community. The main source of income of the farms in the catchment is crop production for fodder for pig breeding. Fertilizers costs and fertilizer leaching as well as the problem of soil loss by erosion are important tasks farmers have to deal with. This makes them additionally interested in the research and the cooperation.

3.3.4 Data management

As indicated in Table B1, most sensors are connected to a computer (IKT server, HOAL PC, Soil Net PC) at the IKT via fast glassfibre LAN. A data base, known as Mydatanet, is run on the IKT server and hosts most of the data. Mydatanet imports the data at 1 min intervals from the data loggers along the stream (discharge and water chemistry parameters) and the rain gauges. Mydatanet features online access and a web-based graphical interface (Fig. 9) to the database which allows a regular check of data and fast identification of specific hydrologic situations and instrumentation failures. Mydatanet also provides for easy importing and downloading, user management, device administration and reporting.

Some sensors are connected through fast glassfibre LAN to dedicated computers. For example, the sensors of the weather station are connected to the HOAL PC, the sensors of the soil moisture network to the Soil Net PC where they are stored as files. Some data (such as the eddy correlation data) are read out manually from the data loggers and uploaded on the data bases on the dedicated computers.

All measured data are stored as two separate layers. The first contains raw data as directly obtained by the instruments. These data are regularly screened for errors and inconsistencies. They are corrected or labelled as missing data according to a set protocol. The corrected data are stored in the second layer with data flagging and a processing report. Data quality check is an important step in data management not only for scientific usage of the data, but also for providing a direct feedback to maintaining and updating instrumentation configurations. All raw and processed data are exported from the various databases and uploaded in consistent CSV file format to an ftp server at TU Wien at bimonthly (raw data) and six-monthly (processed data) intervals. A backup of all data is performed on a daily basis by the grandfather–father–son method. Monthly backups of all databases are kept for one year.

The HOAL manager is responsible for the overall data management process. Two IT professionals (one at IKT, one at TU Wien) are responsible for the back up of the data and hardware maintenance. The quality check and the correction of the data are carried out by the research students as part of their PhD work. The data correction protocols are stored on the ftp server in simple readme text format.

4 Examples of specific hypotheses

Currently, nine research students are conducting their PhD in the HOAL. Based on the literature and previous work in the HOAL the students identify specific hypotheses within their research programmes. Typically, one hypothesis conforms to one research paper they are planning to prepare, but sometimes the hypotheses are more specific. The following steps were adopted in inferring the instrumentation or experimental setup from the hypothesis to be tested.

- Background: importance of the research issue, prior knowledge of the issue and specific research question. In many instances the specific hypotheses are formulated and tested as a collaboration among students (joint science questions) building on previous work.
- Hypothesis: stating the hypothesis from knowledge of the processes in the literature and prior analyses in the catchment.
- Test: anticipating alternative test results and their implications for rejecting (or not rejecting) the hypothesis. If possible, more than one test is performed to test the same hypothesis, preferably based on different data and/or different rationales.
- Experiment: performing the experiment or the monitoring with required sensitivity.
- Outcomes: testing the hypothesis against the results of the experiment or the monitoring in the context of the assumptions involved and implications for the overarching science questions.

Below a number of examples of hypothesis testing are presented to illustrate the approach adopted in the HOAL. They relate to repeatable experiments (Example 1), temporal monitoring (Example 2), spatial monitoring (Example 3) and testing of instruments (Example 4).

4.1 Example 1: What is the source of early stream sediment concentrations?

- Background: understanding the sources of sediments is very relevant for managing contaminants such as phosphorus and for controlling soil loss from agricultural landscapes. During rainfall events, often an early peak in the suspended sediment concentration is observed (Eder et al., 2010). The sediments may either stem from erosion from hillslopes close to the stream or from reactivation of sediments on the stream bed that have been deposited during previous events. Observations of sediment concentrations during natural events are inconclusive, as sediment inputs may occur in a diffuse way along the stream which are difficult to measure. Alternative experiments are needed to test the origin of early suspended sediments in the stream.

- Hypothesis: early suspended sediment concentration peaks in the stream are a result of resuspension of sediments in the streambed deposited during previous events, rather than a result of erosion from the catchment.

- Test 1: does sediment-free water pumped into the stream produce suspended sediment concentrations similar to those observed for natural events? Yes: cannot reject hypothesis. No: reject hypothesis.

- Test 2: do suspended sediment loads decrease for repeated experiments? Yes: cannot reject hypothesis. No: reject hypothesis.

- Experiment: two flushing experiments were conducted by pumping sediment-free water into the stream and measuring flow and sediment concentrations at three sites with high temporal resolution. The discharges were similar to those of early stages of natural events with comparable bed shear stresses.

- Outcomes: at the most upstream section (site 360) of the stream, significant sediment was resuspended from the stream bed with concentrations similar to those of natural events, so the first hypothesis was not rejected. Sediment concentrations and loads decreased along the stream as the flow velocities decreased as a result of the dispersion of the hydrograph (Fig. 10). During the second experiment the sediment load was much smaller than during the first experiment, so hypothesis 2 was not rejected either. This finding was interpreted as the result of the depletion of stream bed sediments during the first experiment. Comparison with natural events supported streambed resuspension as the source of early sediment peaks.

4.2 Example 2: What are the sources and flow paths of event runoff?

- Background: agricultural runoff into surface waters during rainfall events can originate from many different sources (e.g. multiple aquifers, unsaturated zone, event rainfall) and can take multiple interconnected flow paths (e.g. overland flow, macropore flow, matrix flow, tile drainage systems, etc.). Cost-effective mitigation measures of excess nutrients are harmful to the aquatic environment should be targeted on the sources and flow paths that conduct the bulk of the nutrient load rather than all sources and flow paths. Additionally, specific sources and flow paths may dominate during different periods within a runoff event throughout the entire length of the stream. Methods are needed to identify both sources and flow paths.

- Hypothesis: the shallow aquifer contributes the majority of the total discharge at MW during rainfall events.

- Test: does the shallow aquifer contribute less than 50 % to the total event discharge volume as compared to the event rain water and the unsaturated soil water? Yes: reject hypothesis. No: cannot reject hypothesis.

- Experiment: monitor discharge, chloride (Cl) and nitrogen (N) at MW over several years. Perform end-member mixing analysis (EMMA) based on the chemical signatures of the end-member reservoirs (i.e. event rainfall: low Cl, low N; soil water: medium Cl, high N; shallow aquifer: medium Cl, medium N) and assess the uncertainties.

- Outcomes: EMMA suggests that, over the period 2011–2012, the shallow aquifer contributes between 10 and 70 % of the event discharge volume with an average of 45 %, depending on the event magnitude. During small to average events in summer, the shallow aquifer water dominates the total volume of the hydrograph, while the unsaturated soil water tends to contribute very little. Both preferential flow and pressure displacement appear to be the dominant pathways during these periods. During the winter months and events with high rainfall volumes, the contribution of unsaturated soil water and rain water can increase substantially (Fig. 11). This is attributed to high soil saturation conditions during these periods.

4.3 Example 3: How do spatial soil moisture patterns change during rainfall events?

- Background: understanding the controls of spatial soil moisture patterns in small catchments is essential for upscaling soil moisture from point to catchment scales and linking ground data to satellite data. The relative importance of the factors driving the spatial distribution of soil moisture was found to change during the season, e.g. topography may control the soil moisture distribution during wet periods, and vegetation and soil properties may be more dominant during dry conditions (Grayson et al., 1997). The changes in the patterns during rainfall events are less well documented and it has been hypothesised that the relative patterns remain stable (Grayson and Western, 1998). Observations are needed to test whether this is actually the case.

- Hypothesis: during spring rainfall events the relative spatial soil moisture pattern remains stable throughout the events.

- Test: is a clear change in relative soil moisture patterns observable over the catchment? Yes: reject hypothesis. No: cannot reject hypothesis.

- Experiment: soil moisture was monitored at many locations within the catchment before, during and after a large rain event.

- Outcomes: the spatial patterns do change during the rainfall event examined in this particular catchment, both at 5 and 20 cm depth (Fig. 12), so the hypothesis is rejected. Relative soil moisture is more evenly distributed during the event than before, although the centre and the north-eastern part of the catchment are consistently wetter. After the event the soil dries out and the patterns return to a similar state as before the event. The main difference in the patterns is their variance, so a different scaling (rather than by the spatial mean) may produce greater similarity. On the other hand, one would expect bigger changes than those in Fig. 12 for drier antecedent soil moisture as is typical of summer events.

4.4 Example 4: Can faecal indicators be consistently monitored on an on-line basis?

- Background: on-line detection of enzymatic beta-D-Glucurondiase (GLUC) activity has been suggested as a potential surrogate for microbiological faecal pollution monitoring with a capacity for near-real time applications in the context of water safety management. Such measurements will also allow shedding light on microbial transport processes at the catchment scale. While automated measuring devices have already been tested for ground water (Ryzinska-Paier et al., 2014), so far no evaluation exists for surface water. Surface water may involve additional challenges due to higher sediment concentrations and bacterial contamination levels which may contaminate or block inlet pipes and other system components. The HOAL is an ideal test bed for the method due to its highly dynamic runoff, sediment concentrations and bacterial contamination.

- Hypothesis: GLUC activity in surface water can be consistently measured by devices differing in construction (consistent meaning $R^2 > 0.9$ and p value < 0.001).
- Test 1: are measurements of devices with identical constructions consistent? Yes: cannot reject hypothesis. No: reject hypothesis.
- Test 2: are measurements of devices with different constructions consistent? Yes: cannot reject hypothesis. No: reject hypothesis.
- Experiment: four devices for automated GLUC measurements were installed at the catchment outlet and operated in parallel for a period of 12 months (two sets of two identical devices, BACTcontrol and ColiMinder).
- Outcomes: results from Test 1 (Fig. 13, top) show that devices with identical constructions are indeed extremely consistent ($R^2 > 0.9$). Test 2 (Fig. 13, bottom), however, shows that different designs lead to less consistent results ($R^2 = 0.71$), so hypothesis 2 was rejected. The lower correlations in the latter case are mainly due to the different designs and partly related to slightly different intake locations (about 2 m separation) and measurement times (up to 60 min time offset). Overall, the experiments suggest that the instruments are indeed useful for near-real time monitoring of GLUC activity.

5 Lessons learned and outloo

5.1 Lessons regarding science strategy of the HOAL

5.1.1 Long-term experimental infrastructure

The research since the inception of the HOAL has demonstrated that the strategy of base monitoring related to overarching science questions and dedicated monitoring related to specific hypotheses indeed works well. Substantial synergies were realised between the dissertation studies that shared the base monitoring. For example, most students used the runoff measurements at high temporal and spatial resolution in the context of their own specific science questions such as runoff generation, flow paths, nutrient budgeting, sediment transport and evaporation estimation. On the other hand, the dedicated monitoring allowed collection of exactly the information needed to test specific hypotheses and thus maximise the efficiency of the HOAL. Two generations of research students have so far worked in the HOAL. The overall, structured setup geared towards long term research assisted students in building on the findings of the previous generation. When students left, there was sufficient expertise among the team members for a smooth transition to new students. Practical aspects such as the HOAL manager and the web logbook turned out to be valuable in this transition.

5.1.2 Interdisciplinary collaboration

Interdisciplinarity is both a consequence of the type of societally relevant research questions being addressed in the HOAL, and it also provides an opportunity to address more complex research questions than would be possible by researchers from only one discipline. Students have clearly recognised that through collaboration with others they are able to gain knowledge and understanding that enables them to delve deeper into their own research topic (see Carr et al., 2015). Additionally, they often also see immediate benefits to their collaboration in the form of a data set, which provides further motivations for continuing to work collaboratively. However, they also recognised that collaboration across the disciplines can bring additional challenges as time and effort is needed to understand and incorporate knowledge from other research fields. Study sites, such as the HOAL, provide a focal point where researchers from different disciplines can interact, develop joint hypotheses together and work collaboratively on data collection or experimentation. As such, this can be seen to raise the efficiency of interdisciplinary collaboration because research students have greater clarity on who and why they need to collaborate with to overcome specific research challenges in answering their joint research questions.

5.1.3 Networking within the science community and beyond

The collaboration between TU Wien and IKT fully realised the potential of the complementary expertises. Similarly, collaboration with some of the providers of the instrumentation turned out to be very useful and allowed science questions to be addressed (e.g. comparative testing of monitoring microbial pollution proxies) that would be difficult to address otherwise. Collaborations with other research institutions sometimes posed an issue regarding the time axes. Joint projects usually turned out to take longer (and consume more resources) than anticipated. The joint projects were not always the top priority of the project partners which added to delays. A more rigorous planning of joint projects in the future, including set deadlines, deliverables and clear budgets, may help increase the efficiency of such activities. Communication and outreach activities were received well, although there is probably potential for additional activities from local to global scales.

5.2 Lessons regarding implementation

5.2.1 Site selection and hydrological characteristics

The HOAL site turned out to be an excellent choice for the same reasons it was selected in the first place. The different runoff generation mechanisms indeed allowed some very interesting and unique hypothesis testing associated with flow paths and water sources. The proximity of the HOAL to the Institute for Land and Water Management Research was probably one of the most fortunate choices of the entire project. The logistic benefits for maintenance and connection to the power grid and high speed glassfibre LAN turned out to be immense. This is certainly an important lesson learned and we can warmly recommend a similar setup for other Hydrological Laboratories.

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5.2.2 Setting up the HOAL and instrumentation

While the overall science strategy and site selection clearly worked well, the implementation of the instrumentation was not always easy. All instrumentation was finally installed and functional in a similar way as planned but, on the way, there were considerable challenges, even though there was substantial expertise within the team members with field experimentation. With the benefit of hindsight the HOAL team would probably approach some of the installations differently.

Challenges with the flumes: H-flumes were planned for runoff measurements for some of the tributaries within the HOAL. The main motivation for choosing H-flumes over V-notch weirs was the hope that they will be less prone to siltation although, ultimately, siltation was not completely avoided. The choice of H-flumes came at a cost of lower measurement accuracy at low flows. Initially the main scientific interest was on large floods, but soon it became clear that the entire runoff spectrum is of interest. Additionally, the H-flumes were overdesigned. This was partly due to the early focus on floods and partly due to internal communication issues where each of the team members added a “safety margin” to the maximum design flow to ensure that it is never exceeded. Finally, for simplicity only three size classes were constructed and in this step most flumes were additional increased to fit a class. After a year, when the problems became evident, the cross sections of the flumes were narrowed down to improve their accuracy and tipping buckets were added, but the lesson learned is that some extra time and coordination in the initial planning of the flumes would probably have paid off.

Another problem with the flumes was freezing in winter. In the first winter, the team lost a number of pressure transducers (although the same make had worked fine during winter in a different catchment). Later, a heating system was installed and the flumes were insulated but freezing remains a problem in some situations. It was not always easy to seal the flumes to the ground because of erosion processes and leakage occurred repeatedly. One of the practical fixes were lateral metal sheets attached to the flumes and dug into the ground. Regular maintenance is needed to ensure that no leakage occurs. Finally, the positions of the pressure transducer changed due to the technical interventions. Regular checking of the positions and manual discharge measurements on a weekly basis for quality assurance purposes were found to be very important.

Similarly, operation of the soil moisture sensor network turned out to be more time consuming than anticipated. Part of the problem is the agricultural use of the HOAL requires temporary sensors to be removed and replaced once or twice a year in accordance with the agricultural manipulations on the fields. When replacing the sensors that soil profile had obviously been disturbed, so some of the continuity of the measurements was lost. Forested catchments (Bogena et al., 2010) or pastures (Western et al., 1999) would allow more straightforward instrumentation and more consistent soil moisture data.

Overall, there were a range of setbacks which is not surprising given the enormous number of sensors installed in the HOAL, a total of more than 300, in addition to sampling, experiments and surveys. Much of the research focused on high spatial detail which, in many instances, was realised by a large number of sensors at different locations, but any sensor failures during limited periods of time translated to missing data and reduced spatial detail. Other issues included faulty parts of the instruments, faulty software updates and damage to the glass fibre cable during construction of a nearby building. Additionally, compatibility between different sensors-datalogger systems was not always straightforward, for example due to different preset measurement intervals. The lesson learned is that such issues are difficult to avoid and it is important to be flexible and vigilant. A dedicated person (the HOAL manager) responsible for the overall management certainly turned out to be very valuable in minimising the loss of data and maximising their accuracy.

On the other hand, there were a number of things that worked better than anticipated. One of them is the web access to the data in real time which allows an online-check of the measurements. There were numerous instances where measurement or connectivity problems were quickly identified and repaired. The web access also allows changing the sampling discs of the autosampler when needed and to control the sampling intervals remotely according to the current weather and streamflow conditions, which turned out to be useful. Permanent electrical supply throughout the entire length of the stream was a great benefit for the easy installation, testing, and long-term monitoring of equipment. Without a permanent power supply, certain types of equipment would have not been possible to have been installed, while others would have been very difficult to maintain.

5.2.3 Managing the HOAL

The HOAL manager position was filled in early 2013 and the benefits of a manager quickly became apparent. Previously, communication with the land owners was complicated as there was no single contact point of the HOAL Team. Yet, a good system of co-operation is necessary for the installation and operation of instrumentation such as tripod mounted eddy covariance devices and the soil moisture sensors. The addition of the HOAL manager position to the project had a very positive effect on this process. With the manager recruited from the locality, communication with the landowners was now immediate, as was seen for example from the planning of an evaporation field campaign, as the manager works directly with the research students on a daily basis and hence has a detailed knowledge of their research, much more effective and efficient than previously. A good working relationship with the land owners was facilitated by sharing some of the findings of the HOAL, e.g. on erosion sources and potential protection measures, groundwater protection, and fertilizer management, as well as on the weather data.

Similarly, the manager was invaluable for coordinating the maintenance. The implementation of a weekly maintenance plan by the manager ensured that no important work was overlooked. The plan also facilitated the communication between the group members, e.g. when research students were on temporary leave during their research semester abroad. Similarly the web-logbook was instrumental in maximising data quality and ensuring a realistic interpretation of the data. On the other hand, the maintenance turned out to be quite time consuming. For example, the cleaning of the H-flumes at the stream tributaries consumes considerable time resources. Additional maintenance is needed to clean out dead leaves in autumn. Maintenance works also involves mowing the grass around the instrumentation to avoid shading of solar panels. The soil moisture network required substantial maintenance, in particular the end devices buried a few centimetres below ground, which tended to get wet and had to be cleaned.

The main advantages of this iterative, network-based process of conducting hypothesis testing are its flexibility and the encouragement of creative thinking by the students. There were a number of instances where this flexibility allowed exploiting collaborative opportunities. Examples include a field campaign on identifying the relative contributions of transpiration and soil evaporation together with the IAEA and the validation of NASA's SMAP satellite based on soil moisture data in the HOAL.

At the beginning of the project, the data management was not an easy process. The main challenge were in organising and checking data from a large number of different sensors, communication and a consistent protocol between all the people involved. The raw data correction process consumed more resources than anticipated. Eventually, the overall data management approach did run smoothly. Regular backups, and simple and robust data formats (such as the csv file format) for flexible data exchange proved to be useful.

5.3 Lessons regarding hypothesis testing

The general philosophy of a hypothesis based observatory was considered by the HOAL team members to work well. The hypotheses provided guidance for the dedicated monitoring and experimentation and they facilitated the transformation of the research findings into publications. In particular, thinking in terms of hypotheses was found to be useful as it directly links to the research questions addressed in individual papers.

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However, hypothesis testing was not always as clear-cut as one would hope (Chamberlin, 1965; Srinivasan et al., 2015). There were two issues which were related to (a) setting up the hypothesis and (b) the outcomes of the hypothesis testing.

a. *Setting up of the hypothesis:* Setting up of the hypothesis was constrained by the available resources. Once equipment had been purchased other hypotheses were also constrained by the available infrastructure. One of the issues is the sensitivity of the measurements with respect to the hypothesis. For example, soil moisture sensor pairs installed in the field at the same location gave very consistent results but comparisons with the gravimetric method (oven-drying of samples) did not. The main difficulty was the small sampling volume of the sensors and the immense spatial soil moisture variability, particularly near the surface due to burrows, roots, cracks and soil characteristics. It is hence not clear how sensitive the soil moisture network is to catchment scale hypotheses. In the near future, validation will be based on a portable TDR sensor with a sampling volume similar to that of the sensors. In a similar vein, the observations of the saturation and/or overland flow patterns by video monitoring were focussed on a particular 2 ha area that is usually cultivated with maize or winter wheat. When the crops are short the patterns can be clearly observed but when they are tall, usually during May–July, this is no longer possible. However, since the field patches are cultivated at different times, it is possible to switch the observation area to an alternative bare patch to maximise the period of pattern observations within the HOAL. To decide about the best patches, prior planning is needed.

   Clearly, the more complex the processes are, the more difficult it is to set up clear-cut hypotheses (see, e.g., Reischer et al., 2011 for a complex case). As Knorr-Cetina (2013, pp. 4–5) noted, “the products of science are contextually specific constructions which bear the mark of the situational contingency and interest structure of the process by which they are generated,” and “If there is a principle which seems to govern laboratory action, it is the scientists’ concern with making things “work”, which points to a principle of success rather than one of truth. [. . .]

Thus, it is success in making things work which is reinforced as a concrete and feasible goal of scientific action, and not the distant ideal of truth which is never quite attained." It is therefore clear that the outcomes of the hypothesis testing will not be independent of the preconceptions and interests of all those involved. Holländer et al. (2014) illustrates this notion for the more specific case of hydrological predictions.

Some of the examples in this paper do illustrate the difficulty with reducing complex science questions to hypotheses with binary outcomes. Hypothesis Example 2 in this paper is quite specific while a more relevant question would perhaps enquire about the causal mechanisms driving the sources and flow paths of event runoff. Similarly, one is usually more interested in the more complex questions of the mechanisms driving spatial soil moisture patterns rather than simply whether they change during events or not (Example 3). The issue of complex process interactions that cannot be easily disentangled by individual hypotheses permeates much of hydrology, similar to the non-repeatability of experiments. More work on framing relevant and yet testable hypotheses in hydrology is needed (Sivapalan, 2009).

b. *Outcomes of the hypothesis testing:* The second issue was that the outcomes of the hypothesis testing were not always fully conclusive. This is illustrated by the four examples, where rejection (or non-rejection) of the hypothesis was usually associated with some qualifications. Perhaps more importantly, the issue is that, with the exception of a few repeatable experiments performed in the HOAL (such as Example 1), most testing was not repeatable due to the randomness in weather and other boundary and initial conditions which cannot be fully specified (Zehe and Blöschl, 2004; Zehe et al., 2007). The lack of repeatability of experiments and the associated limits to predictability (Blöschl and Zehe, 2005) are a real issue in hydrology. Ideally, one would like to have at least three replicas of the same experiments. There are a few examples where this is already put into practice, such as the Biosphere 2 hillslope experiments performed in a green house (Hopp et al., 2009) but, usually, even dedicated large scale experiments such as the Chicken Creek artificial catchment (Holländer et al., 2009, 2014) do not involve multiple replicas.

A similar question that arises is how representative is the HOAL of other (experimental or larger) catchments around the world, i.e. the question of if and how the findings of the HOAL can be generalised. The diversity of runoff generation processes encountered in the HOAL is considered instrumental in making the findings more generally applicable to a variety of agricultural catchment settings. The students are forced from the beginning of their PhD projects to carefully think about, formulate and interpret their experiments with respect to such broader settings. On the other hand, care needs to be taken in building models that are based on the specifics of the HOAL.

Notwithstanding these caveats related to hypothesis testing, experiences in the HOAL also showed that there were a number of unforeseen opportunities to test hypotheses and acquire knowledge that were not anticipated, i.e. positive surprises. Some of them occurred through collaborations with partners. The HOAL has been shown to numerous guest scientists, it has been used for field training during the Meeting of the European Geosciences Union and it is used as a site for TU Wien courses on field work. Unexpected opportunities that arose from these collaborations were a field campaign on separating transpiration and bare soil evaporation based on isotopic measurements, operated in collaboration with the International Atomic Energy Agency (IAEA) in June 2014. A Picarro isotope analyser system was installed in the field and both institutions benefited from the shared expertises during this field test.

Another example of an unforeseen opportunity was an unplanned, yet very interesting observation in February 2015 when the research students conducted field work to sample stream water quality to test hypotheses regarding diurnal fluctuations relative to summer conditions. A period without snow and rain was selected to ensure no surface water input into the stream. As it turned out, temperatures

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rose slight above zero which melted frozen soil water in the catchment and produced a quite significant discharge into the stream, more than doubling streamflow. The event was neither rain nor snowmelt driven, which is not commonly observed. The comprehensive instrumentation in the HOAL allowed a detailed analysis of the hydrological situation of this interesting event. It was speculated that such mechanisms may occur more often than usually assumed, yet they are rarely considered in rainfall runoff models.

5.4 Outlook

The ambition of the Hydrological Open Air Laboratory (HOAL) in Petzenkirchen is to advance the understanding of water related flow and transport processes involving sediments, nutrients and microbes in small catchments. Overall, the concept of long term facilities that transcend the lifetime of individual projects, a commitment to interdisciplinary research, and the involvement in networks to assist in performing collaborative science has worked well so far.

Two generations of research students have so far pursued research in the HOAL. The third generation of students will address issues of upscaling and hydrological change. The fourth generation of students will be concerned with how all of these findings can be generalised to other climatic and management conditions around the world. More extensive collaborations will allow addressing a wider range of science questions and realise the full potential of an important network within the scientific community. Future societal water challenges revolve around sustainable water management in a changing world (Leibundgut et al., 2014). Hydrological change, hydrological and microbial risks, nutrients and emerging substances are all issues that will likely increase in importance in the near future. Innovative technology and approaches for better understanding water-related processes in the environment are needed.

This paper has focused on the scientific and implementation aspects of the HOAL. There are also financial aspects that are fundamental to the safe operation of the laboratory. Currently, much of the funding comes from the Austrian Sciences Funds, the

TU Wien and the Federal Agency for Water Management. As the activities branch out to a larger number of collaboration partners, care needs to be taken to ensure the long term funding of the Hydrological Open Air Laboratory.

The HOAL is becoming a hub for hosting guest scientists, through a closely knit network with other academic institutions and observatories. The HOAL is special in that many runoff generation processes (surface runoff, spring runoff, tile drainage, runoff from wetlands) can be observed simultaneously and in the high spatial and temporal resolution with which the processes are monitored. This particular profile opens exciting opportunities for complementary, comparative research with different hydrological observatories and experimental catchments in different environments (e.g. Schumann et al., 2010) to foster progress in the interdisciplinary water sciences.

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Table 1. Instrumentation in the HOAL (most of which has 1 min time resolution). Most data are transmitted to the server at the institute by glassfibre cable. For details see Tables B1 and B2, for locations see Figs. 6 and 7.

Compartment	Variables	Locations	Number of stations	Basic/ Dedicated
Atmosphere	Precipitation intensity	Within (or close to) catchment	4	B
Atmosphere	Air temperature, humidity, wind speed and direction (3 heights); atmospheric pressure, incoming and outgoing shortwave and longwave radiation, rain drop size distribution	Weather station	1	B
Atmosphere	Carbon dioxide flux, latent heat flux, sensible heat flux, momentum flux (Eddy correlation)	Weather station and other locations	3	D
Atmosphere	Sensible heat flux (Scintillometer)	Within catchment	1	D
Atmosphere	Wind load	Weather station	1	D
Ground surface	Snow depth	Weather station	1	B
Ground surface	Saturation patterns (photos, video)	Within catchment	1	B
Surface water	Discharge, electric conductivity, temperature, pH, chloride, nitrate	Inlet: piped stream (Sys4)	1	B/D
Surface water	Discharge; partly electric conductivity, temperature, pH, chloride, nitrate	Tile drains (Frau1, Frau2, Sys1, Sys2, Sys3)	5	B/D
Surface water	Discharge, turbidity	Erosion gullies (E1, E2)	2	B
Surface water	Discharge	Springs (Q1, K1)	2	B
Surface water	Discharge; partly electric conductivity, temperature, pH, chloride, nitrate	Wetland runoff (A1, A2)	2	B/D
Surface water	Discharge, electric conductivity, temperature, turbidity, pH, chloride, nitrate, enzymatic activity, UV-Vis fingerprint, video images	Catchment outlet (MW)	1	B/D
Surface water	Runoff water samples (Automatic samplers, 24 bottles each, event triggered)	Inlet (Sys4), Tile drain (Frau2), Erosion gullies (E1, E2), catchment outlet (MW)	6	B/D
Soil	Soil heat flux, soil temperatures	Weather station	1, 2	B
Soil	Soil moisture, soil temperature (in 4 depths, partly 5 depths)	Within catchment	31	D
Soil	Soil moisture (Cosmic ray)	Weather station	1	D
Groundwater	Groundwater level, temperature, partly air pressure	Within catchment	24	B

Table 2. Spatial surveys of catchment characteristics. For details see Tables B1 and B2.

Survey	Variables	Spatial resolution	Date of survey	Basic/ Dedicated
Lidar	Digital elevation model	0.5 m	Mar 2010	B
Soil mapping through auger holes	Soil type	50 m grid	Spring 2010	B
Soil sampling by profiles	Photos, colour, texture, grain size, organic matter, plant available phosphor, pH, potassium of each soil horizon	50 m grid	Summer 2010	B
Geophysics	Georadar profiles	4 profiles	Aug 2010	D
Geophysics	Seismic profiles	7 profiles	Mar 2011	D
Soil moisture survey	Soil moisture	100 pts	Spring 2014	D
Aerial photographs from powered paraglider	Digital surface model, surface roughness, soil loss volumes, erosion patterns	Depending on flight height	bimonthly	D
Agricultural data interviews with farmers	Crops, cultivation period, seeding, fertilization, plant protection, harvest times, harvested biomass, fertiliser and manure application	By field	Annually	B
Water withdrawal interviews with farmers	Water withdrawal from wells	2 wells in catchment	Annually	B

Table A1. Catchment details.

Location:	Near Petzenkirchen, in the western part of Lower Austria Weather station: 48°09′17.7″ N 15°08′54.0″ E Catchment outlet: 48°09′00.9″ N 15°09′10.9″ E
Catchment size:	The catchment area is 65.8 ha.
Climate and runoff:	Mean annual air temperature (1990–2014): 9.5 °C Range (1990–2014): 7.9 °C (1996) to 10.6 °C (1994) Mean monthly air temperature (1990–2014): Jan −0.4 °C, Feb 0.9 °C, Mar 5.1 °C, Apr 9.6 °C, May 14.3 °C, Jun 17.4 °C, Jul 19.2 °C, Aug 18.9 °C, Sep 14.3 °C, Oct 9.4 °C, Nov 4.4 °C, Dec 0.0 °C
	Mean annual precipitation (1990–2014): 823 mm yr^{-1} Range (1990–2014): 591 mm yr^{-1} (2003) to 1090 mm yr^{-1} (2002) Mean monthly precipitation (1990–2014): Jan 48.7 mm, Feb 46.7 mm, Mar 64.9 mm, Apr 50.0 mm, May 78.4 mm, Jun 99.4 mm, Jul 89.5 mm, Aug 95.5 mm, Sep 79.6 mm, Oct 54.8 mm, Nov 62.4 mm, Dec 53.6 mm
	Mean catchment evaporation (1990–2014) based on the water balance: 628 mm yr^{-1}
	Mean annual runoff at catchment outlet (MW): Mean (1990–2014): 4.07 L s^{-1} Range (1990–2014): 1.91 L s^{-1} (2004) to 6.99 L s^{-1} (2013) Mean monthly runoff (1990–2014): Jan 4.91 L s^{-1}, Feb 5.72 L s^{-1}, Mar 5.74 L s^{-1}, Apr 5.04 L s^{-1}, May 4.08 L s^{-1}, Jun 3.92 L s^{-1}, Jul 2.88 L s^{-1}, Aug 3.12 L s^{-1}, Sep 2.82 L s^{-1}, Oct 3.07 L s^{-1}, Nov 3.85 L s^{-1}, Dec 4.12 L s^{-1} Maximum runoff (1990–2014): 2000 L s^{-1} (1 Sep 2002, estimate), 656 L s^{-1} (25 Jun 2013)
Soils:	The soil types are Cambisols (56 %), Planosols (21 %), Kolluvisols (17 %), Gleysols (6 %) and Histosols (< 1 %). Infiltration capacities tend do be medium to low, water storage capacities tend to be high, and shrinking cracks may occur in summer due to high clay contents.
Geology and aquifers:	The subsoil consists of Tertiary sediments of the Molasse zone and fractured siltstone. The shallow aquifer is associated with the water draining the shallow subsurface soil, while the deep aquifer is within the fractured siltstone unit.
Topography:	Elevation range: 268 to 323 m a.s.l. Mean slope: 8 %.
Vegetation/Land use:	At present, 87 % of the catchment area is arable land, 5 % is used as pasture, 6 % is forested and 2 % is paved. The crops are mainly maize, winter wheat and barley.
Fertiliser input	Nitrogen fertiliser input (2010–2013, catchment average): range 140 kg N ha^{-1} (2013) to 210 kg N ha^{-1} (2012) Phosphor fertiliser input (2010–2013, catchment average): range 12 kg P ha^{-1} (2013) to 26 kg P ha^{-1} (2012)
Seitengraben stream:	Length: 620 m, slightly meandering Continuous shaded by deciduous trees and bushes in riparian zone. Biologically active ecosystem with small water animals and plants. Discharges into “Hauptgraben” river which discharges into the Erlauf and finally the Danube.

Table B1. Instrumentation in the HOAL.

Variable	Units	Comp.	No of stations × sensors	Location	Sensor	Sensor type	Temporal resolution (mins)	Data connectivity	Main data storage	Data from (year)
Precipitation	mm min^{-1}	A	4	Catchment	Precipitation gauge	OTT Pluvio	1	P	MN	2010
Air temperature	°C	A	1 × 3	WS	Temperature sensor at 2, 5, 10 m	HMP 155	30	LAN	HP	2012
Air humidity	%	A	1 × 3	WS	Humidity sensor at 2, 5, 10 m	HMP 155	30	LAN	HP	2012
Wind speed and direction	m s^{-1}, °	A	1 × 3	WS	Wind sensor at 2, 5, 10 m	Gill WindSonic	30	LAN	HP	2012
Atmospheric pressure	hPa	A	1	WS	Barometer	EC100	1	LAN	HP	2012
Radiation (incoming shortwave, incoming longwave, outgoing shortwave, outgoing longwave)	W m^{-2}	A	1 × 4	WS	4 component net radiometer	Kipp & Zonen CNR 4	1	LAN	HP	2012
Rain drop distribution, air temperature, relative humidity	Number of drops, °C,%	A	1 × 3	WS	Present weather sensor at 1.7 m	Campbell PWS 100	1	LAN	HP	2012
Carbon dioxide flux, latent heat flux, sensible heat flux, momentum flux	mmol m^{-2} s^{-1}, W m^{-2}, W m^{-2}, kg m^{-1} s^{-2}	A	2	Catchment (movable device)	Open-path eddy-covariance (3-D wind speed, water vapour, carbon dioxide density)	Campbell IRGASON	10 Hz, 30 min aggregation	M	HP	2012/ 2013
Carbon dioxide flux, latent heat flux, sensible heat flux, momentum flux	mmol m^{-2} s^{-1}, W m^{-2}, W m^{-2}, kg m^{-1} s^{-2}	A	1	WS	Closed-path eddy-covariance (3-D wind speed, water vapour, carbon dioxide mixing ratio)	Campbell EC155	10 Hz, 30 min aggregation	M	HP	2013
Momentum and sensible heat flux	W m^{-2}	A	1	Catchment (movable device)	Scintillometer	Scintec SLS-20	1	LAN	HP	2012
Wind load (acceleration)	m s^{-2}	A	1 × 7	WS	Triaxial DC Accelerometer	3713B1110G, MEMS Capacitive	100 Hz	M	HP	2015
Snow depth	m	Surface	1	WS	Snow depth US Sensor	SR50AT	1	LAN	HP	2012
Saturation patterns on land surface	–	Surface	1	WS	Camera. Timelapse pictures, recorded video (on detected motion)	Sanyo VCC-MCH5600P	1	LAN	HP	2013
Discharge	L s^{-1}	SW	1	Sys4 (inlet, piped stream)	H-flume, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Electrical conductivity and water temperature	µS cm^{-1}, °C	SW	1 × 2	Sys4 (inlet, piped stream)	Electric conductivity probe	WTW TetraCon	1	LAN	MN	2011
pH, Cl, NO_3-N	–, mg L^{-1}, mg L^{-1}	SW	1 × 3	Sys4 (inlet, piped stream)	Multiparameter probe	Nadler pH electrode, ion selective electrodes	1	LAN	MN	2011
Discharge	L s^{-1}	SW	1	Frau1 (tile drain)	H-flume, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Discharge (low flows)	L s^{-1}	SW	1	Frau1 (tile drain)	Tipping bucket (counts)	Reed sensor	1	LAN	MN	2011
Discharge	L s^{-1}	SW	1	Frau2 (tile drain)	H-flume, Pressure transducer (water level)	OTT PS1	1	LAN	MN	2011
Discharge	L s^{-1}	SW	1	Sys2 (tile drain)	H-flume, Pressure transducer (water level)	OTT PS1	1	LAN	MN	2011

Table B1. Continued.

Variable	Units	Comp.	No of stations × sensors	Location	Sensor	Sensor type	Temporal resolution (mins)	Data connectivity	Main data storage	Data from (year)
Electrical conductivity and water temperature	$\mu\mathrm{S\,cm^{-1}}$, °C	SW	1 × 2	Frau2 (tile drain)	Electric conductivity probe	WTW TetraCon	1	LAN	MN	2012
pH, Cl, NO_3-N	–, $\mathrm{mg\,L^{-1}}$, $\mathrm{mg\,L^{-1}}$	SW	1 × 3	Frau2 (tile drain)	Multiparameter probe	Nadler pH electrode, ion selective electrodes	1	LAN	MN	2012
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	Sys1 (tile drain)	H-flume, Pressure transducer (water level)	OTT PS1	1	LAN	MN	2011
Discharge (low flows)	$\mathrm{L\,s^{-1}}$	SW	1	Sys1 (tile drain)	H-flume, Tipping bucket (counts)	Reed sensor	1	LAN	MN	2011
Electrical conductivity and water temperature	$\mu\mathrm{S\,cm^{-1}}$, °C	SW	1 × 2	Sys2 (tile drain)	Electric conductivity probe	WTW TetraCon	1	LAN	MN	2011
pH, Cl, NO_3-N	–, $\mathrm{mg\,L^{-1}}$, $\mathrm{mg\,L^{-1}}$	SW	1 × 3	Sys2 (tile drain)	Multiparameter probe	Nadler pH electrode, ion selective electrodes	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	Sys3 (tile drain)	H-flume, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Discharge (low flows)	$\mathrm{L\,s^{-1}}$	SW	1	Sys3 (tile drain)	H-flume, Tipping bucket (counts)	Reed sensor	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	E1 (erosion gully)	H-flume, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Turbidity	$\mathrm{mg\,L^{-1}}$	SW	1	E1 (erosion gully)	Turbidity probe	WTW ViSolid	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	E2 (erosion gully)	H-flume, Pressure transducer (water level)	OTT PS1	1	LAN	MN	2011
Turbidity	$\mathrm{mg\,L^{-1}}$	SW	1	E2 (erosion gully)	Turbidity probe	WTW ViSolid	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	Q1 (spring)	V-notch weir, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	K1 (spring)	V-notch weir, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	A1 (wetland runoff)	H-flume, Pressure transducer (water level)	OTT PS1	1	LAN	MN	2011
Electrical conductivity and water temperature	$\mu\mathrm{S\,cm^{-1}}$, °C	SW	1 × 2	A1 (wetland runoff)	Electric conductivity probe	WTrW TetraCon	1	LAN	MN	2011
pH, Cl, NO_3-N	–, $\mathrm{mg\,L^{-1}}$, $\mathrm{mg\,L^{-1}}$	SW	1 × 3	A1 (wetland runoff)	Multiparameter probe	Nadler pH electrode, ion selective electrodes	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	A2 (wetland runoff)	H-flume, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2011
Discharge (low flows)	$\mathrm{L\,s^{-1}}$	SW	1	A2 (wetland runoff)	H-flume, Tipping bucket (counts)	Reed sensor	1	LAN	MN	2011
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	MW	Thomson weir, stage recorder (water level)	Ott stage recorder	1	M	IKT	1945–2002
Discharge and water temperature	$\mathrm{L\,s^{-1}}$, °C	SW	1	MW	H-flume, Pressure transducer (water level)	Ott PS1	1	M	MN	2002–2009
Discharge and water temperature	$\mathrm{L\,s^{-1}}$, °C	SW	1	MW	H-flume, Pressure transducer (water level)	Druck PTX1830	1	LAN	MN	2009
Discharge	$\mathrm{L\,s^{-1}}$	SW	1	MW	H-flume, Ultrasonic probe (water level)	Endress/Hauser	1	LAN	MN	2010
Electrical conductivity and water temperature	$\mu\mathrm{S\,cm^{-1}}$, °C	SW	1 × 2	MW	Electric conductivity probe	WTW TetraCon	1	LAN	MN	2009

Table B1. Continued.

Variable	Units	Comp.	No of stations × sensors	Location	Sensor	Sensor type	Temporal resolution (mins)	Data connectivity	Main data storage	Data from (year)
Turbidity	mg L^{-1}	SW	1	MW	Turbidity probe	WTW ViSolid	1	LAN	MN	2009
Turbidity	mg L^{-1}	SW	1	MW	Turbidity probe	Hach Lange SOLITAX ts-line sc	1	LAN	MN	only 2010
pH, Cl, NO$_3$-N	–, mg L^{-1}, mg L^{-1}	SW	1 × 3	MW	Multiparameter probe	Nadler pH electrode, ion selective electrodes	1	LAN	MN	2011
beta-D-glucuronidase activity	pmol min^{-1} (100 mL)$^{-1}$	SW	1 × 2	MW	Fluorescence analyser	Photometric cuvette (Coliguard 0025, 0035)	180	P	TU	2011, 2012
beta-D-glucuronidase activity	mMFU/100 mL	SW	1 × 2	MW	Fluorescence analyser	Photometric cuvette (Coliminder A, B)	60	P	VWM	2014
TSS, NO$_3$-N, COD, BOD, TOC, DOC, turbidity, UV254	mg L^{-1}, FNU, Abs m^{-1}	SW	1 × 2	MW	Spectrolyser	s:can spectrolyser UV-Vis, 15/35 mm pathlength, 220–700 nm range	10	M	TU	2013
Visual images of flume	–	SW	1	MW	Camera	Axis P5512-E	1	LAN	HP	2014
Soil heat flux	W m^{-2}	Soil	1 × 2	WS	Soil heat flux −30 cm	Huskeflux HFP01SC	30; 1	LAN	HP	2012
Soil temperature	°C	Soil	2 × 5	WS	Soil temperature at −5, −10 cm, −15, −20, −30 cm	PT107	30; 1	LAN	HP	2012
Soil moisture, soil temperature	% volumetric soil water content, °C	Soil	18 × 4, 2 × 5	Catchment	Permanent soil moisture sensors −5, −10, −20, −50, (2× −100 cm)	Spade-TDT (Jülich)	30	LAN	Soil	2013
Soil moisture, soil temperature	% volumetric soil water content, °C	Soil	11 × 4	Catchment	Temporary soil moisture sensors −5, −10, −20, −50 cm	Spade-TDT (Jülich)	30	LAN	Soil	2013
Soil moisture	% volumetric soil water content	Soil	1	Catchment	Cosmic ray soil moisture neutron probe (680 m footprint, 12–76 cm depth)	CRS 1000/B	60	S	Cosmos	2013
Groundwater level and temperature	cm H$_2$O, °C	GW	23	Catchment near stream (BP01, BP02)	Groundwater dataloggers	SWS Mini-Diver	5–30	M	IKT	2011
Atmospheric pressure and temperature	cm H$_2$O, °C	A	2	near stream (Baro1, Baro2)	Groundwater dataloggers	SWS Baro-Diver	5–30	M	IKT	2011

Compartments (Comp): GW = groundwater, SW = surface water, A = atmosphere.
Location: MW = catchment outlet, WS = Weather station (also see Figs. 6 and 7).
Data connectivity: LAN = glassfibre LAN, M = local storage and manual data transfer, P = GSM phone, S = satellite modem.
Main data storage: Cosmos = Cosmos project server, HP = HOAL PC, IKT = IKT server (plain file system), MN = IKT server (MydataNet), Soil = Soil Net PC, TU = TU server, VWM = VWM server.

Table B2. Laboratory analyses from samples taken in the HOAL.

Variable	Units	Comp.	No of stations × sensors	Location	Sampling	Analysis	Temporal resolution	Main data storage	Data from (year)
pH, EC, SSC, Cl, NO_3, NH_4, P	–, µS cm^{-1}, mg L^{-1}	SW	2	MW	Autosampler Isco 6712	Physical and chemical analysis* (IKT Lab)	Within event	IKT	2009
pH, EC, SSC, Cl, NO_3, NH_4, P	–, µS cm^{-1}, mg L^{-1}	SW	–	MW	Grab samples	Physical and chemical analysis* (IKT Lab)	Weekly	IKT	2010
TOC	mg L^{-1}	SW	1	MW	Grab samples	Thermal catalytic oxidation (IKT Lab)	Within event or weekly	IKT	2013
pH, EC, SSC, Cl, NO_3, NH_4, P	–, µS cm^{-1}, mg L^{-1}	SW	4 × 1	E1, E2 (erosion gullies), Frau2 (tile drain), Sys4 (inlet, piped stream)	Autosampler Isco 6712	Physical and chemical analysis* (IKT Lab)	Within event	IKT	2011 or 2013
DOC, TOC, PO4-P, NH_4-N, NO_3-N, TP, TN, SS, HCO_3, Cl, SO_4, pH, EC, Na, K, Ca, Mg	–, µS cm^{-1}, mg L^{-1}	SW	–	all tributaries	Grab samples	Physical and chemical analysis* (IKT Lab)	Monthly	IKT	2010
Precipitation ^{18}O, ^{2}H		A	1	close to catchment (IKT)	Autosampler Manning S-4040, adapted	Laser spectroscopy (Picarro L1115-i, AIT Tulln)	Event based	IKT	2009
Discharge ^{18}O, ^{2}H		SW	–	MW, all tributaries	Grab samples	Laser spectroscopy (Picarro L1115-i, AIT Tulln)	Within event or monthly	IKT	2009
Discharge ^{3}H		SW	–	Q1	Grab samples	Laser spectroscopy (Picarro L1115-i, AIT Tulln)	Monthly	IKT	2013
Precipitation ^{18}O, ^{15}N		A	–	close to catchment (IKT)	Autosampler Manning S-4040, adapted	Mass spectrometry (DELTA V Plus + GasBench II, Thermo Scientific; L1102-I, Picarro)	Event based	UFZ	2013
Discharge ^{18}O, ^{15}N		SW	–	all tributaries	Grab samples	Mass spectrometry (DELTA V Plus + GasBench II, Thermo Scientific; L1102-I, Picarro)	Monthly	UFZ	2013
E. coli, coliforms	MPN/100 mL	SW	–	MW, partly tributaries	Grab samples	Colilert-18 Quanti-Tray (IKT Lab)	Monthly	TU	2012
E. coli, aerobic spores, clostridium perfringens spores, total cell count	CFU/100 mL	SW	–	MW	Grab samples	TBX Agar ISO 16649-1 (Med Univ Vienna)	Monthly	TU	2012

Main data storage: IKT = IKT server (plain file system), TU = TU server, UFZ = UFZ server.

[*] Note: Physical and chemical analysis (potentiometric, conductometric, filtering, ion chromatographic, photometric).

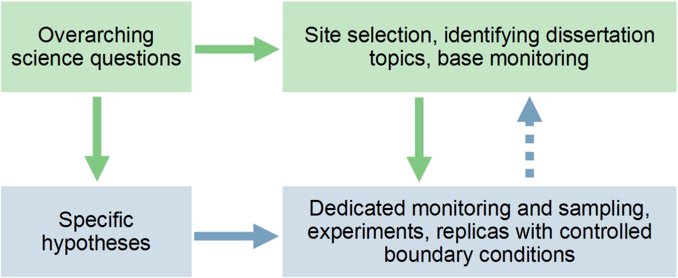


Figure 1. Interplay of hypotheses and experimental planning in the HOAL.

Figure 2. View of the Petzenkirchen HOAL catchment looking south (trees in the centre of the photo constitute the riparian zone of the Seitengraben stream).

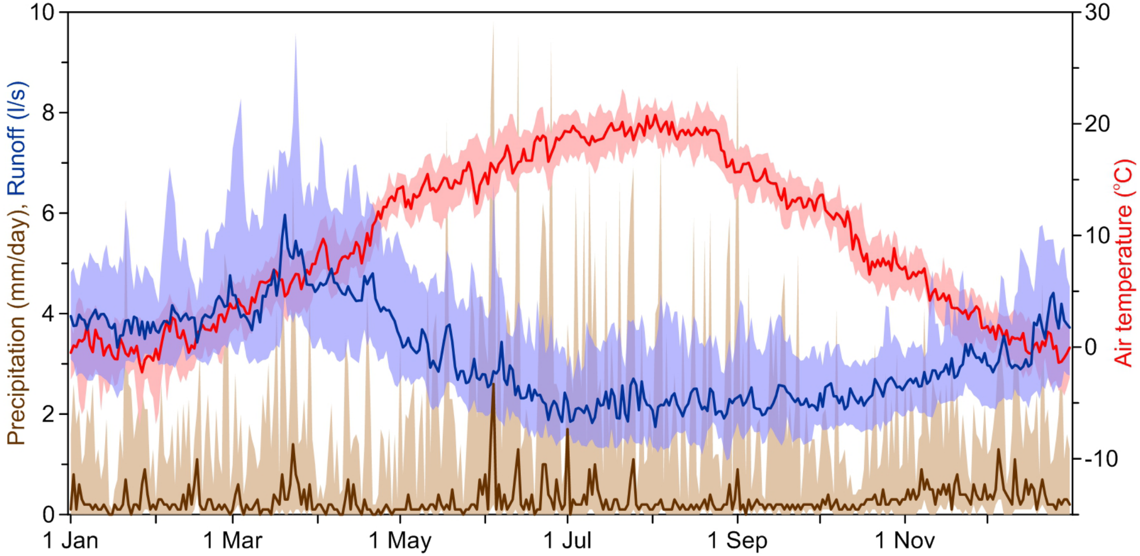


Figure 3. Precipitation and air temperature at the weather station, and runoff at the catchment outlet (MW) of the HOAL. Lines show medians of the period 1990–2014, shaded areas the 25 and 75 % percentiles based on the data aggregated to daily values.

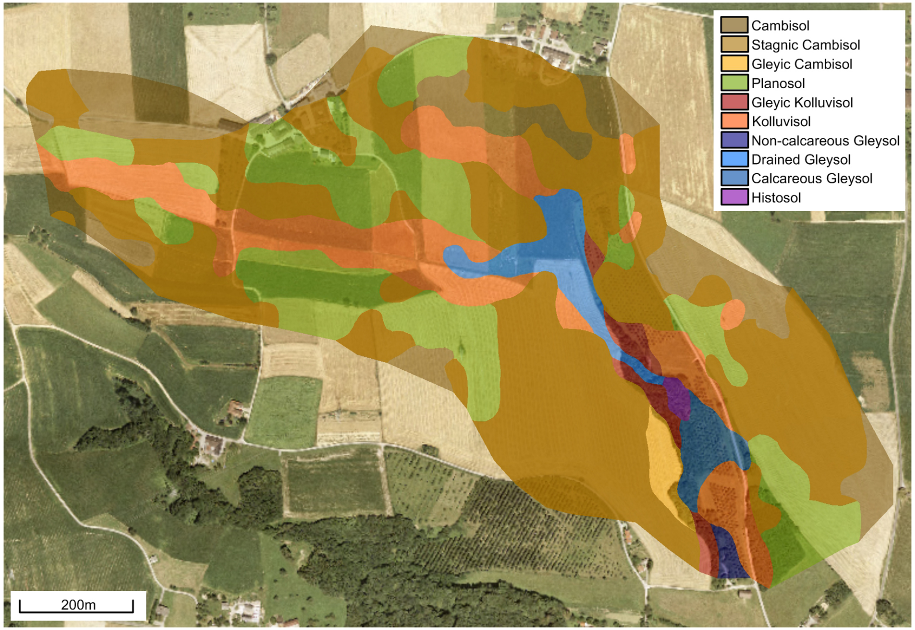


Figure 4. Soil types in the HOAL.

Figure 5. Runoff generation mechanisms in the HOAL.

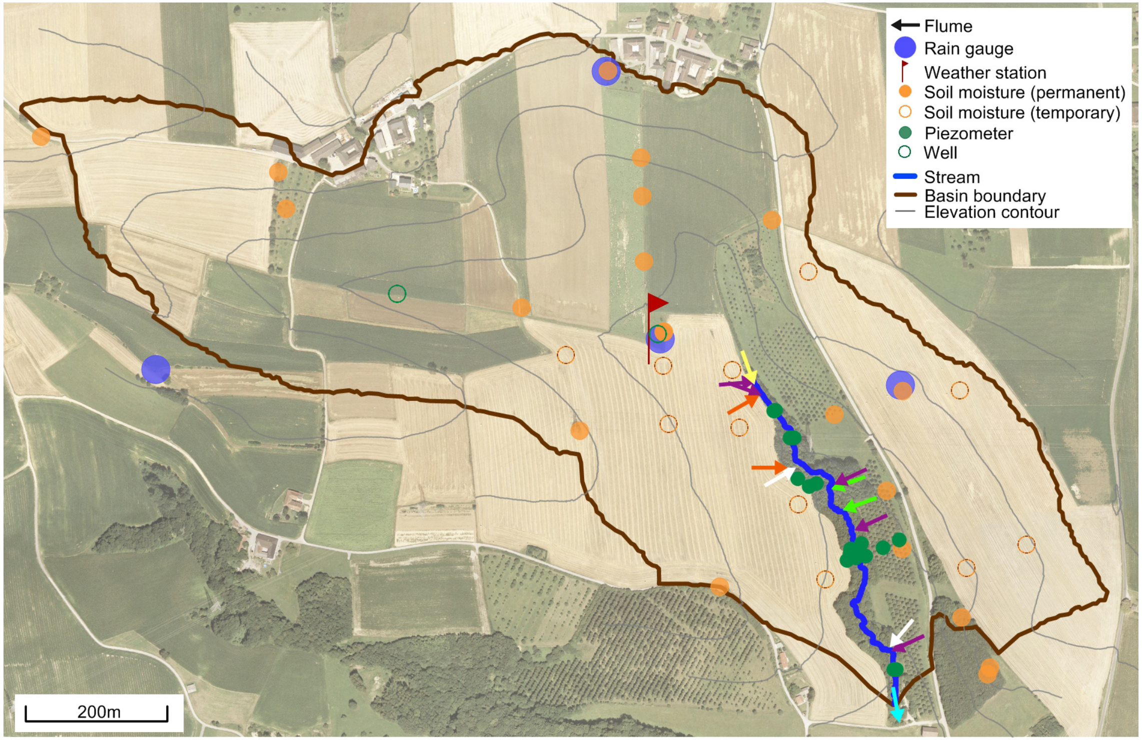


Figure 6. Instrumentation in the HOAL catchment (see Tables 1 and B1).

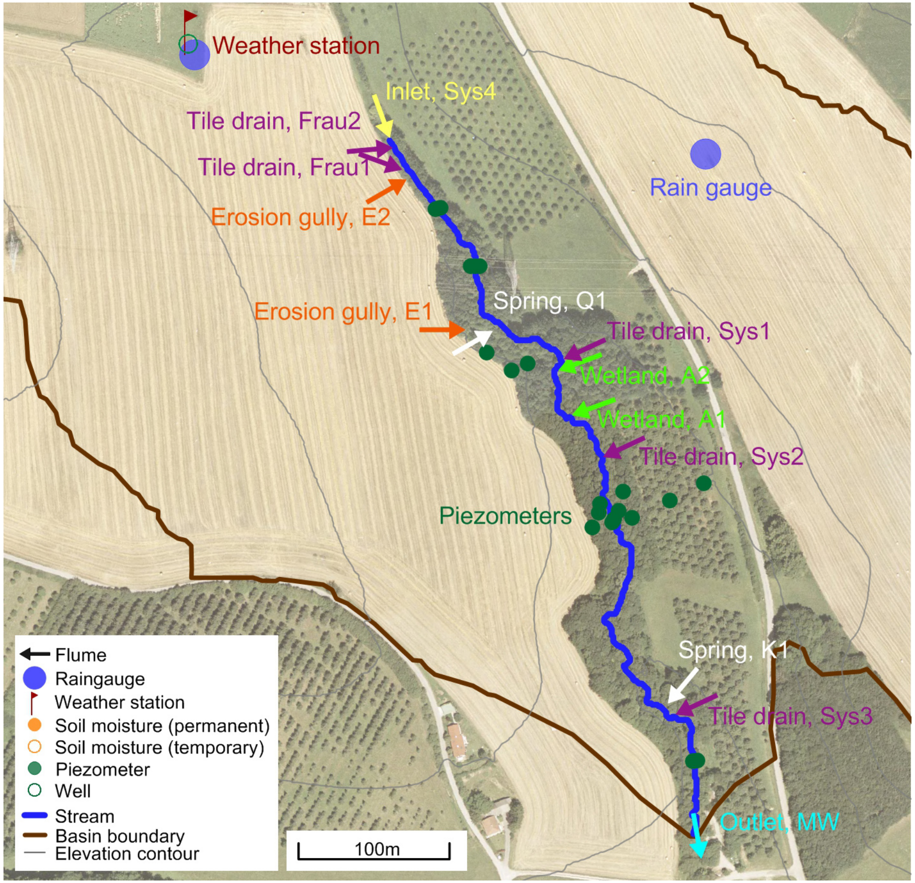


Figure 7. Detail of instrumentation in the HOAL catchment (see Tables 1 and B1).

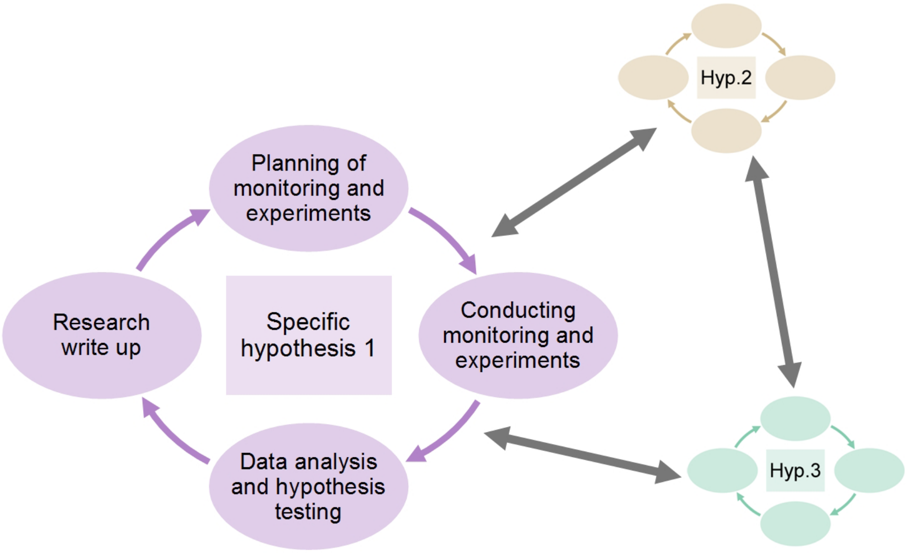
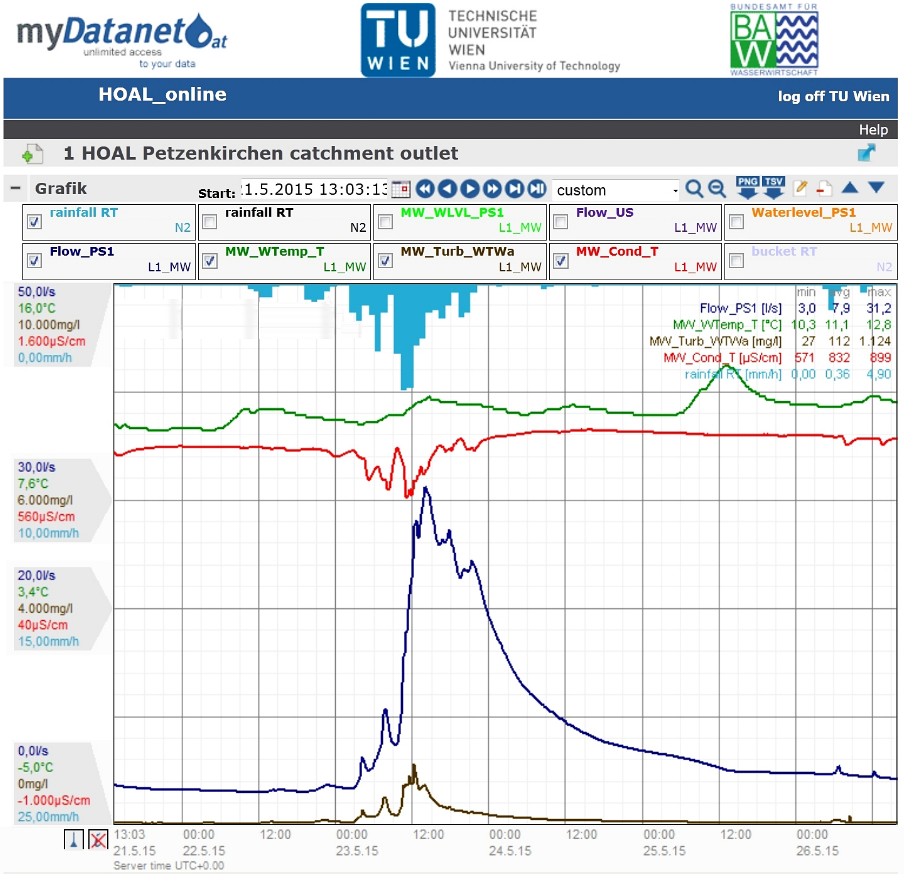


Figure 8. Network-based coordination of hypotheses-guided research.



	min	avg	max
Flow_PS1 [l/s]	3,0	7,9	31,2
MW_WTemp_T [°C]	10,3	11,1	12,8
MW_Turb_WTWa [mg/l]	27	112	1.124
MW_Cond_T [µS/cm]	571	832	899
rainfall RT [mm/h]	0,00	0,36	4,90

Figure 9. Screen shot of web-based real-time monitoring of the data collected in the HOAL.

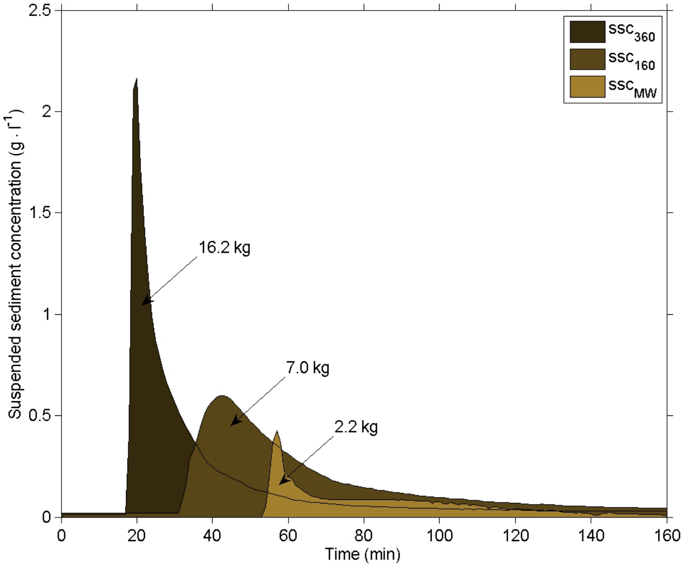


Figure 10. Hypothesis testing Example 1: sediment concentrations for a flushing experiment in August 2011 at the three monitoring locations. 360 is the most upstream location at 360 m from the catchment outlet, MW. From Eder et al. (2014).

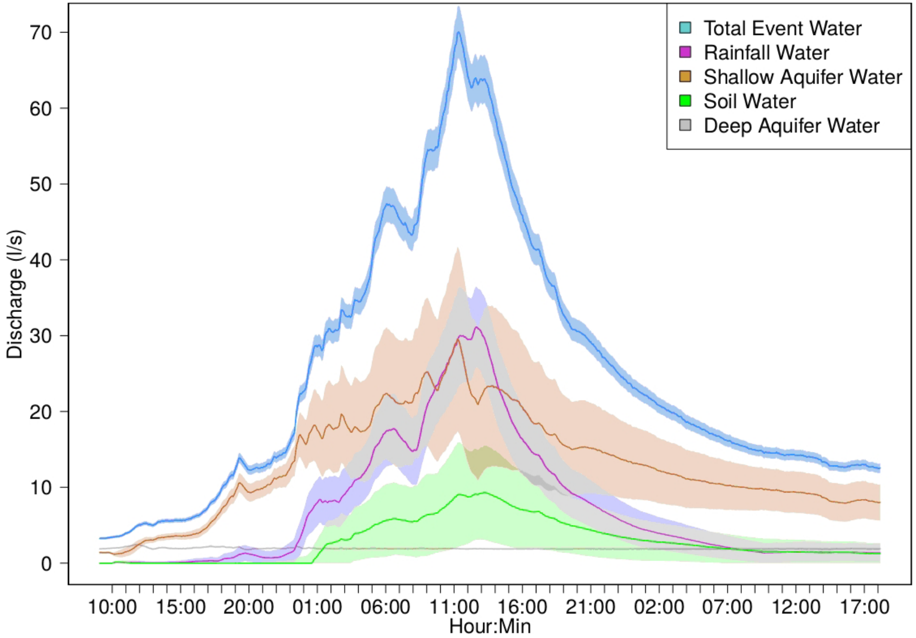


Figure 11. Hypothesis testing Example 2: flow contributions for the event on 20 January, 2012 at MW including uncertainties.

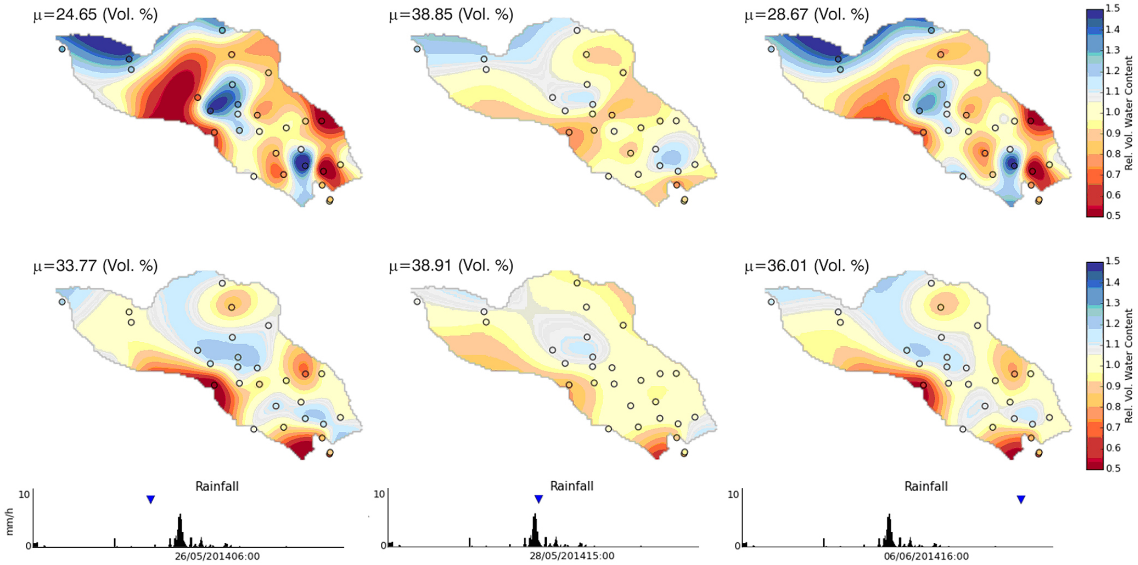


Figure 12. Hypothesis testing Example 3: soil moisture patterns scaled by the mean catchment soil moisture μ before, during and after an event in May 2014. Top and bottom panels show 5 and 20 cm soil moisture, respectively. Circles show measurement locations, patterns are interpolations. Time series at the very bottom show rainfall with the time of the soil moisture patterns indicated by blue triangles.

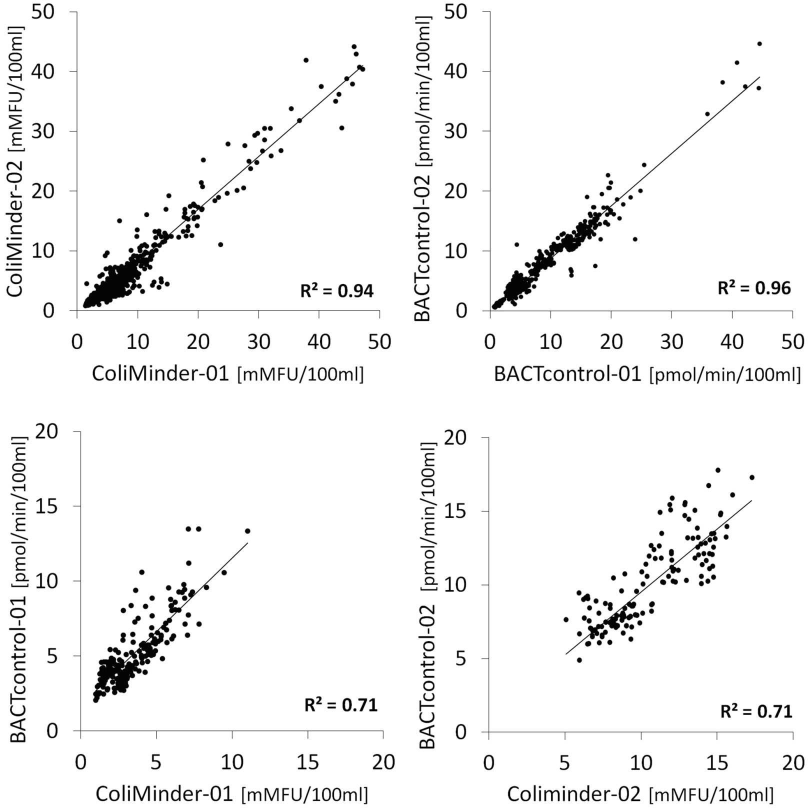


Figure 13. Hypothesis testing Example 4: consistency of online monitoring of microbial faecal pollution by GLUC activity as a surrogate. Top panels (Test 1) compare devices with the same design and assay (BACTcontrol vs. BACTcontrol, ColiMinder vs. ColiMinder). Bottom panels (Test 2) compare devices with different designs and assays (BACTcontrol vs. ColiMinder). The smaller range of the bottom panels is related to differences in the measurement period. All correlations are significant at p values < 0.001.

Figure C1. Photos of the 13 stream gauges in the HOAL.