AgrHyS: An Observatory of Response Times in Agro-Hydro Systems

Ophélie Fovet, Laurent Ruiz, Gérard Gruau, Nouraya Akkal-Corfini, Luc Aquilina, Sylvain Busnot, Rémi Dupas, Patrick Durand, Mikaël Faucheux, Yannick Fauvel, et al.

Published November 29, 2018

Special Section: Hydrological Observatories

Core Ideas

- AgrHyS is a long-term observatory of the agroecosystem.
- AgrHyS supports strongly interdisciplinary environmental research.
- AgrHyS offers an original experimental setup to explore the soil–groundwater–water–plants–atmosphere continuum.
- AgrHyS supports original and innovative techniques for environmental monitoring.

AgrHyS: An Observatory of Response Times in Agro-Hydro Systems

Ophélie Fovet,* Laurent Ruiz, Gérard Gruau, Nouraya Akkal, Luc Aquilina, Sylvain Busnot, Rémi Dupas, Patrick Durand, Mikael Faucheux, Yannick Fauvel, Chris Fléchard, Nicolas Gilliet, Catherine Grimaldi, Yannick Hamon, Anne Jaffrezic, Laurent Jeanneau, Thierry Labasque, Geneviève Le Henaff, Philippe Mérot, Jérôme Molénat, Patrice Petitjean, Anne-Catherine Pierson-Wickmann, Hervé Squividant, Valérie Viaud, Christian Walter, and Chantal Gascuel-Odoux

The AgrHyS is a long-term agro-hydrological observatory dedicated to studying the processes controlling hydro-chemical fluxes in headwater catchments in response to the effects of agricultural. AgrHyS is composed of instrumented catchments located in western France in a temperate oceanic climate that are characterized by shallow groundwater (<8 m deep) over crystalline bedrocks (granite or schist) and is dominated by intensive agriculture with farming. AgrHyS provides long-term observations starting in 1990 and supports highly interdisciplinary studies that provide novel contributions to environmental sciences, including hydrology, geochemistry, agricultural and soil sciences, hydrogeology, bioclimatology, and ecology. Here we describe the observatory sites, observation strategy, data management policy, and data access. The objective is to show how AgrHyS has contributed to research in hydrological and environmental sciences through a review of major insights of the research. This analysis highlights the role of AgrHyS in linking, validating, and enriching successive and complementary projects conducted over the last 25 yr. The second objective is to invite new collaborations with a large scientific community for future research.

Abbreviations: DOC, dissolved organic carbon; DOM, dissolved organic matter; ERO, Environmental Research Observatory; OC, organic carbon; SDI, spatial data infrastructure.

O. Fovet, L. Ruiz, N. Akkal, S. Busnot, R. Dupas, P. Durand, M. Faucheux, Y. Fauvel, C. Fléchard, N. Gilliet, C. Grimaldi, Y. Hamon, A. Jaffrezic, G. Le Henaff, P. Mérot, H. Squividant, V. Viaud, C. Walter, and C. Gascuel-Odoux, UMR SAS, INRA, AgroCampus Ouest, 65 rue de St Brieuc, 35 042 Rennes, France; G. Gruau, L. Aquilina, L. Jeanneau, T. Labasque, P. Petitjean, and A.-C. Pierson-Wickmann, UMR 6118 Géosciences Rennes, CNRS, Univ. Rennes 1, OSU Rennes, 263 avenue du Général Leclerc, 35 042 Rennes, France; J. Molénat, LISAH, Univ. Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France. *Corresponding author (ophelie.fovet@inra.fr).

Received 2 Apr. 2018.
Accepted 21 Aug. 2018.

Citation: Fovet, O., L. Ruiz, G. Gruau, N. Akkal, L. Aquilina, S. Busnot, R. Dupas, P. Durand, M. Faucheux, Y. Fauvel, C. Fléchard, N. Gilliet, C. Grimaldi, Y. Hamon, A. Jaffrezic, L. Jeanneau, T. Labasque, G. Le Henaff, P. Mérot, J. Molénat, P. Petitjean, A.-C. Pierson-Wickmann, H. Squividant, V. Viaud, C. Walter, and C. Gascuel-Odoux. 2018. AgrHyS: An observatory of response times in agro-hydro systems. Vadose Zone J. 17:180066. doi:10.2136/vzj2018.04.0066

The AgrHyS observatory of response times in agro-hydro systems, located in western France, is dedicated to the observation of agro-hydrosystems under a temperate climate characterized by shallow groundwater and intensive agriculture, mainly of annual crops receiving a high amount of mineral and organic inputs. AgrHyS is composed of instrumented catchments where environmental variables are monitored over the long term to study the processes controlling hydro-chemical fluxes in agroecosystems, with the objective of characterizing their response time to climatic and agricultural impacts. AgrHyS contains two sites—the Kervidy-Naizin catchment and the Kerbernez catchment—where research has been conducted since the early 1970s. In 2002, AgrHyS was declared by the French Ministry of Research as an Environmental Research Observatory (ERO). Whereas a recent review by Gascuel-Odoux et al. (2018) analyzes the coevolution of research topics with observatories and methods used in Environmental Sciences based on the 50-yr history of the Kervidy-Naizin site, the present article highlights the synergies between the observations at the two sites based on the review of the missions and accomplishments of AgrHyS hydrological observatory since.

Long-term observatories, such as AgrHyS, serve different missions and have several objectives: facilitate research, provide reference data sets, test methodologies, train new scientists, and educate the public.

The main activity performed in AgrHys is scientific research. The evolution of the science questions that have guided the strategy of observations over time and the main characteristics of the catchments are described herein. Observations are conducted to test hypotheses and understand processes, but over the years, they also led to the identification of new environmental issues for science and society (Gascuel-Odoux et al., 2018).

AgrHyS also produces data sets that will serve as references for biophysical systems. The characterizations and monitoring performed in AgrHys are described based on the level of their acquisition (basic long-term observations, dedicated observations associated with specific research programs, experiments, and surveys). Producing relevant datasets requires continuously updating methodologies. New technologies that can monitor multiple parameters in a more automated way or at higher frequency must be tested and validated before widespread adoption. Observatories such as AgrHyS are particularly suitable for testing new technologies because the long-term observations already conducted (basic set) provide a good comparison data set. A special focus is given on innovative methods tested in AgrHyS (Ayraud et al., 2008; Faucheux and Fovet, 2014; Floury et al., 2017; Gilliet et al., 2018; Jeanneau et al., 2014; Merot et al., 1994, 1995).

One of the major interests of environment observatories is to provide physical ranges and trends of spatial or temporal variation for parameters or processes that can be compared with observations. This can contribute to cross-calibration of models and meta-analyses. For such goals, all data and associated metadata have to be made available to the scientific community. The data management policy and the database of AgrHyS and its access procedure are discussed below.

Major scientific advances achieved at the AgrHyS observatory are also reviewed herein. An additional important product of the AgrHyS observatory team is the formalization of a representative understanding of hydrological systems, which are transferable to other catchments. Accordingly, AgrHys contributes largely to the production and development of modeling approaches. Observations are a basis for modeling designed to test hypotheses (Beaujouan et al., 2001; Dupas et al., 2016; Fovet et al., 2015a; Gascuel-Odoux et al., 2010; Hrachowitz et al., 2014; Molenat et al., 2008; Ruiz et al., 2002a, 2002b) or to explore scenarios (Beaujouan et al., 2002; Benhamou et al., 2013; Durand et al., 2015; Moreau et al., 2012; Salmon-Monviola et al., 2013).

Additionally, training and education is important for the AgrHyS observatory. On average, AgrHyS sites host field studies for about seven PhD or Master's degree students yearly. No fewer than three Master 2 curriculums include practical work and field trips that are built on AgrHyS sites and datasets. Many researchers conducting projects on AgrHyS are teachers who build part of their lectures on the observations from AgrHyS. Occasionally, these sites also support outreach to water managers, policymakers, and local farmers.

Finally, we present the perspective for the development of AgrHyS in relation to emergent scientific questions, methodological advances, and integration within national and international networks of observatories.

Historical Context

The catchments of AgrHyS were instrumented for assessing the effects of agriculture in France and Europe on water and soil quality. French Brittany, western France, is emblematic of the agricultural revolution: since the Second World War, it has been one of the most productive agricultural regions in Europe. Intensive farming has deeply modified landscapes: from "bocage" closed by hedgerow networks to open fields, drained wetlands, and the massive replacement of continuous grasslands by annual arable crops. The first results in the mid-1970s showed a rapid increase of nitrate concentrations in streams and rivers. Effects on the catchment water balance and on soil losses by erosion were also suspected. In the mid-1990s, awareness of environmental damages due to agricultural intensification led to implementation of environmental policies (e.g., the 1991 European Nitrates Directive) to relax the agricultural pressures on environmental resources (mainly water and soil in those days). Despite the reductions in fertilizer inputs and improved management of farm manure, nitrate concentrations in rivers and streams remained stable and high, revealing much longer response times of catchment systems than expected (e.g., Howden et al., 2011a, 2011b; Jarvie et al., 2013).

After such observations, the question of response times of catchments became central for water management. For research, it implied the need to characterize solutes and water pathways within the system, which control both their residence times and reactivity. Agricultural scientists, hydrologists, soil scientists, and hydro-biogeochemists worked together at the small catchment scale to understand the response times of surface water to changes in land management. Shared research observatories are ideal supports for such interdisciplinary approaches toward understanding the processes controlling catchment responses. Long-term observations led to formulating hypotheses. Additional punctual data collection enabled testing these hypotheses, and the modeling approaches provided conceptualization to generalize the understanding. Thus, the catchment scale was recognized to be relevant for developing a systemic approach to evaluating the impacts of agricultural systems on the environment. Consequently, the exploration of environmental parameters was extended to the whole catchment to understand the spatial organization of landscapes (soil maps, spatial rainfall variability) and intensified in specific hot spots (wetlands, groundwater) moving from the rainfall–discharge relation, as an in-out approach, to a landscape hydrology–hydrochemistry approach and using a wide range of chemical species as geochemical tracers. The observation activity was amplified regarding the number of monitored compartments and species. The complementarity of the monitoring between both sites was designed according to the need for characterizing both transit times and reactivity: high temporal resolution of the monitoring and sampling in Kervidy-Naizin catchment focusing on the stream and high spatial resolution in Kerbernez catchments over outlets and merely groundwater. In the mid-2000s, the study of the nutrient cycles altered by intensive agriculture was also extended to determine the importance of the gaseous phases of the N cycles (N cascade; Galloway et al., 2003) and the linkage between geochemical C–N–P cycles. This systemic approach of catchments as agroecosystems led to investigating the role of biological factors in those cycles, progressively involving microbiologists and soil ecologists in the observatory.

As the observation data records were extended, the relevance of such observatories to conduct new observations increased. Since the 1970s, AgrHyS has offered a unique opportunity for Environmental Sciences to capitalize on long-term observations. Indeed, all the acquired knowledge contributed to the design of new campaigns and the interpretation of their results. Therefore, environmental observatories became ideal support for enhancing interdisciplinary approaches. Moreover, considering the temporal and spatial scales of processes that control water and solute transfer in catchments, the investigation of these processes requires pluri-decadal data time series. In 2002, under the name of ERO, AgrHyS became part of a network of catchments and sites that increasingly allowed synergy and complementarity among existing research sites.

Catchment Characteristics

Sites of the AgrHyS ERO are headwater catchments and first- and second-order streams (Fig. 1). The Kervidy-Naizin catchment covers 5 km^2 in central Brittany (latitude, 47.95; longitude, −2.8; WGS84). The Kerbernez site has a network of seven catchments with areas between 0.1 and 0.6 km^2 in southwestern Brittany (latitude, 47.94; longitude, −4.1; WGS84).

The climate is temperate and humid at both sites with a regional west–east gradient between sites. Average values of water balance terms are given in Table 1. The geological bedrock consists of low-permeability crystalline rocks with a similar structure: above the impervious bedrock there is a fissured and fractured layer in which water is likely to percolate deeply. The fractured layer is mantled by a weathered layer where shallow groundwater can fluctuate. In the Kervidy-Naizin site, the bedrock is composed of upper Proterozoic schists, whereas in the Kerbernez site it is granite known as the Leucogranodiorite of Plomelin. The two major bedrock types of the Brittany region are thus represented in the AgrHyS ERO. The weathered zone is 1 to 30 m deep in the Kervidy-Naizin site, with hydraulic conductivity ranging from 4×10^{-6} to 2×10^{-5} m s^{-1} and 40 to 50% total porosity. In the Kerbernez site, the weathered layer is 20 to 40 m deep, with hydraulic conductivity between 2×10^{-6} and 5×10^{-4} m s^{-1} and 42 to 60% total porosity.

Slopes are gentle at both sites (<5% on average). The soils are silty loams in Kervidy-Naizin between 0.5 and 1.5 m deep, and in Kerbernez there is mainly sandy loam that is 0.8 m deep on average. Soils are well drained except in bottomlands close to the streams, where water excess leads to hydromorphic, poorly drained soils and Albeluvisols (Fig. 2). Soil hydraulic conductivity at saturation ranges from 10^{-5} to 10^{-6} m s^{-1} in Kervidy-Naizin and from 10^{-5} to 10^{-4} ms^{-1} in Kerbernez. The superficial soil layers (0–40 cm in Kervidy-Naizin and 0–20 cm in Kerbernez) are rich in organic matter (2.5–6.5% in Kervidy-Naizin and 4.5–6% in Kerbernez).

Land use is dominated by intensive agriculture, with systems mixing cropping and indoor dairy and pig farming. In 2013, these catchments were mainly covered by maize, straw cereals, and grasslands. In Kervidy-Naizin these main land cover types correspond to 38, 30, and 15% of arable area, respectively, whereas in Kerbernez they vary between 10 and 70%, between 5 and 24%, and between 0 and 6% of arable area, respectively, depending on the catchment. In some Kerbernez catchments, the number of abandoned or converted fields (i.e., into a golf course) is increasing.

Basic Long-Term Observations

The current observation protocol of AgrHyS consists of long-term records of meteorological, hydrological, and hydro-chemical variables and land cover maps. The longest time series started in 1993. The variables currently available in the long-term observation set are detailed in Table 2 according to the location, frequency of acquisition, and onset year of acquisition, and the corresponding station locations are shown in Fig. 1.

Weather

Since 1993, the Kerbernez and Kervidy-Naizin sites have been equipped with a weather station located 1 km from the farthest outlets (Fig. 1). The station records hourly rainfall, air and soil temperatures, air humidity, global radiation, and wind direction and speed, which allows the calculation of daily Penman evapotranspiration.

Discharge

Between 1995 and 1997, the outlets were equipped with U-notch or V-notch weirs for monitoring the stream water level. Most gauging stations are automated and use float-operated sensors that record stream level sub-hourly (from 1 to 10 min). In a few outlets in Kerbernez (Table 2), stream level is measured manually every month to catch base flow variations. Stream flow is deduced from the stream level with a rating curve. Since 1999, the level sensors have been connected to a data logger.

Groundwater Levels

From 1997 to 2005, a network of piezometers was installed in the two sites to monitor shallow groundwater fluctuations and variations in its chemical composition (see below). Currently, 31 piezometers are monitored on AgrHyS sites. They are between 3 and 20 m deep and are encased within PVC tubes screened along the bottom 0.5 or 1.0 m of their length. The space around the PVC tube is backfilled with sand, bentonite, and concrete. The water table level is measured using automatic transducer sensors, sometimes coupled with temperature and electrical conductivity sensors that record water table data every 15 min in most piezometers (and manually in the others every month).

Stream Water, Groundwater, and Rain Water Chemical Composition

Various elemental concentrations are analyzed in the water sampled at AgrHyS sites depending on the station: major anions (Cl,

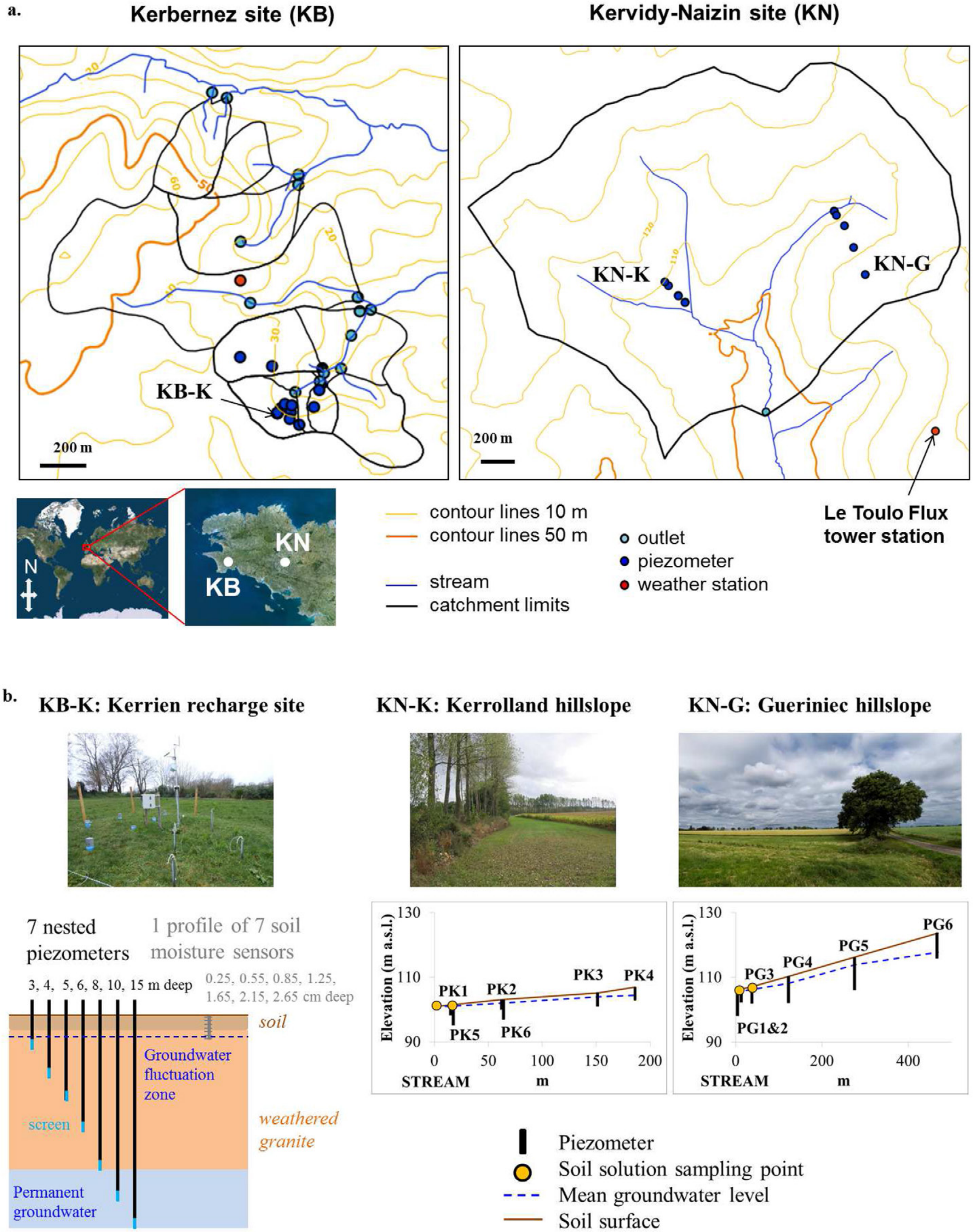

Fig. 1. (a) Location of the sites and main stations of the AgrHyS observatory, and (b) detailed equipment of highly instrumented stations or transects located on the site maps as labeled in both panels.

NO_2, NO_3, SO_4), major cations (Ca, Mg, K, Na), dissolved organic C (DOC) and dissolved inorganic C (sometimes coupled with Fe), total and soluble reactive phosphorus, and suspended solids. These concentrations are measured using grab sampling mostly. Various water quality parameters are also measured using sensors (electrical conductivity, temperature, turbidity, NO_3 and DOC concentrations, and total reactive and total P concentrations).

Grab samples have been conducted since 1993 in the stream to collect in situ standard physicochemical data. Monitoring has been intensified since 1999. Rain water composition has been investigated since 2010. The highest frequency of sampling in the stream (Kervidy outlet) is 1 d since 1999 (Fig. 3), and the highest frequency of groundwater sampling (Kerbernez piezometers) is 1 wk (between 2005 and 2012). Automatic samplers are used to sample storm flow events every 10 to 30 min over 10 h, which is consistent with the duration of such events in the catchments. The sampling is started when stream level reaches a threshold determined according to base flow conditions. Between 4 and 10 events are monitored every year. Since 2007, some complementary, nearly continuous (15–10 min) monitoring of physicochemical variables has been conducted using dedicated sensors: turbidity and concentrations of NO_3, organic C, and P in stream water and temperature and electrical conductivity in stream and groundwater.

Table 1. Average values and standard deviation of hydro-meteorological variables at the AgrHyS observatory sites.

Parameter	Kervidy-Naizin	Kerbernez
Rainfall, mm yr^{-1}	837 ± 219	1114 ± 237
Penman potential evapotranspiration, mm yr^{-1}	699 ± 58	680 ± 29
Temperature, °C		
Average	11.2 ± 0.6	12.0 ± 0.5
Maximal	32.6 ± 3.2	30.7 ± 2.6
Minimal	−5.0 ± 2.0	−5.8 ± 5.4
Annual runoff, mm yr^{-1}	325 ± 186	227 ± 115 to 448 ± 304†

† Depending on the outlet.

Land Cover

The evolution of land cover from one year to another is a basic variable of the observatory. Depending on the year, land cover data were obtained by farm survey or in-field observations or were

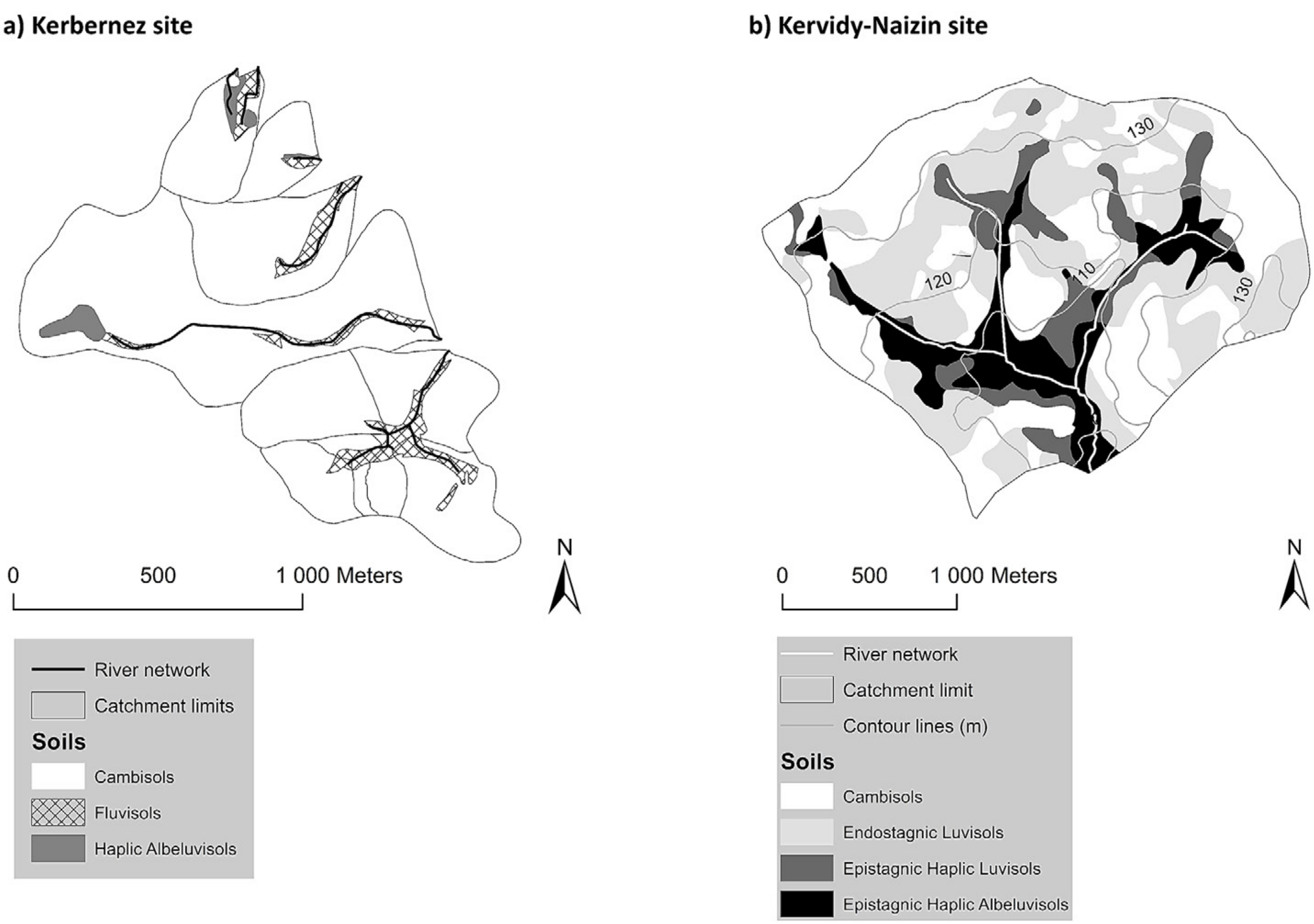

Fig. 2. Soil maps of the sites according to the classification of IUSS Working Group WRB (2006).

Table 2. Basic and dedicated long-term observations currently conducted at the AgrHyS observatory. Frequencies of observations are associated to each variable in the neighbor column as well as the date of the monitoring onset.

Stations	Atmospheric variables†			Hydrological variables‡			Other physical variables			Chemical variables§		
	Variable	Time step	First date	Variable	Time step	First date	Variable	Time step	First date	Variable	Time step	First date
							Kerbernez					
1 Weather station	air and soil temperature, global radiation and PAR, wind speed and direction, rain, humidity	1 h	1993							bulk in rainwater: NO_3, Cl, SO_4, NH_4, Ca, Mg, Na, total N	1 mo	2013
3 Outlets				stream level	6 min	1998 or 2002	temperature	10 min	2010 or 2013	NO_3, SO_4, Cl	8/yr	1991 or 2001
							EC	10 min	2013			
							pH,	8/yr	2001			
2 Outlets				stream level	6 min	1998 or 2002	pH, temperature, EC	8/yr	2001	NO_3, SO_4, Cl	8/yr	1997
2 Outlets				stream level	8/yr	1998	pH, temperature, EC	8/yr	2001	NO_3, SO_4, Cl	8/yr	1991 or 2001
1 Hyporheic zone							temperature	10 min	2012			
7 Piezometers				water table level	15 min	2001 or 2005	temperature	15 min	2007 or 2010	NO_3, SO_4, Cl	8/yr	2001 or 2005
							EC	15 min	2010 or 2013			
							pH	8/yr	2001 or 2005			
5 Piezometers				water table level	15 min	2001 or 2005	temperature	15 min	2007 or 2010	NO_3, SO_4, Cl	8/yr	2001 or 2005
							pH, EC	8/yr	2001 or 2005			
3 Piezometers				water table level	15 min	2001 or 2005				NO_3, SO_4, Cl	2/yr	2001 or 2005
3 Piezometers				water table level	15 min	2001 or 2005	temperature, EC	15 min	2010 or 2013	NO_3, SO_4, Cl	2/yr	2001 or 2005
							pH, EC	2/yr	2001 or 2005			
1 Piezometer				water table level	8/yr	2001	pH, temperature, EC	2/yr	2001			
3 Soil profiles				21 soil moistures	30 min	2010						
							Kervidy-Naizin					
1 Weather station	air and soil temperature, global radiation and PAR, wind speed and direction, rain, humidity	1 h	1993							bulk in rain water: NO_3, Cl, SO_4, NH_4, Ca, Mg, Na, total N	1 mo	2013

Stations	Atmospheric variables†			Hydrological variables‡			Other physical variables			Chemical variables§		
	Variable	Time step	First date	Variable	Time step	First date	Variable	Time step	First date	Variable	Time step	First date
1 Flux tower	net radiation and PAR, air temperature + humidity, atmospheric pressure, rain, heat flux, wind speed and direction	30 min	2015							CO_2 flux to atmosphere	20 Hz	2015
	soil moisture (−5, −20, −50 cm)	30 min	2015	soil temperature, EC	30 min	2015						
	actual ET	20 Hz	2015									
Kervidy outlet				stream level 1 min		1994	temperature	10 min	2010	NO_3	1 d + 15 min + 5 storms/yr	1993 (<daily), 1999 (daily), 2010 (15 min)
										DOC	1 d + 15 min + 5 storms/yr	1999 (daily), 2010 (15 min)
							EC		2013	SO_4, Cl	1 d + 5 storms/yr	1993 (<daily), 1999 (daily)
										DIC	1 d + 5 storms/yr	1999 (daily)
							turbidity		2004	SS	3 d + 5 storms/yr	2007
										total P, SRP	1 d + 30 min + 5 storms/yr	2007 (biweekly), 2013 (daily), 2016 (30 min)
Kervidy outlet's hyporheic zone							temperature	10 min	2010			
9 Piezometers				water table level 15 min		1998	temperature	10 min	2007 or 2010	NO_3, SO_4, Cl, DOC, DIC	4/yr	2000
										soil solution concentration in NO_3, SO_4, Cl, DOC, DIC, SRP, Fe II	1 wk to 1 mo	2013
1 Piezometer				water table level 15 min		1998	temperature	15 min	2010	NO_3, SO_4, Cl, DOC, DIC	4/yr	2000
				soil moisture (−5 cm) 30 min		2013	soil temperature (−5 cm)	30 min	2013	NO_3, SO_4, Cl, DOC, DIC	4/yr	2000
2 Piezometers				water table level 4/yr		1998	temperature	15 min	2010	NO_3, SO_4, Cl, DOC, DIC	4/yr	2000

† ET, evapotranspiration; PAR, photosynthetically active radiation.
‡ EC, electroconductivity.
§ DIC, dissolved inorganic C; DOC, dissolved organic C; SRP, soluble reactive phosphorus; SS, suspended solids.

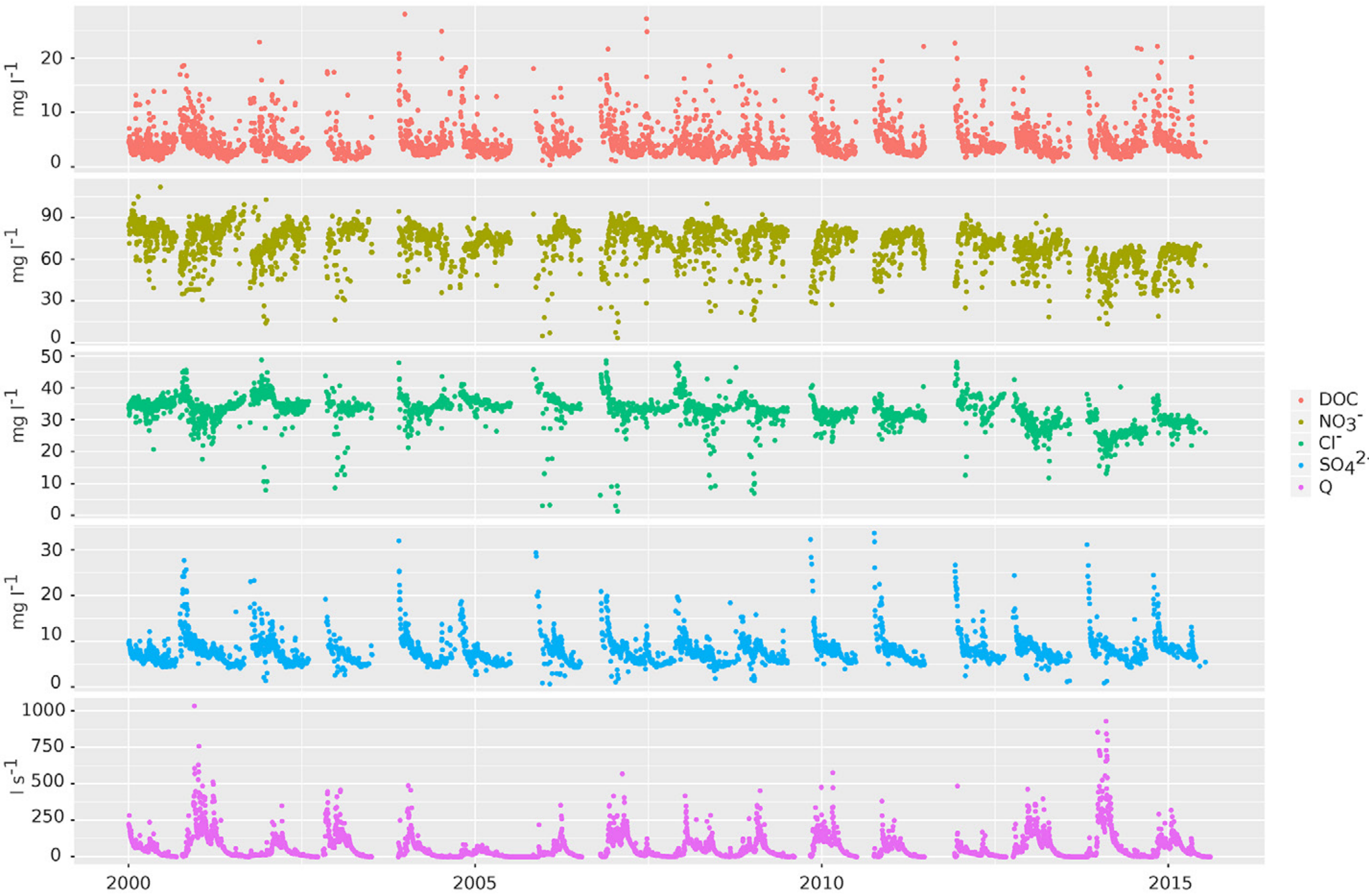

Fig. 3. Daily multiparameter time series at the Kervidy-Naizin outlet.

reconstructed from remote data by analyzing and classifying the information contained in images. The main annual land use in each field is recorded, at least in the case of cover crops. The land cover maps over the period 1993 to 2018 account for the modifications of the field limit over time.

Dedicated Long-Term Observations

AgrHyS is a real-life laboratory for research dedicated to specific research issues. Such studies benefit from the basic observation data sets and can reciprocally produce new data collection. Part of these additional observations is conducted for the duration of the project or even through several successive projects, leading to dedicated medium- to long-term data sets.

Soils

The first soil maps were established in the early stages of the research sites (Lamandé, 2003; Walter, 1993) (Fig. 2) to provide an extensive description of the spatial organization of soils and connect them to their hydrological and geochemical functioning (Walter and Curmi, 1998). High-resolution soil maps (1:10,000 and 1:25,000) have been established on the basis of four criteria: soil parent material, soil depth, soil redoximorphic conditions, and soil types as defined in the French soil classification (Baize et al., 2002). The physicochemical properties of soils (texture, pH, nutrient content, organic matter, trace elements) have been measured over the catchment, and hydrodynamic properties of soil horizons (hydraulic conductivity, porosity) have been quantified for the main soil types. In more recent research projects, additional soil collection campaigns have been conducted in the Kervidy-Naizin site to quantify C, N, and P stocks in the soil compartment and to characterize the biochemical processes controlling C, N, and P cycling in soils. Detailed data on soil C, N, and P content; soil aggregation; and microbial communities (molecular microbial biomass estimated by soil DNA recovery, bacterial and fungal communities analyzed by 16S and 18S rRNA gene pyrosequencing) (Matos-Moreira et al., 2017) have been collected. These data are captured in databases, which will allow for long-term monitoring of soil evolution (e.g., in C content) if such sampling campaigns are renewed.

Soil moisture sensors have been in use since 2010 in specific locations of the catchments and according to different strategies. At the Kerbernez site, 21 frequency domain reflectometry sensors are coupled with nested piezometers to monitor the groundwater recharge process. Volumetric soil water content is recorded at −0.25, −0.55, −0.85, −1.25, −1.65, −2.15, and −2.65 m depths (Fig. 1b) over three profiles; groundwater fluctuations below are also recorded. At the Kervidy-Naizin sites, time domain reflectometry sensors (often coupled with temperature sensors) are used either on soil profile (at −5, −20, and

−50 cm deep) or in the upper layer of soil (−5 cm) to interpret measurements of gaseous fluxes (CO_2, N_2O) conducted in successive research projects. The time step of acquisition ranges from 15 to 30 min.

Soils are key components to understanding the exports of several chemical elements to surface water. At the Kerbernez sites, successive PhD theses focused on the composition of recharge and on its variation with time and with space along the hillslope. Recharge water was sampled using profiles of ceramic cups between −25 cm and −2.5 m on which suction was applied for water collection (Legout et al., 2005, 2007). At the Kervidy-Naizin site, the chemical composition of soil water has been investigated since 2011 over a succession of projects focused on organic matter and P. Bottomland soils and wetland soils have been instrumented with zero-tension lysimeters and mini-piezometers to allow the sampling of free water in soils (Denis et al., 2017a, 2017b; Dupas et al., 2015b; Gu et al., 2017; Lambert et al., 2011). These samples are analyzed to determine their concentrations in anions, dissolved C (and Fe), and dissolved P, in addition to any other variables of interest. This soil water monitoring set up has been deployed on the Kervidy-Naizin site only and for monitoring the water chemistry over the soil–groundwater–stream continuum.

Agricultural Practices and Activities

To further interpret and model nutrient transfer over catchments, detailed information about agricultural practices is needed. Such information includes crop rotations (to control land cover maps and to fill potential gaps in them), fertilizer application, phytosanitary application, crop residues management, livestock size and types, animal feeding, and manure and dejection management. Farming activity is a key characteristic of AgrHyS because it leads to a diversity of inputs (nutrients, veterinary products) in the ecosystem. The acquisition of such information on agricultural practices and systems requires detailed farm surveys, which are too demanding and too expensive to be conducted every year. The number of farms in the study catchment is thus a key element for the feasibility of such surveys. On the Kerbernez site, where each catchment is composed of a few fields only, the survey is focused on the two most instrumented catchments and is conducted every 4 yr. The Kervidy-Naizin site includes 47 farms, all or part of whose fields are within the boundaries of the catchment. Therefore, such surveys are usually conducted within dedicated projects, and three detailed surveys were conducted since 1993: Cheverry conducted a study in 1993 (Cheverry, 1998, p. 85–108), in 2008 a survey focused on the livestock production system at the farm scale, and in 2013 a survey founded on a specific study of dynamics of organic matter investigated the cropping systems (i.e., crop rotations and crop management practices at the field scale for each farm) (Viaud et al., 2018).

Surface–Atmosphere Exchange Fluxes

Because evapotranspiration is a key component of the water budget, it is important to verify estimates provided by models using actual measurements of evapotranspiration. Eddy covariance–based flux towers that allow for such measurements (Lee et al., 2004) are expensive and have one important limitation in the context of catchment hydrology because the fluxes are typically measured at the field scale, rather than across the whole landscape. A flux tower station was installed in 2015 over grazed grassland (Fig. 1a), recording surface/atmosphere H_2O and CO_2 fluxes continuously over a few years to capture their seasonal and interannual variability. During the day, CO_2 fluxes are linked to H_2O fluxes via photosynthesis and transpiration of the vegetation, which is controlled by bulk canopy stomatal conductance; during the night soil and plant respiration proceed. Fluxes are measured by eddy covariance, and a set of ancillary meteorological and soil variables is recorded on site (Table 2). The measurement height is 2 m, corresponding to a flux footprint of the order of 1 to 3 ha depending on wind speed, atmospheric turbulence, and stability.

Analyzing Water Chemistry at Higher Temporal Resolution

The generation of new monitoring tools is emerging with a lot of promises for improving the understanding of hydrochemical processes with higher temporal frequency of water composition observations (van Geer et al., 2016; Wade et al., 2012). Indeed, despite the wide availability of techniques for continuous monitoring of hydrological variables, the continuous monitoring of water quality in situ is still technically challenging for use in management. As a research observatory, AgrHyS ERO is also a place for technical innovation because the high number of monitored parameters provides an ideal framework for testing new tools. Thus, several technologies have been or are being tested regarding their ability to provide water concentrations at resolution >1 h.

Sensors that estimate concentrations using indirect methods including in situ ionic specific probes and spectrophotometric probes were installed in 2010 to monitor NO_3, Cl, and organic C concentrations. They have been tested in stream and piezometers on both AgrHyS sites, leading to satisfactory results for the spectrophotometer, which records NO_3 and dissolved organic C every 15 min (Faucheux and Fovet, 2014). Ionic specific probes have been found more reliable for spatial campaigns than for continuous monitoring at a given point.

The most recent generation of tools is based on river bank side analyzers, which pump water directly from the stream and determine concentrations by direct physicochemical methods equivalent to those used in the laboratory in real time, avoiding storage and transport issues. Recent research revealed that the improvement of P monitoring frequency was key for characterizing storm processes and for estimating annual P exports (Minaudo et al., 2017). Thanks to this project, a P analyzer has recorded total and reactive P in the Kervidy-Naizin site since 2016 every 30 min (Jordan et al., 2007). The challenge to increase the temporal resolution of analysis for various chemical elements in water is also taken up with the development of a river laboratory prototype (Floury et al., 2017). A second prototype measures major ion concentrations (by ionic chromatography), dissolved silica (colorimetry), and organic C (acid mineralization and infrared CO_2 measurement) approximately every 30 min in stream water at the outlet of the Kervidy-Naizin site. Such records help to reduce the uncertainty associated with elemental balances of catchments and help to track hydrological flow paths.

Dedicated Campaigns and Experiments

Campaigns for Dynamic Mapping of Wetlands in Space and Time

According to their role in overland flow generation (Beven and Kirkby, 1979) and their role as hot spots for biogeochemical reactions (Sabater et al., 2003), wetlands have been the subject of several research projects. In impervious bedrock low-order catchments such as those of AgrHyS, wetlands result from the combination of climate, topography, and geomorphology zones in areas where the water table intercepts shallow soil horizons (Crave and Gascuel-Odoux, 1997). Such combinations are dynamic in space and time. Wetlands inventories have been made on the field by visual identification and by helicopter-borne radar (Gineste et al., 1998; Merot et al., 1994). Thanks to the inventory, a method for mapping those wetlands from a digital elevation model and using a climate-topographic index (Merot et al., 2003) has been developed and used on other AgrHyS sites.

Geophysical Campaigns and Experimental Determination of Hydrodynamic Properties

To characterize the hydrodynamic properties of the weathered rock, slug tests and pumping tests were performed in some of the piezometers to provide estimates of hydraulic conductivity (Martin et al., 2006; Molenat and Gascuel-Odoux, 2002; Molénat et al., 2005; Pauwels, 1994; Vouillamoz, 2003).

In the Kerbernez site, these tests were combined with geophysical surveys (electrical imaging, electromagnetic and magnetic resonance sounding) and indicate that the thickness of the weathered granite increases from upslope toward downslope areas of the catchments in the form of a deep graben structure (Legchenko et al., 2004). Subsequently, an experimental determination of weathered material was performed using the Wind method (Rouxel et al., 2012), showing that the retention curve of weathered granite is different from soil retention curves and cannot be easily estimated using pedotransfer function approaches.

Tracer Experiments and Use of Geochemical and Isotopic Tools

Hydrological and geochemical deconvolution can use various tracers to identify contributive flow paths and biogeochemical reaction processes or to estimate water and element residence times in catchment compartments such as soil, vadose zone, or groundwater. Various tracers have been used on AgrHyS sites for different objectives.

In the Kervidy-Naizin site, a lot of projects were dedicated to storm flow generation and associated exports of dissolved organic matter (DOM). Storm flow deconvolutions based on water isotopes ($\delta^{18}O$) showed the small portion of recent water in storm hydrographs (Merot et al., 1995), pointing to the importance of old water from soil and groundwater in the genesis of storm flow. Then, several tracer approaches were used and compared to identify and quantify the contributions of different compartments to DOC export during storm events and thereby also to improve our understanding of subsurface flows. The $\delta^{13}C$ of C (Lambert et al., 2011, 2013, 2014), the fluorescence signature, and the molecular composition of DOM (Denis et al., 2017a; Jeanneau et al., 2014) confirmed the major contribution of riparian wetlands to storm DOC and emphasized a secondary contribution of downslope areas, which decreased along successive storms. The fluorescence signature also emphasized the potential direct contribution of animal manure to the stream DOM during intense spring storm events.

In the Kerbernez sites, tracer experiments have been conducted to gain a better understanding in groundwater recharge. The first attempt to use ^{2}H in tracer campaigns at the scale of shallow piezometers was not conclusive, most likely because of excessive transfer times. Tracer experiments with Br and ^{2}H helped to estimate the water velocity in soils and showed the bimodal properties of the velocities. Enzymatic activity was also used in combination with solute concentrations in laboratory experiments to characterize the biogeochemically reactive transfer in the soil and the weathered zone, showing that heterotrophic denitrification was the dominant process (Legout et al., 2005, 2007). Groundwater age was determined using atmospheric tracer chlorofluorocarbons and SF6, highlighting the distinction between the weathered zone (where apparent ages ranged from 12 to 25 yr) and the weathered-fissured and fractured parts (where apparent age increased with depth and was >25 yr) (Ayraud et al., 2008; Molénat et al., 2013). In both AgrHyS sites, shallow groundwater feeds the streams; therefore, different experimental tools have been explored to quantify the subsurface fluxes and their temporal or spatial variations. Preliminary tests on radon were started in 2015, and studies on temperature using distributed temperature sensing by optic fiber were started in 2016).

Atmospheric Emissions and Deposition

Atmospheric mass transfer of key elements (water vapor, CO_2, N species), as part of complex and multiple pedosphere/hydrosphere/biosphere/atmosphere interactions, is important for the understanding and mass budgeting of soil and hydrological compartments within a landscape-like catchment, even at the scale of headwater catchments. The N cascade (Galloway et al., 2003) illustrates the importance of those interactions in an elemental budget. The understanding of the hydrochemical fluxes (H_2O, C, and N, in particular) and their importance in biogeochemical cycles thus requires adequate monitoring of element fluxes and concentration in the atmosphere. Several campaigns have been conducted since 2007 on AgrHyS sites to assess various fluxes, such as CO_2, N_2O, and NH_3, at the landscape scale. For example, Buysse et al. (2016) measured soil CO_2 efflux with closed dynamic respiration chambers over a 1-yr period (36 weekly to biweekly measurement dates) at 22 sites across the Kervidy-Naizin catchment. They found that water regime, land-use, and crop rotation significantly affect soil CO_2 emissions, with lower emissions observed in poorly drained soils either due to lower respiration or to limited CO_2 transport in saturated soils. A network of passive and low-cost sensors for atmospheric NH_3, which integrates concentrations over monthly periods, was also established across the catchment (Tang et al., 2001). These low-resolution atmospheric NH_3 data were complemented by mobile NH_3 plume measurement campaigns, downwind of the main agricultural NH_3 sources (animal housing), using fast-response (1 s) quantum cascade laser technology. These datasets were used to improve landscape-scale estimates of total NH_3 emissions as well as local dry deposition, which contribute significantly to the total N load of agroecosystems in areas of intensive animal farming (Bell, 2017).

Data Management and Policy

A database dedicated to basic long-term observations was created in 2002 and is now fed with observations related to the specific research projects hosted at the AgrHyS site. It is a POSTGRESQL database hosted on a virtual server provided by INRA InfoSol Orléans. The data are accessible via a web connection (https://www6.inra.fr/ore_agrhys_eng/Data). Recent and ongoing work on this database includes data not archived in the initial version (data before 1999–2000) and has reorganized the data integration process according to the evolution of sensor technologies and associated evolution of treatment methods and tools during the past decade.

The structure of the database has been reviewed to allow for the dissemination of raw information and expert knowledge used to process data. All treatments are thus trackable by comparison of raw and processed data, and qualification procedures for processed data can be automated thanks to this tracking by assigning a reliability score. Thanks to this double information, the treatment procedures can be shared between operators. All data for which treatments are performed outside the AgrHyS observatory team (e.g., weather data processed by INRA AgroClim research unit, past data processed by operators that are no longer part of the team, chemical analyses processed by laboratory) are only provided as processed data qualified as "unknown reliability." AgrHyS is contributing to the Open Data initiative with respect to the FAIR guiding principles (findability, accessibility, interoperability, reusability). Special care is given to data that can be related to personal information (e.g., about individual farmers, such as specific practices or punctual gaseous emissions from livestock buildings) with respect to the General Data Protection European Regulation and the associated French Data Protection Act (Loi Informatique & Libertés), which guarantees data privacy when relevant.

Different services have been developed to facilitate data access and reuse while insuring their interoperability thanks to the respect of international standards. All services and data are accessible thanks to a spatial data infrastructure (SDI) named GeoSAS (based on the SDI GeOrchestra, http://geowww.agrocampus-ouest.fr/portails/?portail=vidae). The metadata catalog is integrated into the GeoNetwork open source. Spatial data are stored on the open source GeoServer designed for interoperability and linked to a visualizing interface for locating and downloading monitoring stations and spatial data. Another service provided by GeoSAS SDI is a tool named VIDAE (http://agrhys.fr/BVE/vidae/) devoted to the visualization and extraction of temporal time series. Both raw and processed data are accessible via this tool, which allows requests about time steps and reliability scores for data download. Each data point is identified by a location (station) and a variable that combines the measured parameter (e.g., "stream level" or "NO_3 concentration") and the measurement method (e.g., "automatic level sensor" or "ionic chromatography on a grab sample at a given laboratory") to ensure the traceability of data acquisition.

New Insights and Novel Scientific Findings

Major Contributions to Hydrological and Biogeochemical Sciences

Over the years, the research conducted at AgrHyS sites has contributed to new insights into the hydrological sciences. In the early stages (1990–2000), novel findings highlighted the role of landscape geomorphology on water flow paths and their dynamics. This was achieved by assessing the role of bottomlands on surface flows (Merot and Bruneau, 1993) and then refining the delineation of variable contributive area concepts (Crave and Gascuel-Odoux, 1997; Merot et al., 1994, 1995), studying the effect of hillslope geomorphology (Beaujouan et al., 2001) and then the role of hedgerow network (Benhamou et al., 2013; Merot, 1999; Viaud et al., 2005) on water and dissolved N fluxes. The AgrHyS site also hosted several pioneer studies of hydrograph separations (Durand and Torres 1996; Merot et al., 1995; Morel et al., 2009) that were continued later using DOM as a tracer of water pathways (Denis et al., 2017a, 2017b; Jeanneau et al., 2014; Lambert et al., 2011). Another key contribution from AgrHyS site highlights shallow groundwater seasonal and its interannual fluctuations as a major driver of hydrological and chemical fluxes in such crystalline systems by controlling fluxes and storages (Martin et al., 2006; Molenat and Gascuel-Odoux, 2001; Molenat et al., 2008; Ruiz et al., 2002a, 2002b) as well as the connectivity (Dupas et al., 2015a, 2015c; Fovet et al., 2018; Gu et al., 2017) and the onset of specific biogeochemical processes (e.g., reductive dissolution of soil Fe oxides that induce nitrate reduction or P release) or location of biogeochemically reactive hot spots in the landscape (Grybos et al., 2009; Lambert et al., 2014; Legout et al., 2007; Oehler et al., 2009). This key role of shallow groundwater is of major importance because it reveals high response times of surface water quality to changes in agricultural inputs in such agroecosystems (Ayraud et al., 2008; Fovet et al., 2015a; Molenat and Gascuel-Odoux, 2002, Molénat et al., 2013). Indeed, transit times of water and solutes have been shown to be very variable and much higher than expected considering that, in such systems with a hard rock aquifer and oceanic climate, subsurface pathways are rather short and storage capacity is low compared with annual drainage.

AgrHyS contributions also enhance the biogeochemical sciences with original characterization of fractured schist reactivity (Pauwels, 1994) and unique characterization of groundwater age in shallower parts of a weathered aquifer (Ayraud et al., 2008; de Montety et al., 2018). Due to their specificity of human activities with intensive agriculture, including farming systems, AgrHyS sites were also a unique opportunity to investigate the effect of local anthropization on weathering and acidification processes (Pierson-Wickmann et al., 2009a, 2009b), which have been mostly studied in pristine areas. AgrHyS sites have also supported considerable work on the biogeochemistry of wetland soils, including OM, Fe, rare Earth elements, and P speciation, and combined controls exerted by soil characteristics, hydroclimate variability, and topography on the occurrence and intensity of biogeochemical reactions in those soils (Davranche et al., 2011, 2013, 2015; Gu et al., 2017, 2018; Grybos et al., 2007, 2009; Pourret et al., 2007, 2010). Finally, research conducted on AgrHyS observatory led to major contributions in highlighting and quantifying the role of wetland soils on the export of DOM and P in headwater lowland catchments on impervious bedrock (Gu et al., 2017; Humbert et al., 2015; Lambert et al., 2013; Morel et al., 2009).

After a decade of observations, AgrHyS started to offer a unique opportunity to conduct long-term analyses, in particular for investigating the effect of seasonal, interannual, and multiannual variability of climatic features and farming practices on water and nutrient fluxes. Original data treatments methods and approaches to unravel such effects have been tested and developed on this unique data set (Aubert et al., 2013a, 2013b, 2014; Dupas et al., 2015c). Detailed analyses of how seasonality is structured over the climatic interannual variability and how it structures the catchment behavior regarding chemical elements was only possible thanks to daily long records at daily frequency (Humbert et al., 2015) (Fig. 3) combined with storm records at sub-hourly frequency (Dupas et al., 2015a, 2015c; Vongvixay et al., 2018). Modeling studies are also strongly enriched with such long-term and multiparameter and multicompartment data sets (Fovet et al., 2015b; Salmon-Monviola et al., 2013) because they offer a unique case for testing how well the model is constrained and how realistic it behaves regarding multiple criteria (Fovet et al., 2015b; Hrachowitz et al., 2014).

A Place for Stimulation of Interdisciplinary Approaches

A major feature of AgrHyS is its role in support of interdisciplinary approaches. Such an observatory is unique in its ability to make researchers from various disciplines work together on both scientific and technical or methodological issues. Since the beginning, AgrHyS sites have been designed with an interdisciplinary approach combining the monitoring of hydro-meteorological variables and of water quality parameters with soil characterization (Le Bissonnais et al., 2002; Matos-Moreira et al., 2017; Walter, 1993) and agricultural systems description and understanding. This has helped to realize that understanding the relations between agriculture and its environment despite nonstationary conditions (climate variability) and buffering effects due to residence times and biogeochemical transformations requires integrative approaches that involve hydrology, biogeochemistry, soil science, geophysics, bioclimatology, agricultural science, and ecology. The long-term dimension of the observatory is crucial here because building such integrative science needs time and has been possible because of shared field work and shared perceptual models between researchers from various disciplines on those sites. Therefore, AgrHyS observatory appears as a major lever for building up and accumulating knowledge on agroecosystems. Such levers are required to improve the understanding in Environmental Sciences because of the complexity of the subject, the huge range of spatial and temporal scales at which the key controlling processes operate, and the strong unsteadiness of its forcing variables (i.e., climate and human activities).

Perspectives

Research Perspectives and Implications for Monitoring Strategies

AgrHys has generated major advances in knowledge on processes governing water and solutes in agrosystems. This constitutes a solid basis to explore the large knowledge gaps remaining on emerging science questions, such as the coupling of nutrient cycles or the fate of chemical pollutants with nonconservative behavior. An integrated approach is needed because the response time of agroecosystems to anthropic forcing depends not only on pollutant properties but also on their interactions or the existence of underestimated legacy stores.

For example, observations are extended to biological and ecological parameters such as soil microbial diversity and abundance, which started in 2013, and more recently aquatic macroinvertebrates and soil mesofauna. This development follows from the integration of soil and atmosphere variables and is consistent with the international trend of moving from hydrological observatories to critical zone observatories, in which the role of living organisms on processes and properties is central. Indeed, AgrHyS is part of the French National distributed Infrastructure on Critical Zone Observatories (OZCAR), established in 2017, which aims at promoting interdisciplinary approaches at the lithosphere–atmosphere–hydrosphere–biosphere interface (Gaillardet et al., 2018).

Another development is the monitoring of emerging pollutants, which are a growing concern for society. Since 2013, pioneering surveys have been conducted at the AgrHys observatory on drug residuals in the environment. Farming catchments have a major stake regarding these products because of their intensive use in veterinary services. The first outcomes of these projects and methods for the detection and measurement strategies of these products in soils and surface waters have been recommendations.

Perspectives for the AgrHyS Observatory Missions

The activities related to testing innovative techniques and measurement methods have been increasing since 2010. The Critex project (2012–2019, https://www.critex.fr/) has enhanced these activities, and the length of available data sets and their diversity in terms of parameters place the AgrHyS sites at major relevance for testing new measurement methods or considering new parameters to measure. Also, AgrHyS benefits from the skills required for such activities thanks to the experience acquired by the scientific and technical staff on those sites in terms of monitoring methodologies over the years. Development of low-cost sensors is also important for environmental sciences to achieve a better spatial resolution, which is critical to tackle upscaling issues (e.g., by equipping nested catchments).

The era of Big Data brings every day new questions and options and new challenges with respect to data management and sharing. Therefore, AgrHyS is engaged in several initiatives that aim at anticipating and exploring new tools relevant for managing and diffusing its data sets, in accordance with the European INSPIRE directive and the Open Science movement. Great attention is given to improve and upgrade the interoperable services for publishing data from observatories in particular with Open Geospatial Consortium standards, such as the Sensor Observation Service standard.

Perspectives for AgrHyS Network and Collaborations

To combine their dual objectives of addressing issues raised by society and advancing general scientific knowledge, observatories such as AgrHys must develop connections both locally with stakeholders and globally with the scientific community.

The knowledge and skills acquired at the observatory can contribute to improving water management at the local and regional scales. Regional collaborations of AgrHyS are developed with local water managers and policymakers. Thus, an important ambition is to extrapolate them at the scale of the whole Brittany region (Abbott et al., 2018). Actions in this direction have already been conducted with up-scaling studies from the Kervidy-Naizin catchment to the Blavet River basin (2000 km^2).

Outreach of research performed in AgrHys has the potential to contribute to understanding and better managing all agro-hydro-systems affected by intensive agriculture. For this, academic collaborations are expanding at the national and European levels (Wade et al., 2002; Duretz et al., 2011; Fléchard et al., 2011). In 2010, AgrHyS was a founding member of the French network of hydrological observatories federating the French Community of Critical Zone research. In 2017, the network grew with the creation of French Research Infrastructure on Critical Zone Observatories (IR OZCAR), which include Hydrogeological observatories, Glaciers Observatories, and Peats Observatories (Gaillardet et al., 2018). This national infrastructure is part of a European initiative for building a European Community of Critical Zone and Long-term Ecosystems Observatories. Such national and international communities have a key role for multiplying interdisciplinary approaches and exploring a diversity of pedo-climatic contexts over a range of anthropogenic forcing. This would allow a step forward in comparative studies conducted over a few sites (Dupas et al., 2017; Mellander et al., 2018) toward a gradient approach. According to the diversity of sizes in those observatories, it is also an opportunity to explore up-scaling and downscaling effects within those contexts.

Acknowledgments

The AgrHyS observatory exists thanks to the constant support from INRA (Département Environnement et Agronomie and Direction Scientifique Environnement) and CNRS, which provide recurring funds and dedicated technical staff. This allows the generation of funding through research projects conducted on the observatory through several agencies such as ANR, PIA (equipex), INSU, Agence de L'Eau Loire Bretagne, and Region Bretagne. We thank the PhD and Master's students and the post-doctoral fellows for their major contributions to this collaborative project; the scientists who participated in and coordinated research projects on AgrHyS observatory; the technical field and laboratory staff from SAS and Geoscience Rennes research units; and the farmers at the two sites for providing data and access to their fields and farms. Advances on the database and information system were carried out thanks to collaboration with Arnaud Dubreuil and the team of VIDAE project.

References

Abbott, B.W., G. Gruau, J.P. Zarnetske, F. Moatar, L. Barbe, Z. Thomas, et al. 2018. Unexpected spatial stability of water chemistry in headwater stream networks. Ecol. Lett. 21:296–308. doi:10.1111/ele.12897

Aubert, A.H., C. Gascuel-Odoux, G. Gruau, N. Akkal, M. Faucheux, Y. Fauvel, et al. 2013a. Solute transport dynamics in small, shallow groundwater-dominated agricultural catchments: Insights from a high-frequency, multisolute 10 yr-long monitoring study. Hydrol. Earth Syst. Sci. 17:1379–1391. doi:10.5194/hess-17-1379-2013

Aubert, A.H., J.W. Kirchner, C. Gascuel-Odoux, M. Faucheux, G. Gruau, and P. Merot. 2014. Fractal water quality fluctuations spanning the periodic table in an intensively farmed watershed. Environ. Sci. Technol. 48:930–937. doi:10.1021/es403723r

Aubert, A.H., R. Tavenard, R. Emonet, A. de Lavenne, S. Malinowski, T. Guyet, et al. 2013b. Clustering flood events from water quality time series using Latent Dirichlet Allocation model. Water Resour. Res. 49:8187–8199. doi:10.1002/2013WR014086

Ayraud, V., L. Aquilina, T. Labasque, H. Pauwels, J. Molenat, A.C. Pierson-Wickmann, et al. 2008. Compartmentalization of physical and chemical properties in hard-rock aquifers deduced from chemical and groundwater age analyses. Appl. Geochem. 23:2686–2707. doi:10.1016/j.apgeochem.2008.06.001

Baize, D., D. King, and M. Jamagne. 2002. The "Référentiel Pédologique" a sound reference base for soils: A tool for soil designation. In: E. Micheli et al., editors, Soil classification. Res. Rep. 7 Euro 20398 EN. European Soil Bureau Network. p. 85–92.

Beaujouan, V., P. Durand, and L. Ruiz. 2001. Modelling the effect of the spatial distribution of agricultural practices on nitrogen fluxes in rural catchments. Ecol. Modell. 137(1):93–105. doi:10.1016/S0304-3800(00)00435-X

Beaujouan, V., P. Durand, L. Ruiz, P. Aurousseau, and G. Cotteret. 2002. A hydrological model dedicated to topography-based simulation of nitrogen transfer and transformation: Rationale and application to the geomorphology-denitrification relationship. Hydrol. Processes 16:493–507. doi:10.1002/hyp.327

Bell, M. 2017. Emission, dispersion and deposition of ammonia from the plot to the landscape scale. Ph.D. diss. Univ. Bretagne Loire, Agrocampus Ouest, Rennes, France.

Benhamou, C., J. Salmon-Monviola, P. Durand, C. Grimaldi, and P. Merot. 2013. Modeling the interaction between fields and a surrounding hedgerow network and its impact on water and nitrogen flows of a small watershed. Agric. Water Manage. 121:62–72. doi:10.1016/j.agwat.2013.01.004

Beven, J., and M.J. Kirkby. 1979. A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrol. Sci. J. 24(1):43–69. doi:10.1080/02626667909491834

Buysse, P., C.R. Flechard, Y. Hamon, and V. Viaud. 2016. Impacts of water regime and land-use on soil CO2 efflux in a small temperate agricultural catchment. Biogeochemistry 130:267–288. doi:10.1007/s10533-016-0256-y

Cheverry, C. 1998. Agriculture intensive et qualité des eaux. INRA, Paris.

Crave, A., and C. Gascuel-Odoux. 1997. The influence of topography on time and space distribution of soil surface water content. Hydrol. Processes 11:203–210. doi:10.1002/(sici)1099-1085(199702)11:2<203::aid-hyp432>3.0.co;2-k

Davranche, M., A. Dia, M. Fakih, B. Nowack, G. Gruau, G. Ona-nguema, et al. 2013. Organic matter control on the reactivity of Fe(III)-oxyhydroxides and associated As in wetland soils: A kinetic modeling study. Chem. Geol. 335:24–35. doi:10.1016/j.chemgeo.2012.10.040

Davranche, M., G. Gruau, A. Dia, R. Marsac, M. Pédrot, and O. Pourret. 2015. Biogeochemical factors affecting rare earth element distribution in shallow wetland groundwater. Aquat. Geochem. 21:197–215. doi:10.1007/s10498-014-9247-6

Davranche, M., M. Grybos, G. Gruau, M. Pédrot, A. Dia, and R. Marsac. 2011. Rare earth element patterns: A tool for identifying trace metal sources during wetland soil reduction. Chem. Geol. 284:127–137. doi:10.1016/j.chemgeo.2011.02.014

de Montety, V., L. Aquilina, T. Labasque, E. Chatton, O. Fovet, L. Ruiz, et al. 2018. Recharge processes and vertical transfer investigated through long-term monitoring of dissolved gases in shallow groundwater. J. Hydrol. 560:275–288. doi:10.1016/j.jhydrol.2018.02.077

Denis, M., L. Jeanneau, P. Petitjean, A. Murzeau, M. Liotaud, L. Yonnet, and G. Gruau. 2017a. New molecular evidence for surface and sub-surface soil erosion controls on the composition of stream DOM during storm events. Biogeosciences 14:5039–5051. doi:10.5194/bg-14-5039-2017

Denis, M., L. Jeanneau, A.-C. Pierson-Wickman, G. Humbert, P. Petitjean, A. Jaffrézic, and G. Gruau. 2017b. A comparative study on the pore-size and filter type effect on the molecular composition of soil and stream dissolved organic matter. Org. Geochem. 110:36–44. doi:10.1016/j.orggeochem.2017.05.002

Dupas, R., C. Gascuel-Odoux, N. Gilliet, C. Grimaldi, and G. Gruau. 2015a. Distinct export dynamics for dissolved and particulate phosphorus reveal independent transport mechanisms in an arable headwater catchment. Hydrol. Processes 29:3162–3178. doi:10.1002/hyp.10432

Dupas, R., G. Gruau, S. Gu, G. Humbert, A. Jaffrezic, and C. Gascuel-Odoux. 2015b. Groundwater control of biogeochemical processes causing phosphorus release from riparian wetlands. Water Res. 84:307–314. doi:10.1016/j.watres.2015.07.048

Dupas, R., P.-E. Mellander, C. Gascuel-Odoux, O. Fovet, E.B. McAleer, N.T. McDonald, et al. 2017. The role of mobilisation and delivery processes on contrasting dissolved nitrogen and phosphorus exports in groundwater fed catchments. Sci. Total Environ. 599-600:1275–1287. doi:10.1016/j.scitotenv.2017.05.091

Dupas, R., J. Salmon-Monviola, K.J. Beven, P. Durand, P.M. Haygarth, M.J. Hollaway, et al. 2016. Uncertainty assessment of a dominant-process catchment model of dissolved phosphorus transfer. Hydrol. Earth Syst. Sci. 20:4819–4835. doi:10.5194/hess-20-4819-2016

Dupas, R., R. Tavenard, O. Fovet, N. Gilliet, C. Grimaldi, and C. Gascuel-Odoux. 2015c. Identifying seasonal patterns of phosphorus storm dynamics with dynamic time warping. Water Resour. Res. 51:8868–8882. doi:10.1002/2015WR017338

Durand, P., P. Moreau, J. Salmon-Monviola, L. Ruiz, F. Vertes, and C. Gascuel-Odoux. 2015. Modelling the interplay between nitrogen cycling processes and mitigation options in farming catchments. J. Agric. Sci. 153:959–974. doi:10.1017/S0021859615000258

Durand, P., and J.L.J. Torres. 1996. Solute transfer in agricultural catchments: The interest and limits of mixing models. J. Hydrol. 181:1–22. doi:10.1016/0022-1694(95)02922-2

Duretz, S., J.L. Drouet, P. Durand, N.J. Hutchings, M.R. Theobald, J. Salmon-Monviola, et al. 2011. NitroScape: A model to integrate nitrogen transfers and transformations in rural landscapes. Environ. Pollut. 159:3162–3170. doi:10.1016/j.envpol.2011.05.005

Faucheux, M., and O. Fovet. 2014. Mesures in situ et à haute fréquence de la chimie d'un cours d'eau par spectrophotométrie UV-visible. Cah. Tech. INRA 82:1–15.

Flechard, C.R., E. Nemitz, R.I. Smith, D. Fowler, A.T. Vermeulen, A. Bleeker, et al. 2011. Dry deposition of reactive nitrogen to European ecosystems: A comparison of inferential models across the NitroEurope network. Atmos. Chem. Phys. 11:2703–2728. doi:10.5194/acp-11-2703-2011

Floury, P., J. Gaillardet, E. Gayer, J. Bouchez, G. Tallec, P. Ansart, F. Koch, et al. 2017. The potamochemical symphony: New progress in the high-frequency acquisition of stream chemical data. Hydrol. Earth Syst. Sci. 21:6153–6165. doi:10.5194/hess-21-6153-2017

Fovet, O., G. Humbert, R. Dupas, C. Gascuel-Odoux, G. Gruau, A. Jaffrezic, et al. 2018. Seasonal variability of stream water quality response to storm events captured using high-frequency and multi-parameter data. J. Hydrol. 559:282–293. doi:10.1016/j.jhydrol.2018.02.040

Fovet, O., L. Ruiz, M. Faucheux, J. Molenat, M. Sekhar, F. Vertes, et al. 2015a. Using long time series of agricultural-derived nitrates for estimating catchment transit times. J. Hydrol. 522:603–617. doi:10.1016/j.jhydrol.2015.01.030

Fovet, O., L. Ruiz, M. Hrachowitz, M. Faucheux, and C. Gascuel-Odoux. 2015b. Hydrological hysteresis and its value for assessing process consistency in catchment conceptual models. Hydrol. Earth Syst. Sci. 19:105–123. doi:10.5194/hess-19-105-2015

Gaillardet, J., I. Braud, F. Hankard, S. Anquetin, O. Bour, and N. Dorfliger. 2018. OZCAR: The French network of critical zone observatories. Vadose Zone J. 17:180067. doi:10.2136/vzj2018.04.0067

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling, and B.J. Cosby. 2003. The nitrogen cascade. BioScience 53:341–356. doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Gascuel-Odoux, C., O. Fovet, G. Gruau, L. Ruiz, and P. Merot. 2018. Evolution of scientific questions over 50 years in the Kervidy-Naizin catchment: From catchment hydrology to integrated studies of biogeochemical cycles and agroecosystems in a rural landscape. Cuad. Invest. Geogr. 44:535–555. doi:10.18172/cig.3383

Gascuel-Odoux, C., M. Weiler, and J. Molenat. 2010. Effect of the spatial distribution of physical aquifer properties on modelled water table depth and stream discharge in a headwater catchment. Hydrol. Earth Syst. Sci. 14:1179–1194. doi:10.5194/hess-14-1179-2010

Gilliet, N., O. Fovet, C. Grimaldi, and M. Ndom. 2018. Mesure en continu de la concentration en matières en suspension dans des petits cours d'eau par turbidimétrie. Cah. Tech. INRA 93.

Gineste, P., C. Puech, and P. Merot. 1998. Radar remote sensing of the source areas from the Coet-Dan catchment. Hydrol. Processes 12:267–284. doi:10.1002/(SICI)1099-1085(199802)12:2<267::AID-HYP576>3.0.CO;2-G

Grybos, M., M. Davranche, G. Gruau, and P. Petitjean. 2007. Is trace metal release in wetland soils controlled by organic matter mobility or Fe-oxyhydroxides reduction? J. Colloid Interface Sci. 314:490–501. doi:10.1016/j.jcis.2007.04.062

Grybos, M., M. Davranche, G. Gruau, P. Petitjean, and M. Pédrot. 2009. Increasing pH drives organic matter solubilization from wetland soils under reducing conditions. Geoderma 154:13–19. doi:10.1016/j.geoderma.2009.09.001

Gu, S., G. Gruau, R. Dupas, C. Rumpel, A. Creme, O. Fovet, et al. 2017. Release of dissolved phosphorus from riparian wetlands: Evidence for complex interactions among hydroclimate variability, topography and soil properties. Sci. Total Environ. 598:421–431. doi:10.1016/j.scitotenv.2017.04.028

Gu, S., G. Gruau, F. Marique, R. Dupas, P. Petitjean, and C. Gascuel-Odoux. 2018. Drying/rewetting cycles stimulate release of colloidal-bound phosphorus in riparian soils. Geoderma 321:32–41. doi:10.1016/j.geoderma.2018.01.015

Howden, N.J.K., T.P. Burt, F. Worrall, S. Mathias, and M.J. Whelan. 2011a. Nitrate pollution in intensively farmed regions: What are the prospects for sustaining high-quality groundwater? Water Resour. Res. 47:W00I02. doi:10.1029/2011wr010843

Howden, N.J.K., T.P. Burt, F. Worrall, and M.J. Whelan. 2011b. Monitoring fluvial water chemistry for trend detection: Hydrological variability masks trends in datasets covering fewer than 12 years. J. Environ. Monit. 13:514–521. doi:10.1039/c0em00722f

Hrachowitz, M., O. Fovet, L. Ruiz, T. Euser, S. Gharari, R. Nijzink, et al. 2014. Process consistency in models: The importance of system signatures, expert knowledge, and process complexity. Water Resour. Res. 50:7445–7469. doi:10.1002/2014WR015484

Humbert, G., A. Jaffrezic, O. Fovet, G. Gruau, and P. Durand. 2015. Dry-season length and runoff control annual variability in stream DOC dynamics in a small, shallow groundwater-dominated agricultural watershed. Water Resour. Res. 51:7860–7877. doi:10.1002/2015WR017336

IUSS Working Group WRB. 2006. World reference base for soil resources: A framework for international classification, correlation and communication. World Soil Resour. Rep. 103. FAO, Rome.

Jarvie, H.P., A.N. Sharpley, P.J.A. Withers, J.T. Scott, B.E. Haggard, and C. Neal. 2013. Phosphorus mitigation to control river eutrophication: Murky waters, inconvenient truths, and "postnormal" science. J. Environ. Qual. 42:295–304. doi:10.2134/jeq2012.0085

Jeanneau, L., A. Jaffrezic, A.C. Pierson-Wickmann, G. Gruau, T. Lambert, and P. Petitjean. 2014. Constraints on the sources and production mechanisms of dissolved organic matter in soils from molecular biomarkers. Vadose Zone J. 13(7). doi:10.2136/vzj2014.02.0015

Jordan, P., A. Arnscheidt, H. McGrogan, and S. McCormick. 2007. Characterising phosphorus transfers in rural catchments using a continuous bank-side analyser. Hydrol. Earth Syst. Sci. 11:372–381. doi:10.5194/hess-11-372-2007

Lamandé, M. 2003. Effets de l'interaction des pratiques culturales et des communautés lombriciennes sur la structure du sol et son fonctionnement hydrique. Ph.D. diss. ENSA de Rennes, Rennes, France.

Lambert, T., A.-C. Pierson-Wickmann, G. Gruau, A. Jaffrezic, P. Petitjean, J.-N. Thibault, and L. Jeanneau. 2013. Hydrologically driven seasonal changes in the sources and production mechanisms of dissolved organic carbon in a small lowland catchment. Water Resour. Res. 49:5792–5803. doi:10.1002/wrcr.20466

Lambert, T., A.-C. Pierson-Wickmann, G. Gruau, A. Jaffrezic, P. Petitjean, J.N. Thibault, and L. Jeanneau. 2014. DOC sources and DOC transport pathways in a small headwater catchment as revealed by carbon isotope fluctuation during storm events. Biogeosciences 11:3043–3056. doi:10.5194/bg-11-3043-2014

Lambert, T., A.-C. Pierson-Wickmann, G. Gruau, J.-N. Thibault, and A. Jaffrezic. 2011. Carbon isotopes as tracers of dissolved organic carbon sources and water pathways in headwater catchments. J. Hydrol. 402:228–238. doi:10.1016/j.jhydrol.2011.03.014

Le Bissonnais Y., S. Cros-Cayot, and C. Gascuel-Odoux. 2002. Topographic dependence of aggregate stability, overland flow and sediment transport. Agronomie 22:489–501. doi:10.1051/agro:2002024

Lee, X., W. Massman, and B. Law, editors. 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Atmos. Oceanogr. Sci. Libr. 29. Kluwer Acad. Publ., Dordrecht, the Netherlands.

Legchenko, A., J.-M. Baltassat, A. Bobachev, C. Martin, H. Robain, and J.-M. Vouillamoz. 2004. Magnetic resonance sounding applied to aquifer characterization. Ground Water 42:363–373. doi:10.1111/j.1745-6584.2004.tb02684.x

Legout, C., J. Molenat, L. Aquilina, C. Gascuel-Odoux, M. Faucheux, Y. Fauvel, and T. Bariac. 2007. Solute transfer in the unsaturated zone-groundwater continuum of a headwater catchment. J. Hydrol. 332:427–441. doi:10.1016/j.jhydrol.2006.07.017

Legout, C., J. Molenat, S. Lefebvre, P. Marmonier, and L. Aquilina. 2005. Investigation of biogeochemical activities in the soil and unsaturated zone of weathered granite. Biogeochemistry 75:329–350. doi:10.1007/s10533-005-0110-0

Martin, C., J. Molenat, C. Gascuel-Odoux, J.M. Vouillamoz, H. Robain, L. Ruiz, et al. 2006. Modelling the effect of physical and chemical characteristics of shallow aquifers on water and nitrate transport in small agricultural catchments. J. Hydrol. 326:25–42. doi:10.1016/j.jhydrol.2005.10.040

Matos-Moreira, M., B. Lemercier, R. Dupas, D. Michot, V. Viaud, N. Akkal-Corfini, et al. 2017. High-resolution mapping of soil phosphorus concentration in agricultural landscapes with readily available or detailed survey data. Eur. J. Soil Sci. 68:281–294. doi:10.1111/ejss.12420

Mellander, P.-E., P. Jordan, M. Bechmann, O. Fovet, M.M. Shore, N.T. McDonald, and C. Gascuel-Odoux. 2018. Integrated climate-chemical indicators of diffuse pollution from land to water. Sci. Rep. 8:944. doi:10.1038/s41598-018-19143-1

Merot, P. 1999. The influence of hedgerow systems on the hydrology of agricultural catchments in a temperate climate. Agronomie 19:655–669. doi:10.1051/agro:19990801

Merot, P., and P. Bruneau. 1993. Sensitivity of bocage landscapes to surfaces run-off: Application of the Kirkby index. Hydrol. Processes 7:167–176. doi:10.1002/hyp.3360070207

Merot, P., A. Crave, C. Gascuelodoux, and S. Louhala. 1994. Effect of saturated areas on backscattering coefficient of the ers-1 synthetic-aperture radar-first results. Water Resour. Res. 30:175–179. doi:10.1029/93WR02920

Merot, P., B. Ezzahar, C. Walter, and P. Aurousseau. 1995. Mapping waterlogging of soils using digital terrain models. Hydrol. Processes 9:27–34. doi:10.1002/hyp.3360090104

Merot, P., H. Squividant, P. Aurousseau, M. Hefting, T. Burt, V. Maitre, et al. 2003. Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. Ecol. Modell. 163:51–71. doi:10.1016/S0304-3800(02)00387-3

Minaudo, C., R. Dupas, C. Gascuel-Odoux, O. Fovet, P.-E. Mellander, P. Jordan, et al. 2017. Nonlinear empirical modeling to estimate phosphorus exports using continuous records of turbidity and discharge. Water Resour. Res. 53:7590–7606. doi:10.1002/2017WR020590

Molenat, J., and C. Gascuel-Odoux. 2001. Role of shallow groundwater in nitrate and herbicide transport in the Kervidy agricultural catchment (Brittany, France). IAHS Publ. 269:347–351.

Molenat, J., and C. Gascuel-Odoux. 2002. Modelling flow and nitrate transport in groundwater for the prediction of water travel times and of consequences of land use evolution on water quality. Hydrol. Processes 16:479–492. doi:10.1002/hyp.328

Molénat, J., C. Gascuel-Odoux, L. Aquilina, and L. Ruiz. 2013. Use of gaseous tracers (CFCs and SF6) and transit-time distribution spectrum to validate a shallow groundwater transport model. J. Hydrol. 480:1–9. doi:10.1016/j.jhydrol.2012.11.043

Molénat, J., C. Gascuel-Odoux, P. Davy, and P. Durand. 2005. How to model shallow water-table depth variations: The case of the Kervidy-Naizin catchment, France. Hydrol. Processes 19:901–920. doi:10.1002/hyp.5546

Molenat, J., C. Gascuel-Odoux, L. Ruiz, and G. Gruau. 2008. Role of water table dynamics on stream nitrate export and concentration in agricultural headwater catchment (France). J. Hydrol. 348:363–378. doi:10.1016/j.jhydrol.2007.10.005

Moreau, P., L. Ruiz, T. Raimbault, F. Vertes, M.O. Cordier, C. Gascuel-Odoux, et al. 2012. Modeling the potential benefits of catch-crop introduction in fodder crop rotations in a western europe landscape. Sci. Total Environ. 437:276–284. doi:10.1016/j.scitotenv.2012.07.091

Morel, B., P. Durand, A. Jaffrezic, G. Gruau, and J. Molenat. 2009. Sources of dissolved organic carbon during stormflow in a headwater agricultural catchment. Hydrol. Processes 23:2888–2901. doi:10.1002/hyp.7379

Oehler, F., P. Durand, P. Bordenave, Z. Saadi, and J. Salmon-Monviola. 2009. Modelling denitrification at the catchment scale. Sci. Total Environ. 407:1726–1737. doi:10.1016/j.scitotenv.2008.10.069

Pauwels, H. 1994. Natural denitrification in groundwater in the presence of pyrite: Preliminary results obtained at Naizin (Brittany, France). Mineral. Mag. 58A:696–697. doi:10.1180/minmag.1994.58A.2.100

Pierson-Wickmann, A.-C., L. Aquilina, C. Martin, L. Ruiz, J. Molenat, A. Jaffrezic, and C. Gascuel-Odoux. 2009a. High chemical weathering rates in first-order granitic catchments induced by agricultural stress. Chem. Geol. 265:369–380. doi:10.1016/j.chemgeo.2009.04.014

Pierson-Wickmann, A.-C., L. Aquilina, C. Weyer, J. Molénat, and G. Lischeid. 2009b. Acidification processes and soil leaching influenced by agricultural practices revealed by strontium isotopic ratios. Geochim. Cosmochim. Acta 73:4688–4704. doi:10.1016/j.gca.2009.05.051

Pourret, O., A. Dia, M. Davranche, G. Gruau, O. Hénin, and M. Angée. 2007. Organo-colloidal control on major- and trace-element partitioning in shallow groundwaters: Confronting ultrafiltration and modelling. Appl. Geochem. 22:1568–1582. doi:10.1016/j.apgeochem.2007.03.022

Pourret, O., G. Gruau, A. Dia, M. Davranche, and J. Molenat. 2010. Colloidal control on the distribution of rare earth elements in shallow groundwaters. Aquat. Geochem. 16:31–59. doi:10.1007/s10498-009-9069-0

Rouxel, M., L. Ruiz, J. Molenat, Y. Hamon, G. Chirie, and D. Michot. 2012. Experimental determination of hydrodynamic properties of weathered granite. Vadose Zone J. 11(3). doi:10.2136/vzj2011.0076

Ruiz, L., S. Abiven, P. Durand, C. Martin, F. Vertes, and V. Beaujouan. 2002a. Effect on nitrate concentration in stream water of agricultural practices in small catchments in Brittany: I. Annual nitrogen budgets. Hydrol. Earth Syst. Sci. 6:497–505. doi:10.5194/hess-6-497-2002

Ruiz, L., S. Abiven, C. Martin, P. Durand, V. Beaujouan, and J. Molenat. 2002b. Effect on nitrate concentration in stream water of agricultural practices in small catchments in Brittany: II. Temporal variations and mixing processes. Hydrol. Earth Syst. Sci. 6:507–514. doi:10.5194/hess-6-507-2002

Sabater, S., A. Butturini, J.C. Clement, T. Burt, D. Dowrick, M. Mariet Hefting, et al. 2003. Nitrogen removal by riparian buffers along a European climatic gradient: Patterns and factors of variation. Ecosystems 6:0020–0030. doi:10.1007/s10021-002-0183-8

Salmon-Monviola, J., P. Moreau, C. Benhamou, P. Durand, P. Merot, F. Oehler, and C. Gascuel-Odoux. 2013. Effect of climate change and increased atmospheric CO_2 on hydrological and nitrogen cycling in an intensive agricultural headwater catchment in western France. Clim. Change 120:433–447. doi:10.1007/s10584-013-0828-y

Tang, Y.S., J.N. Cape, and M.A. Sutton. 2001. Development and types of passive samplers for monitoring atmospheric NO_2 and NH_3 concentrations. Sci. World 1:513–529. doi:10.1100/tsw.2001.82

van Geer, F.C., B. Kronvang, and H.P. Broers. 2016. High-resolution monitoring of nutrients in groundwater and surface waters: Process understanding, quantification of loads and concentrations, and management applications. Hydrol. Earth Syst. Sci. 20:3619–3629. doi:10.5194/hess-20-3619-2016

Viaud, V., P. Durand, P. Merot, E. Sauboua, and Z. Saadi. 2005. Modeling the impact of the spatial structure of a hedge network on the hydrology of a small catchment in a temperate climate. Agric. Water Manage. 74:135–163. doi:10.1016/j.agwat.2004.11.010

Viaud, V., P. Santillàn-Carvantes, N. Akkal-Corfini, C. Le Guillou, N.C. Prévost-Bouré, L. Ranjard, and S. Menasseri-Aubry. 2018. Landscape-scale analysis of cropping system effects on soil quality in a context of crop-livestock farming. Agric. Ecosyst. Environ. 265:166–177. doi:10.1016/j.agee.2018.06.018

Vongvixay, A., C. Grimaldi, R. Dupas, O. Fovet, F. Birgand, N. Gilliet, and C. Gascuel-Odoux. 2018. Contrasting suspended sediment export in two small agricultural catchments: Cross-influence of hydrological behavior and landscape degradation or stream bank management. Land Degrad. Dev. 29:1385–1396. doi:10.1002/ldr.2940

Vouillamoz, J.-M. 2003. La caractérisation des aquifères par une méthode non invasive: Les sondages par résonance magnétique protonique. Ph.D. diss. Univ. Paris XI.

Wade, A.J., P. Durand, V. Beaujouan, W.W. Wessel, K.J. Raat, P.G. Whitehead, D. Butterfield, K. Rankinen, and A. Lepisto. 2002. A nitrogen model for European catchments: INCA, new model structure and equations. Hydrol. Earth Syst. Sci. 6:559–582. doi:10.5194/hess-6-559-2002

Wade, A.J., E.J. Palmer-Felgate, S.J. Halliday, R.A. Skeffington, M. Loewenthal, H.P. Jarvie, et al. 2012. Hydrochemical processes in lowland rivers: Insights from in situ, high-resolution monitoring. Hydrol. Earth Syst. Sci. 16:4323–4342. doi:10.5194/hess-16-4323-2012

Walter, C. 1993. L'estimation de propriétés du sol par krigeage d'indicatrices confrontée à celle dérivée d'une carte pédologique. Sci. Sol 31:215–231.

Walter, C., and P. Curmi. 1998. Les sols du bassin versant du Coet-Dan: Organisation, variabilité spatiale et cartographie. In: C. Cheverry, editor, Agriculture intensive et qualité des eaux. INRA Editions, La Géraudière, France. p. 85–108.