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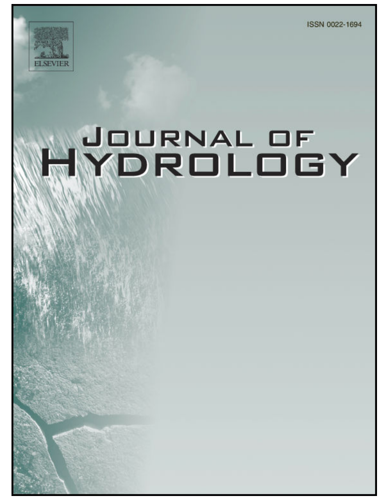

Review papers

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A French hydrologist's research for sustainable agriculture

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Abstract

Here we highlight the career contributions of Chantal Gascuel-Odoux in hydrology, soil science and agronomy. These contributions are divided into four main categories: i) Influence of soil and subsoil properties on hydrological processes; ii) Water, solute and particulate transfer at the catchment scale; iii) Design of integrated approaches to landscapes and territorial management; iv) Contributions to public policies and public debates. We conclude by emphasising Chantal's human qualities, which we particularly appreciate as former mentees.

Introduction

As a hydrologist at the French agricultural research institute INRAE[1], Chantal Gascuel-Odoux has always conducted research with an interdisciplinary dimension, embedded in environmental sciences. In her research, hydrology intersects most often with soil science and agronomy, the disciplines of her closest colleagues at her research unit, SAS (Soil, Agro- and HydroSystems, Spatialization). However, her collaborations and

[1] Before 2020, INRAE, the National Research Institute for Agricultural, Food and the Environment, was INRA, the National Institute of Agricultural Research.

interdisciplinary research span a much broader range of disciplines and expertise, such as social sciences, aquatic ecology and computer science.

This vast range of collaborations reflects Chantal's curiosity and embodies her conviction that collaboration is key to research. Above all, she considers that interdisciplinary research is crucial to address societal challenges related to agriculture, food and the environment. Understanding Chantal's contributions to scientific knowledge of and societal debates around agriculture and the environment requires understanding the societal context of Brittany, in western France, where she has spent most of her career. Beginning in the 1960s, Brittany experienced rapid development of intensive agriculture, particularly confined animal production. Because of its temperate oceanic climate and shallow soils and aquifers, water pollution by nitrate, phosphorus (P) and pesticides soon surged (Aubertot et al., 2007; Gascuel et al., 2015). Today, Brittany is a region of Europe emblematic for its high nutrient loads and subsequent eutrophication problems in both tourist-oriented coastal bays and reservoirs used for drinking water (Le Moal et al., 2019). In this context, understanding hydrological and biogeochemical processes in the Brittany region aims mainly to understand the degradation of water quality and find solutions to improve the situation.. The impact of Chantal's research goes far beyond the regional context, however, as she always endeavours to identify and highlight generic knowledge in every study, even when it relies on data from one or a few local study sites.

When Chantal started her career in the mid-1980s, publishing in English in international journals was not an obvious choice for French researchers. It is noteworthy that her first international article was published in French in the *Journal of Hydrology*, before English became the dominant language of global scientific communication (Gascuel-Odoux and Mérot, 1986)! Chantal was one of the first researchers at SAS to disseminate her research in English, and we consider her responsible for the internationalization of the unit, first as a researcher and then as unit director. Subsequently, Chantal and her colleagues increasingly published their research in international journals, including the *Journal of Hydrology*. The internationalization of her research also led her to participate in European research projects (e.g. COST actions) and to co-author many articles with international teams, mainly in European countries facing similar problems with diffuse agricultural pollution, such as the United Kingdom (UK), Ireland and the Netherlands. Her international research career is also marked by two scientific visits, one to the French National Research Institute for Sustainable Development (IRD) in Dakar, Senegal (1991-1992), and the other to the University of British Colombia, Vancouver, Canada (2006-2007). The Ph.D. students that Chantal supervises are certain to have the opportunity for a short-term scientific visit to a foreign country to broaden their horizons!

Chantal’s career is also marked by her institutional involvement within the SAS unit, more broadly at INRAE and in French research in general. In 2000, she co-founded the Armorican Centre for Environment Research (CAREN) with Philippe Davy (CNRS) to federate research teams from several institutes (INRAE, CNRS, University of Rennes) working on environmental sciences in Rennes, France. CAREN became OSUR (Observatoire des Sciences de l’Univers de Rennes) in 2010 under the leadership of Gilles Pinay (CNRS), and Chantal served as its vice-director. She was also the director of the SAS unit - with nearly 100 people - from 2004-2011. Since 2016, Chantal has also served part-time as Deputy Scientific Director for the Environment at INRAE, where she actively investigates and promotes agroecology as a discipline that returns ecology to the centre of agricultural system design (Caquet et al., 2020b; Gascuel-Odoux et al., 2022; Gascuel and Magda, 2015).

This article reviews Chantal’s contributions to hydrology and related disciplines. As we limit it to a review of her published articles, we felt it was important to present Chantal’s institutional involvement in the introduction. However, this introduction, like the review that follows, is far from complete, because she has made many diverse contributions. We hope, however, that the present reflection on her career highlights its unique features (Figure 1). In this review article, we divided Chantal’s scientific contributions into four main categories: 1) influence of soil and subsoil properties on hydrological processes; 2) water, solute and particulate transfer at the catchment scale; 3) design of integrated approaches to landscapes and territorial management; 4) contributions to public policies and public debate.

Figure 1. Chantal Gascuel-Odoux in 2022, with the current CEO of INRAE Philippe Mauguin (left) and former CEO Marion Guillou (right). Credit: UMR SAS.

1. Influence of soil and subsoil properties on hydrological processes

Since the 1980s, Chantal and colleagues (particularly Philippe Mérot, INRAE) have analysed and modelled runoff generation and groundwater dynamics. Along with colleagues from the SAS unit, she conducted research to identify the relevant scales of the spatial variability in infiltration, runoff and the distribution of saturated areas. Since the pioneering studies of Betson (1964) and Dunne and Black (1970) in the United States, Weyman (1970, 1973) in the UK and Cappus (1960) in France, runoff generation in saturated areas was considered a key factor that controlled stream flow generation. Early interactions with Keith Beven (Univ. of Lancaster, UK), Mike Kirby (Univ. of Leeds, UK) and Philippe Davy (CNRS, France) convinced Chantal that shallow groundwater played a major role in the hydrological and biogeochemical functioning of catchments. Consequently, they decided in the mid-1990s to study and develop models of shallow groundwater dynamics.

1.1. Spatial variability in infiltration and runoff

At the beginning of her career (including her PhD research 1981-1984), Chantal investigated spatial variability in runoff and water infiltration at the field scale. Knowledge of the spatial variability in soil physical properties was required to address several agricultural issues, such as wetland preservation in agricultural areas. Three main objectives governed her studies in this field: (i) quantifying spatial variability, (ii) analysing correlation(s) between hydrological and soil factors and (iii) producing soil maps. Chantal and colleagues used geostatistics and isotopic tracer methods such as ^{18}O to study water movement, soil water content (Gascuel-Odoux and Mérot, 1986), soil properties (Gascuel-Odoux, 1987; Gascuel-Odoux and Merot, 1991) and the rainfall rate (Mérot et al., 1989). Starting from in-situ measurements and sampling, both methods improved mapping of water movement and soil characteristics (Gascuel-Odoux and Boivin, 1994; Gascuel-Odoux et al., 1991). Chantal has promoted the use of geostatistics to define appropriate strategies for soil sampling and the spatial resolution of in-situ measurements. Chantal and colleagues also conducted early research on the ability of a helicopter-borne C-band scatterometer radar to map the extent of saturated areas (Brun et al., 1990). In particular, they demonstrated benefits of using ERS-1 synthetic aperture radar backscatter to map these extents (Mérot et al., 1994). These studies paved the way for using remote sensing to map saturated areas and to limit parameter ranges of uncertainty in hydrological models such as Topmodel (Franks et al., 1998).

With a fine knowledge of soil properties, Chantal and colleagues have used several approaches to study runoff generation in rural contexts. From in-situ measurement of overland flow in an agricultural field, they identified local microtopography, soil crusting and the spatial distribution of soil patches with high hydraulic conductivity as the main factors that control runoff (Gascuel-Odoux et al., 1996). From experiments and computer modelling, they showed that flow-path connectivity at the square-meter scale depends on the ratio of the mean slope to random roughness, which controls transfers within the soil surface and may change significantly over time during a storm event (Darboux et al., 2002). While runoff may be triggered on the upper part of hillslopes, sheet flow is low, and the runoff coefficient decreases as the slope length increases. Infiltration and soil deposition are particularly active in concave parts of hillslopes, regardless of the characteristics of storm events, and are enhanced by hedgerow networks (Mérot et al., 1999). This result contradicts the intuitive model of downstream amplification of runoff through aggregation in the drainage area. It also supports the assumption of a threshold of spatial scale at which to define the head of channel networks, at least in temperate regions such as Brittany. After this major observation, Chantal and colleagues worked to improve maps of surface-flow connectivity using digital elevation models (DEMs) by representing the influence of hedgerows and field networks on the drainage area (Aurousseau et al., 2009; Gascuel-Odoux et al., 2011; Tortrat et al., 2003).

1.2. Riparian wetland mapping

Because riparian wetlands in agricultural landscapes strongly influence hydrology, water quality and biodiversity, their degradation in intensive agricultural landscapes is of great concern. To address the need for reliable wetland mapping, Chantal and colleagues developed a hydrological typology of wetlands (Durand et al., 2000; Mérot et al., 2006). First, potential wetlands are defined by soil properties and topographic data that can be derived from available databases and DEMs. Second, existing wetlands are mapped from in-situ observation of soil water content and wetland vegetation. Third, effective wetlands are defined for a variety of ecosystem services related to hydrology, water quality and biodiversity. Mapping these three types of wetlands requires different levels of investigation effort. This study was the basis for the inventory of valley-bottom wetland maps currently used in Brittany (Gascuel et al., 2009) and for the PEEW (Potential, Existing and Effective Wetlands) method, which provides a framework for organizing knowledge about wetland management (Mérot et al., 2006).

1.3. Characterization and modelling of shallow groundwater

Since the 1990s, Chantal and colleagues have assessed the ability of hydrological models to predict spatial variability in groundwater levels in catchments. Attracted by Topmodel’s ability to capture with elegant simplicity the dynamics and dominant controls of shallow groundwater hydrology in a semi-distributed form (Beven et al., 2020), they considered this model as a reference. This led Chantal to collaborate with Keith Beven to conduct one of the first studies of the influence of temporal and spatial resolutions on model parameterization and simulations (Bruneau et al., 1995).

Specifically, she worked to determine the appropriate modelling approach for predicting dynamics of the water table and stream runoff simultaneously in catchments dominated by saturated subsurface flow (Gascuel-Odoux et al., 2010b; Martin, 2003; Martin et al., 2006; Molenat, 1999; Molenat et al., 2005). Chantal has always been convinced that the spatial distribution of shallow groundwater must be predicted well to simulate matter fluxes and travel times in catchments (section 2). Furthermore, she showed that groundwater is the main component of stream flow during both base flow conditions and storm events (Gascuel-Odoux et al., 1999; Molénat et al., 1999). Her research has made good use of the number and quality of water-table records in the catchments of the AgrHyS observatory ("Agro-Hydro Systems", Gascuel-Odoux et al., 2018). High-frequency records (< 1 h) from wells on transects extending down hillslopes provided the data necessary to analyse the ability to simulate spatio-temporal dynamics of shallow groundwater. In this regard, Topmodel's assumptions appear to work well for simulating stream flow and the water table in valley bottoms but less well for simulating midslope and upslope areas. Relaxing two of Topmodel's assumptions – steady-state spatial subsurface flux and topographic assumptions – significantly improve water-table simulations for these two areas (Molenat et al., 2005). The question is then how much the representation of geometry (e.g. depth, thickness) of the soil and subsoil, as well as the hydraulic properties of groundwater systems, can be simplified while still achieving acceptable simulations of the water table, transit time and solute fluxes. Spatial simulations of the water table were less sensitive to the geometry of the subsoil than to the spatial distribution of hydraulic conductivity (Martin et al., 2006). Consequently, Chantal analysed the relevance of considering homogeneous hydraulic geometry (i.e. soil and subsoil thickness and depth) and properties (e.g. hydraulic conductivity, drainable porosity). Using the HillVi model (Weiler and McDonnell, 2004), she demonstrated that considering lateral variations in hydraulic properties along the hillslope improves the spatial prediction of water tables only slightly (Gascuel-Odoux et al., 2010b). She concluded that i) there is some incommensurability in comparing point observations to grid-averaged predictions and ii) improving spatial simulations of water table requires fitting local transmissivity to local water-table observations, which would require acquiring these observations.

2. Water, solute and particulate transfer at the catchment scale

Since the early 1990s, Chantal's research has focussed mainly on water, solute and particulate transfer in agricultural catchments. She has considered the understanding of processes that underlie these transfers as a key scientific challenge to preserve and/or restore water quality in the face of high agricultural pressures and climate change. In the context of the severe nitrate contamination of water that western France was experiencing, Chantal advanced knowledge of the nitrogen (N) cycle and nitrate transfer at the catchment scale. However, as water quality should be evaluated as a whole, she collaborated with other colleagues, especially Gérard Gruau (CNRS, France), Catherine Grimaldi (INRAE, France) and Aline Dia (CNRS, France), to extended the study of matter transfer to carbon (C), P and suspended sediments. They soon perceived the need for long-term and spatially distributed hydrological and concentration time series, associated with the observation of agricultural practices. To this end, she actively contributed to the development of the AgrHys research observatory in Brittany (Figure 2; Fovet et al., 2018b). This long-term observatory has focused since 1992 on headwater catchments (Kervidy-Naizin 5 km² and Kerbernez, 1.2 km²), and characterized by hard rock aquifers, an oceanic climate, and dominance of agricultural land uses devoted to animal farming. The AgrHyS observatory is dedicated to the investigation of the biogeochemical response times of catchments to variations in climate and agriculture, with a focus on the following elements: water, nitrogen, carbon and phosphorus. Chantal has (co-)supervised 11 PhD thesis that have analyzed AgrHys observational data from (Gascuel-Odoux et al., 2018). To promote the observatory, develop scientific collaborations and investigate scientific questions over a wider range of hydroclimatic conditions, Chantal has worked to integrate the observatory into a national (OZCAR; (Gaillardet et al., 2018) and a European network (eLTER). Through collaborations, her research has also benefited from observations from research catchments outside of France (e.g. Ireland, Norway). Extrapolation of results acquired in headwater catchments, associated with the needs and requests of local and national water managers, have led her and colleagues to extend the study of transfers to mesoscale catchments and national scales. To this end, Chantal has also used operational water information and monitoring databases.

Figure 2. Aerial photography of the Kervidy-Naizin catchment. Credit: Air Papillon.

2.1. Groundwater nitrate transfer: from estimation of travel time to connectivity analysis

Chantal and colleagues have addressed groundwater nitrate transfer in agricultural catchments for the past 30 years. It is useful to recall the scientific context in the 1990s, when she began this research. Most studies focussed mainly on storm events to understand the main hydrological and biogeochemical processes that control dynamics of solute concentrations and fluxes in stream water. In addition, solute transfer times in headwater catchments with shallow groundwater were assumed to be short, due to the shallow groundwater and short travel distances along hillslopes from the soil to a stream. In this context, Chantal and Philippe Davy explored two topics: i) estimating travel times in shallow groundwater systems and ii) exploring relationships between the dynamics of shallow groundwater and stream nitrate concentration at seasonal and annual scales. The objective of this research was to better understand and predict long-term dynamics of stream nitrate concentrations and fluxes (section 3).

How long does it take a solute to travel from the soil to a stream? This question was initially motivated by water-management concerns. In a context of high nitrate contamination of streams and rivers, several research teams and especially Chantal's, were challenged by water-management agencies and public authorities to estimate how much time it would take stream water quality to recover after implementing good agricultural practices. Subsequently, Chantal and colleagues used a variety of approaches to quantify groundwater travel time. Spectral analysis of long time series of in-stream solute concentrations led to the conclusion that mean travel time in the Kervidy-Naizin catchment (Brittany) exceeded 1.3 years (Molénat et al., 1999). Computer simulations performed later with distributed physical-based groundwater models predicted that travel times varied greatly across catchments, taking up to 3 years in the Kervidy-Naizin catchment (Molénat and Gascuel-Odoux, 2002) and 14 years in the Kerbernez catchments (Brittany) (Martin et al., 2006). Further research by Chantal and colleagues confirmed the magnitude of previously estimated mean transit times while emphasizing their high uncertainties. They did this by i) using spectral analysis of stream-solute-concentration time series and gaseous tracers (CFCs and SF_6), in collaboration with Luc Aquilina (Univ. of Rennes 1), to calibrate a groundwater model (Molénat et al., 2013) and ii) applying a conceptual compartment-based model calibrated with long time series of solute concentration (Fovet et al., 2015). The results of these studies were in line with those of other studies of catchment transit times (e.g. (Kirchner et al., 2000; McGuire et al., 2002; Stewart and Fahey, 2010).

Chantal has also extensively studied the influence of groundwater dynamics on stream nitrate concentrations. She began from observations that stream water concentrations varied not only in the short term due to storm events but in the long term, at seasonal and annual scales. Understanding low-frequency variations requires understanding nitrate groundwater transfer and interactions between groundwater and surface water. One main advance of Chantal and colleagues was to develop a conceptual model based on the connectivity of hydrological compartments in a catchment to explain seasonal dynamics (Molenat et al., 2008). Stream nitrate concentration in most agricultural catchments with shallow groundwater was shown to follow an annual cycle, with the highest concentrations in winter and the lowest in summer (Aubert et al., 2013b; Martin et al., 2004; Molénat and Gascuel-Odoux, 2002). Meanwhile, a steady-state spatial distribution of nitrate concentration in groundwater, with a decreasing pattern from upslope to downslope, was revealed as a common characteristic of the two catchments in the AgrHys observatory (Martin et al., 2004; Molénat and Gascuel-Odoux, 2002). High nitrate concentrations in upslope areas behave as an infinite pool at the multi-annual scale (Ruiz et al., 2002). Chantal and colleagues showed that riparian zones, where the water table rises to the soil surface, are hot-spots of denitrification that result in nitrate concentrations near zero (section 3). With these elements, the concept of connectivity assumes that stream nitrate concentration depends on the connection of hydrological compartments (i.e. high-nitrate groundwater upslope, a nitrate-free riparian zone and low-nitrate deep groundwater), with the connection and disconnection of these compartments controlled by temporal dynamics of the groundwater level along the hillslope. Ocampo et al. (2006a, b) in the Susannah Brook catchment (Australia), and Wriedt and Rode (2006) in the lowland Schaugraben catchment (Germany) also demonstrated the ability of hydrological connectivity to explain variations in stream nitrate concentration. The connectivity assumption has also been confirmed since then by the study and modelling of long-term (> 10 years) stream nitrate concentration (Aubert et al., 2013a; Strohmenger et al., 2021). The connectivity concept has also helped guide the design of conceptual compartment-based models to explore the response of stream water quality to climatic and anthropogenic forcing (section 2.3).

2.2. Influence of riparian wetland dynamics on sediment and phosphorus transfer

Unlike nitrate, suspended sediments and P forms are transferred mainly via surface and shallow-subsurface flowpaths (Lefrançois et al., 2007; Vongvixay et al., 2010). Consequently, they are transferred mainly during short storm events, which implies specifically monitoring and analysing them during these events. Chantal and colleagues, particularly Catherine Grimaldi, analysed the shape and direction of concentration-discharge hysteresis loops to differentiate events with a proximal source (in- or near the stream: clockwise hysteresis) from those with a more distal source along the hillslope (anticlockwise hysteresis). In a grassland catchment in which cattle had access to the stream, Lefrançois et al. (2007) showed that suspended sediments originated mainly from the stream channel and banks, either by hydraulic erosion or cattle trampling. The high seasonal availability of suspended sediments during the grazing season (Lefrançois et al., 2007) and the sharp decrease in suspended-sediment fluxes after construction of watering troughs (Vongvixay et al., 2018) confirmed the crucial role of bank degradation by cattle in the suspended-sediment dynamics of this catchment. In contrast, an arable catchment with supposedly higher potential for hillslope erosion but the presence of woody vegetation or grass buffer strips along the stream had one-fifth the suspended-sediment fluxes (Vongvixay et al., 2018). In this catchment, stream protection limited the delivery of eroded soil from arable fields during most (but not the largest) storm events.

Chantal and colleagues' research on suspended sediment paved the way for research on particle-associated contaminants, specifically forms of P. Results for the Kervidy-Naizin catchment showed, however, that a large percentage of P (13-48% of annual load) is transferred in dissolved forms (Minaudo et al., 2017) and that storm dynamics of dissolved P are not synchronous with those of particulate P (Dupas et al., 2015b). Dupas et al. (2015b) concluded that particulate and dissolved P forms have different spatial origins in the landscape and are transferred by different mechanisms. Particulate P originates from resuspension of streambed sediments, bank erosion and occasionally from erosion on hillslopes. In contrast, dissolved P originates from riparian soils when fluctuations in the shallow groundwater level connect them to the stream. Monitoring P concentration in the soil water of the riparian zone revealed that alternating dry and wet phases in these zones fosters P solubilisation (Dupas et al., 2015c). It is therefore essential not to rely only on riparian buffers to limit P transfer to streams, as the P that they retain may be remobilized. Management efforts should therefore limit erosion at its original source, place buffer features (e.g. grass strips, hedgerows) upslope of riparian wetlands and extract P from these hydrologically connected zones (Dupas et al., 2017).

2.3. Development of an integrated conceptual model of solute and particulate transfer in headwater catchments

In the 2010s, Chantal and colleagues have developed conceptual models of solute and particulate transfer in agricultural headwater catchments that went beyond earlier disjointed work on nitrate and phosphorus exports (Gascuel-Odoux et al., 2018). The work relied strongly on long-term and high-frequency monitoring of the concentrations of multiple constituents in the Kervidy-Naizin catchment (i.e. daily since 2000 and, for several parameters, sub-hourly since 2011) (Fovet et al., 2018b). Water-quality monitoring at the outlet of the 5-km² catchment is supplemented with measurements in several other environmental compartments, such as the soil, groundwater and atmosphere. To interpret these data, Chantal and colleagues conceptualized a catchment as a set of compartments, each with static chemical signatures (Aubert et al., 2013b). Concentration dynamics at the outlet are then conceptualized as a mixing of compartment contributions (Figure 3). To add complexity, one can also consider dynamic chemical signatures, when biogeochemical reactions or agricultural management modifies concentrations (Aubert et al., 2013a). Chantal and colleagues have applied this representation of a catchment to develop perceptual models, formal end-member-mixing analyses (Durand and Juan Torres, 1996) and FLEXIBLE mixing reservoir models (Fovet et al., 2015; Hrachowitz et al., 2014; Strohmenger et al., 2021).

In addition to dividing a catchment into compartments, Chantal and colleagues also divided time into characteristic time scales: long-term (multi-annual), seasonal (intra-annual) and storm events, e.g. (Strohmenger et al., 2020). While environmental studies often aggregate data at different time scales, she has specifically focussed on interactions between time scales. For example, (Aubert et al., 2013b) showed that seasonal cycles of nitrate, chloride, sulphate, dissolved organic C (DOC) and dissolved inorganic C depended on each year's mean weather conditions (hot/cold vs. dry/wet). Martin et al., (2004) showed that seasonal nitrate cycles can even reverse (i.e. winter maxima become summer maxima) due to a catchment's recovery from high N inputs. Another example of interaction between time scales is the analysis and interpretation of how storm-event dynamics vary among seasons. Aubert et al. (2013c) used Latent Dirichlet Allocation models and showed that storm dynamics of four solutes (i.e. nitrate, chloride, DOC and sulphate) depend on antecedent hydrological conditions. Dupas et al. (2015d) used dynamic time warping techniques and showed that P-transfer dynamics during spring storms differ from those during autumn and winter storms, highlighting the risk of incidental P losses after spreading animal waste in spring. More recently, Fovet et al. (2018a) showed that storm-event dynamics of nitrate and DOC during autumn rewetting of the catchment differ from those during the rest of the year; they attributed this difference to contributions of riparian wetlands in autumn. Along with these methods, Chantal and colleagues also used frequency analysis, which showed that the fractal scaling of water quality observed in forested catchments can also be observed in intensive agricultural catchments (Aubert et al., 2014).

In addition to studying individual chemical elements in a disjointed manner, Chantal played a pioneering role in developing joint conceptual models C-N-P cycles and their interactions in agricultural landscapes. This evolution from a focus on nitrate (section 2.2) to coupled C-N-P cycles accompanied a change in water managers' concerns from drinking water production (often with nitrate standard not being met) to reaching a good ecological status of surface water in contexts with a high risk of eutrophication (Le Moal et al., 2019). Joint understanding of C-N-P cycles and transfer is crucial to understand how the concentration of each element is controlled by that of the others and how their relative concentrations influence aquatic ecosystems. This work is also motivated by the necessity to identify potential risks of pollution swapping when dealing with one element without considering the others. Strohmenger et al. (2020) showed that dynamics of nitrate and DOC concentrations are opposite at annual, seasonal and storm-event scales, while P dynamics are independent of those of the other two. The ratios of pairs of elements may vary more when dynamics of the elements are asynchronous or out-of-phase and vary less when their dynamics are in-phase. Guillemot et al. (2021) confirmed these results using data from 180 headwater catchments in Brittany and found that the temporal opposition between nitrate and DOC (and the independence of P) is also spatially valid across Brittany. Minaudo et al. (2019) also found temporal opposition between nitrate and forms of P at the seasonal and storm-event scales, and attributed it to different dominant sources for both nutrients: diffuse sources for N and a combination of diffuse and point sources for P.

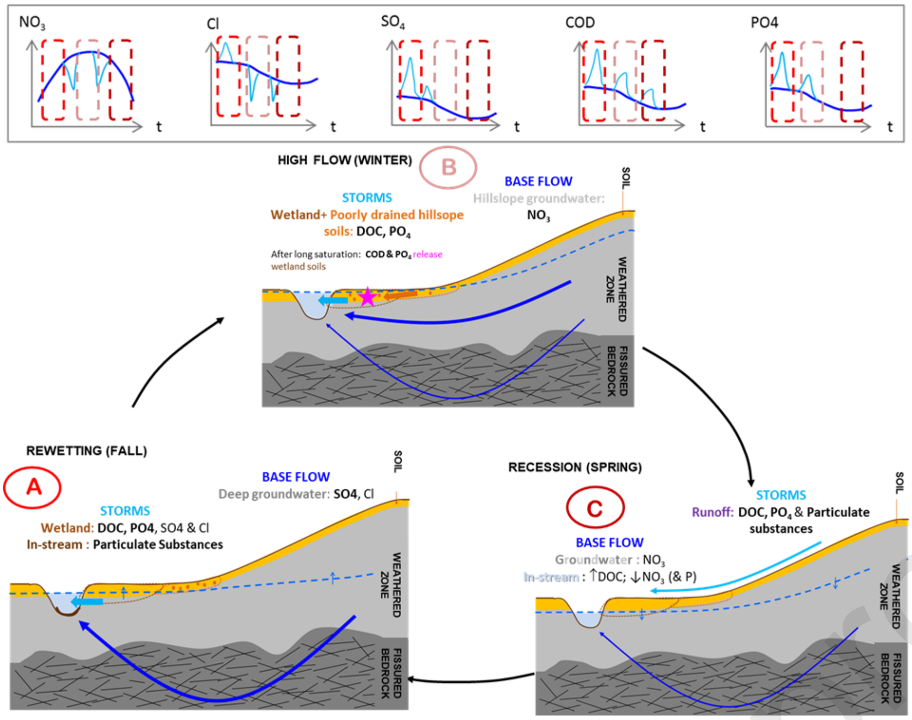

Figure 3. A conceptual framework for carbon, nitrogen and phosphorus transfer in headwater catchments during baseflow and stormflow conditions, developed by Chantal Gascuel-Odoux and colleagues. Inspired by Fovet et al. (2018a) (modified).

2.4. Retrospective and prospective analysis of the influence of climate on water quality

The influence of climate change on surface water quality in agricultural catchments greatly concerns the scientific community and water managers. Analysis of 16 years of meteorological data from the Kervidy-Naizin catchment revealed an increase in temperature but no overall trend in annual discharge, although winters tended to become wetter and summers tended to become drier (Strohmenger et al., 2020). These observations of recent trends are consistent with predictions of climate models for the region, although the predicted trend in annual rainfall is uncertain (Mérot et al., 2014). Predicting responses of hydrological systems to these changes is challenging due to the complexity of the processes involved, the many feedback loops that exist and potential interactions with changes in land management (Blöschl et al., 2019).

Chantal's contributions to understanding the influence of climate variability on water quality have relied mainly on retrospective analysis of long-term monitoring data (Dupas et al., 2018; Gascuel-Odoux et al., 2010a; Mellander et al., 2018; Strohmenger et al., 2020). Disentangling the influence of climate from that of changes in land management is especially challenging, especially for regions whose agriculture has changed greatly the past several decades (Dupas et al., 2016; Strohmenger et al., 2020). Using public water-quality data from Brittany, Gascuel et al. (2010a) and Dupas et al. (2018) highlighted the existence of mesoscale (2-6 year) variations in discharge that drive synchronous variations in nitrate concentrations and fluxes (Figure 4). Here, discharge is taken as an integrative indicator of several climatic variables: rainfall and evapotranspiration, itself influenced by temperature. These mesoscale variations may mask improvements in land management in certain years or exaggerate these improvements in other years; thus, water quality must be observed for more than 5-10 years to reliably assess effects of improved land management on water-quality trends.

In addition to analysing public data, monitoring research catchments provides both more variables and a higher temporal resolution. Using high-frequency nitrate and P concentration data from France, Ireland and Norway, Mellander et al. (2018) hypothezised a connection between the North Atlantic Oscillation (NAO) index and nutrient concentrations. The index's influence (positive or negative) varied among catchments and often differed between nitrate and P. Because these data were available only during an upward trend in the NAO index (2010-2016), future analysis should cover several cycles of the index. Piazza et al. (2018) observed similar connections between inter-annual variations in anion concentrations and the El Niño-Southern Oscillation (ENSO) index in nested catchments of the subtropical zone. In contrast, the data analysis of Strohmenger et al. (2020) considered several hydroclimatic variables instead of a single integrated variable such as discharge or the NAO or ENSO index. Their results highlighted the joint influence of changes in climate and land management on long-term trends in nitrate (decreasing), P (decreasing) and DOC (increasing). They also highlighted effects of extreme climatic conditions, whose frequency is predicted to increase, such as flushing episodes with high DOC concentration after a long summer drought or a disproportionate influence of large storm events on P transfer.

Finally, Chantal also participated in prospective studies that used the integrated agro-hydrological model TNT2 (Salmon-Monviola et al., 2013) (section 3.1). Salmon-Monviola et al. (2013) simulated the influence of temperature, rainfall and increased atmospheric carbon dioxide on water and N cycles in the Kervidy-Naizin catchment, and highlighted the importance of understanding how the functioning of riparian wetlands would respond to climate change. Overall, the synergetic effect of increasing temperature, decreasing rainfall and increasing carbon dioxide concentration is predicted to decrease N loads in the catchment's stream, but uncertainties remain about how farming practices will respond to climate change (and other incentives) and then interact with the direct effects of climate change to influence water and N cycles.

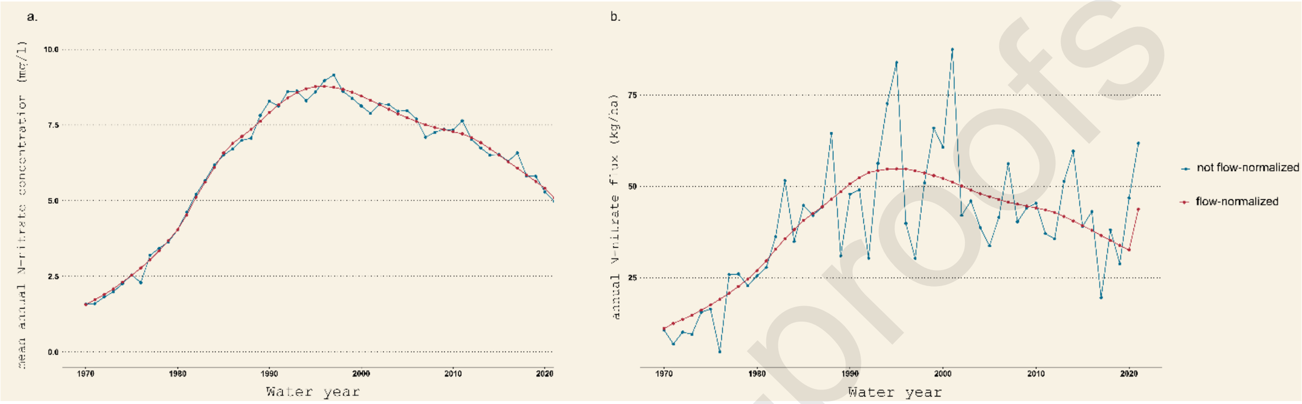

Figure 4. Long-term (1970-2021) mean and flow-normalized mean annual nitrate concentration (a) and flux (b) at the outlet of the Elorn catchment, western France (260 km²). The data was obtained through WRTDS modelling with monthly data of concentration monitoring and daily discharge (Hirsch et al., 2010). The gap between the mean and flow-normalized mean estimations of concentrations or fluxes shows the influence of 5-10 years interannual climatic variations, which may interfere with the estimation of long-term trends when using too short time-series. This figure is inspired by Gascuel-Odoux et al. (2010a).

3. Integrating hydrology into the design of integrated approaches to landscapes and territorial management

Several projects that Chantal has conducted investigate how understanding hydrological processes can contribute to environmental management in agricultural areas. In the late 1990s, many studies reported degradation of water resources, and her research aimed to assess impacts of agriculture on water quality. Later, her research moved from impact assessments toward the design of sustainable rural landscapes, in a context in which the global environmental situation had become alarming (Caquet et al., 2020a). Indeed, the need to act became urgent (IPBES, 2019;

IPCC, 2014) and challenged the scientific community to provide evidence-based contributions to sustainable societal development in a changing environment (Montanari et al., 2013). In this context, a “territory”, as a geographic area and its relevant physical and societal dimensions, is relevant for considering interactions among different agricultural systems, cultivated and uncultivated areas, and agricultural and non-agricultural stakeholders (Gascuel and Magda, 2015; Peyraud et al., 2015). This section illustrates Chantal’s contributions to the management of agricultural areas, from assessing impacts on water bodies to designing landscapes.

3.1. Integrating hydrology with other disciplines

Some researchers see hydrology as a single holistic discipline, while others see it as a group of distinct sub-disciplines (Baveye, 2011). In recent years, hydrology has evolved towards more interdisciplinary perspectives (McCurley and Jawitz, 2017) to address complex scientific questions, such as those raised by Critical Zone science (Brantley et al., 2017; Gaillardet et al., 2018), and current challenges, such as the water-energy-food nexus (Montanari et al., 2015; Wagener et al., 2010). Through collaborations, Chantal has contributed actively to developing broad understanding of hydrological processes. The research conducted within these collaborations has related agricultural practices to water quality at catchment outlets and highlighted the need to combine thorough understanding of catchment hydrology with that of agricultural systems.

For example, she worked with a local Chamber of Agriculture to assess, based on field experiments, effects of maize-cropping techniques (e.g. a mixed weeding strategy, no-tillage) on herbicide transfer by surface runoff. Results showed that compared to conventional chemical weeding, a mixed weeding strategy reduced herbicide concentrations by ca. 75% and fluxes by up to 90%. They also observed that no-tillage increased soil infiltrability by a factor of 5-10, which greatly reduced surface runoff and herbicide transfer (by up to 90%) compared to those of conventional tillage (Heddadj and Gascuel, 2001). To explore agricultural practices to reduce N transfer to streams, Chantal helped Patrick Durand (INRAE) and other colleagues develop integrated agro-hydrological models (Moreau et al., 2012). Whereas field experiments are complex and costly, particularly at the landscape level, integrated modelling can predict whether changes in agricultural practices are likely to reach a targeted reduction in nitrate concentrations in groundwater or streams. They used the spatially distributed agro-hydrological model TNT2 (Beaujouan et al., 2001), which couples a crop model (Brisson et al., 1998) with a hydrological model (based on Topmodel (Beven, 1997)) to predict the ability of introducing cover crops (i.e. fast-growing crops that are grown between successive main crops) to reduce N losses at the catchment scale (Durand et al., 2015).

Agro-hydrological models, especially spatially distributed models, generate a large amount of spatio-temporal data of various formats and semantics. Due to technological barriers that prevent efficient data processing, only daily flux and concentrations at the catchment outlet are usually analysed, even though higher temporal or spatial resolutions may be simulated. Thus, tools are needed to store, display and analyse this spatio-temporal information and turn it into useful knowledge that helps understand agro-environmental systems and adaptations to meet environmental targets. To address this issue, Chantal worked with computer scientists, in particular Marie-Odile Cordier (INRIA, France), to investigate the use of innovative machine-learning techniques with data simulated by such models and extract knowledge about complex rural landscapes. Symbolic-learning techniques helped them identify spatial patterns of herbicide sinks or sources and factors that explained herbicide transfer along the river network (Trépos et al., 2012, 2013). Chantal and colleagues also developed a data warehouse to analyse output of the process-based model using online analytical processing (Bouadi et al., 2017). Using this approach enabled quantifying impacts of agricultural practices on N emissions at multiple spatio-temporal scales by providing relevant ways to identify and analyse where and why N pollution occurs in a catchment.

3.2. Integrated catchment modelling

Chantal has co-led several projects to develop integrated models designed to support the management of rural areas. Using these models has facilitated dialogue among local stakeholders around land-management scenarios, for example by exploring ex-ante simulations of impacts of changes in agricultural practices on water quality (Gascuel and Magda, 2015). One main innovation of Chantal and colleagues has been to consider both farming and biophysical systems and their interactions in their modelling approaches to encompass the entire causal chain from farming activities to water pollution and to find ways to adapt farming systems to environmental objectives.

With computer scientist Frederic Garcia (INRAE), Chantal led a study of interactions between farmers' technical decisions and biophysical systems in the development of the decision-oriented Sacadeau model (Gascuel-Odoux et al., 2009; Salmon-Monviola et al., 2011). By predicting sources of water pollution by maize herbicides, Sacadeau aims to help decision-makers decrease water pollution at the catchment level. Sacadeau combines a farmer-decision submodel based on technical and environmental conditions developed with agricultural experts, a temperature-based crop-phenology submodel and a submodel of water and chemical transfer within agricultural catchments. In the transfer submodel, Chantal developed an innovative approach to modelling surface drainage networks that determines surface water connectivity by considering the topography between and within farm fields, hedgerows, roads and ditches (Aurousseau et al., 2009; Gascuel-Odoux et al., 2011). This "landscape drainage network" considers both farming systems and landscape features, unlike a traditional drainage network extracted from DEM data alone. The spatial representation based on this landscape drainage network has been useful for assessing effects of land use, agricultural practices and the landscape on herbicide contamination of stream water.

Many biophysical models, such as SWAT (Arnold et al., 1998), SHETRAN (Birkinshaw and Ewen, 2000), TNT2 (Beaujouan et al., 2001, 2002) and DNMT (Liu et al., 2005), operate at the catchment scale and simulate effects of agricultural practices on N transfer and transformation. However, they do not represent consistent farming systems because they do not explicitly represent farmer decisions. This is particularly critical for mixed farming systems, in which processes such as fodder production and manure spreading of cropping and livestock systems are closely related. In other words, when a model simulates large changes in the cropping system, there is no guarantee that it will simulate production of enough forage for animals or that the amount of manure applied in the model will equal the amount of manure produced (Durand et al., 2015). To address this gap and assess effects of different dairy farming systems on catchment N dynamics, Patrick Durand, Chantal and colleagues developed the Casimod'N model (Figure 5), which couples a farmer-decision model with the TNT2 model (Moreau et al., 2013). Casimod'N simulates farming systems explicitly through production strategies and farmer decisions, and translates these decisions into management practices. Representing these strategies when simulating management practices ensures that i) simulated fodder production matches livestock-feed requirements, ii) livestock-feeding and manure-management strategies are consistent with each other and iii) specific farm constraints (e.g. distances between fields) are met. Applying Casimod'N to the Yar catchment (Brittany) in a project co-led by Chantal and Laurent Ruiz (INRAE) demonstrated that such models can be powerful and relevant tools to redesign farming systems (Durand et al., 2015; Gascuel et al., 2015; Moreau et al., 2013). Here, she made a decisive contribution by building a multidisciplinary research group.

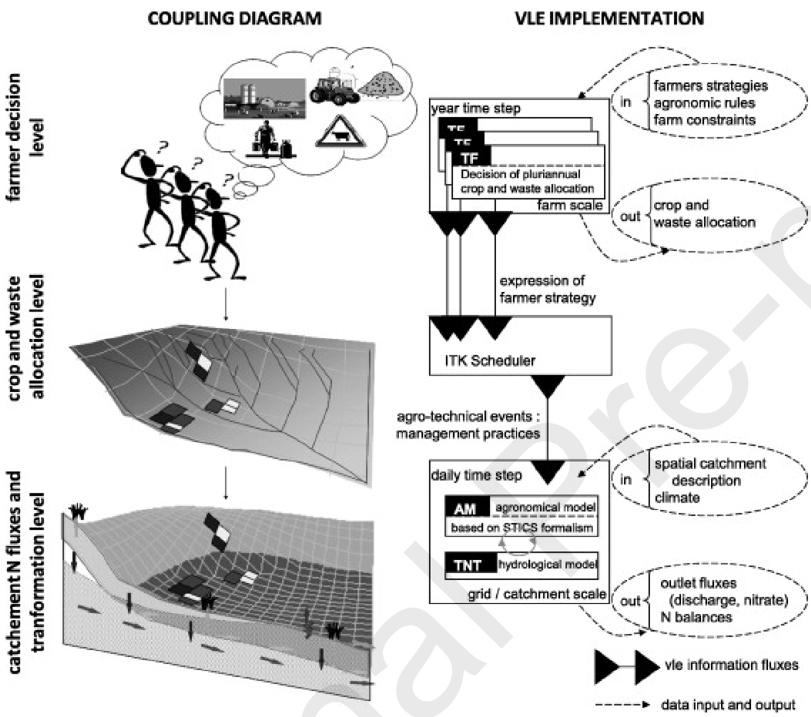

Figure 5. Diagram of the CASIMOD'N model and its implementation in the Virtual Laboratory Environment (VLE) CC-BY-CA Moreau et al. (2013)

3.3. Integrating hydrological sciences with non-academic stakeholders

The international research agenda of the 2000s and 2010s, as described in the Prediction in Ungauged Basins (Hrachowitz et al., 2013) and Panta Rhei (Montanari et al., 2013) initiatives, challenged the scientific community to make progress in transferring knowledge about well-known research sites to poorly gauged, monitored or documented catchments for which societal issues are strong. In accordance with this agenda, Chantal co-led several projects to conceptualize farming systems in catchments affected by water pollution. In these projects, scenarios of agricultural practices at farming-system and catchment scales were co-built with local non-academic stakeholders from the agricultural and/or water-management sector. This co-building allows future scenarios to be explored, while the integrated models described previously (section 3.2) can predict impacts of these scenarios on water resources.

To develop the decision-oriented Sacadeau model (Gascuel et al., 2009; Salmon-Monviola et al., 2011), the farmer-decision submodel that represents farmers' constraints and strategies was built first, in collaboration with advisers from the Brittany Chamber of Agriculture. Their expertise enabled definition of decision rules for crop sowing and weeding strategies and their distribution among fields. Then, different symbolic-learning techniques were applied to model predictions to identify situations that would decrease water pollution by herbicides and make sense for stakeholders (Trépos et al., 2012).

In the ACASSYA project, researchers worked with local stakeholders to reconcile agriculture – especially dairy farming – with coastal activities in areas affected by coastal eutrophication (Gascuel et al., 2015). Thus, researchers, farmers, local authorities and environmental managers co-built knowledge about current and future dairy farming systems to design new systems compatible with the vulnerability of downstream ecosystems. The project combined virtual experiments conducted with the Casimod'N model (Moreau et al., 2013) with field experiments on pilot farms. Results showed that co-building knowledge required "on-going dialogue, reflexivity, and long-term involvement by researchers" (Levain et al., 2015). Using integrated models that couple farmer-decision, crop and hydrological models enabled stakeholders to discuss and adopt scenarios (Durand et al., 2015; Gascuel et al., 2015; Moreau et al., 2013).

3.4. Making scientific knowledge accessible and relevant for water and environmental managers

Chantal has promoted the development of methods to improve water management that are scientifically sound and operational. For example, considerable effort was made to transfer knowledge about critical source areas of pollutants into a decision support tool called Territ'eau (Gascuel-Odoux et al., 2011; Gascuel et al., 2009). Territ'eau helps stakeholders define action plans that include changes in agricultural practices and systems as well as restoration and preservation of semi-natural areas in rural landscapes.

At the end of the 1990s, as agriculture continued to intensify and landscape features such as the functional role of landscape features as potential buffer for diffuse pollution (Dorioz et al., 2010; Gascuel-Odoux et al., 2011; Gascuel et al., 2008). Chantal helped identify landscape features that can serve as a buffer of diffuse N and P pollution. She helped develop pioneer approaches for predicting and mapping these landscape features and assessing their effectiveness as buffers (section 1.2). For example, modifying the topographic index by considering downslope topography enabled prediction of wetland extents in hydrosystems controlled by subsurface groundwater (Gascuel et al., 1998). Later, Mérot et al. (2006) used this modified index to develop the PEEW method for wetland management that decision-makers and local managers can apply directly.

4. Contributing to public policies and public debate

Chantal has also contributed to non-academic publications that involved hydrology and that were intended to guide public policy-makers and local water managers, as well as contribute to public debate. They are examples of how hydrological research can help address human-induced societal issues (Montanari et al., 2015; Wagener et al., 2010).

4.1. Contributions to joint scientific assessments

In France, Ministries can request joint scientific assessments on any subject which summarize validated scientific knowledge in response to a complex question related to a strong and urgent societal issue. In them, a group of experts analyses the international scientific literature to inform public debate about the given question. Chantal contributed to the joint scientific assessment “Pesticides, agriculture and the environment: reducing the use of pesticides and limiting their environmental impact” (Aubertot et al., 2007), which updated knowledge about and data on agricultural use of pesticides, their contamination of environmental compartments and impacts on non-target organisms and ecosystems. Chantal specifically contributed to the chapters related to hydrological transfers (i.e. buffer zones, transfer indices and models), examining pesticide drift in the environment and discussing crop management strategies and spatial configurations to reduce it. Chantal co-led another joint scientific assessment entitled "Causes, mechanisms, consequences and predictability of eutrophication phenomena" (Le Moal et al., 2019; Pinay et al., 2018) that highlights the general increase in N and P fluxes to oceans and agriculture's increased contribution to them during the 20th century. To predict eutrophication risk, nutrient transfer and transformation processes need to be considered along with climatic variability and ecological vulnerability of downstream ecosystems. Control strategies can occasionally use engineered nutrient-removal techniques but will first require source reduction.

4.2. Tools and expertise for public water policies

Chantal led several national studies to help the French National Office for Water and Aquatic Environments (ONEMA from 2006-2016, now merged with other agencies into the National Office for Biodiversity) report to the European Commission regarding French objectives of the Water Framework Directive. These studies harmonized methods for estimating N and P emissions to all French rivers. The methods are based on the Nutting model (NUTrient Transfer modelllNG), which uses a statistical approach to estimate nutrient loads from multiple variables, including N and P surpluses and catchment characteristics. Dupas et al. (2013) compared national and regional calibrations of the Nutting-N model in two regions of France. Regional models generally showed better fit but larger uncertainty in parameter estimates when the calibration data did not include enough catchments or variability in land and river characteristics. Dupas et al. (2015a) estimated that 53% of the soil N surplus and 95% of the P surplus is retained and that this apparent retention is driven by annual runoff and hydrological connectivity, respectively.

4.3. Contributions to scientific resource centres

Chantal took an active role in creating a resource centre with the National Office for Water and Aquatic Environments for Drinking Water Protection to help local authorities design more ambitious and effective action plans for managing water resources (Menard et al., 2014). This resource centre aims to facilitate coordination among stakeholders and to disseminate documents and methods. It provides case studies in which (i) outputs from biophysical models are presented to stakeholders, as in Dupas et al. (2015a), and (ii) local experts identified the critical role of crop rotations, especially the periods between main crops, via participatory modelling. Another resource centre called Creseb (Resource and Expertise Centre for Water in Brittany) was created in 2011 to transfer up-to-date scientific knowledge to local and regional water managers. Chantal was President of its scientific and technical board for four years. During this period, she promoted the topics of hydromorphology, diffuse agricultural pollutants, floods and support for transitions in territorial projects.

Conclusion

As a researcher, team leader, unit director and deputy scientific director of a national research institute, Chantal Gascuel-Odoux has successfully led several careers at once. We have traced and summarized Chantal's vision, objectives and achievements over the past 40 years, essentially limiting the article to the field of water sciences, in relation to the scope of the *Journal of Hydrology*. Nevertheless, Chantal's interdisciplinary approach also led her to conduct important research in soil science and agronomy. Furthermore, she has conducted her research along with collective institutional responsibilities at the national level. In doing so, Chantal has gained national and international recognition within the hydrology community. Her contribution to agricultural research and development in France was recognized in 2014 when she was awarded the rank of "Knight of the Legion of Honour", the highest French order of merit.

We also want to emphasise Chantal's human qualities. Guided by a strong sense of collective work and driven by a clear idea of what science, and public research in particular, must provide to society, Chantal has always been attentive and benevolent towards her mentees and all of the colleagues, students, technicians, engineers and researchers with and for whom she has worked.

Chantal has helped define the directions of future research in landscape agroecology necessary to design sustainable agricultural systems. She has paved the way for young researchers to conduct high-quality research that meets societal needs. The relative effects of human activities and the climate on C-N-P cycles and the eutrophying impacts of major contaminants on aquatic ecology are among the research fields that Chantal has opened up and that we will be exploring in the years and decades to come.

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- Career contributions of Chantal Gascuel-Odoux in hydrology, soil science and agronomy
- Influence of soil and subsoil properties on hydrological processes
- Water, solute and particulate transfer at the catchment scale
- Design of integrated approaches to landscapes and territorial management
- Contributions to public policies and public debate