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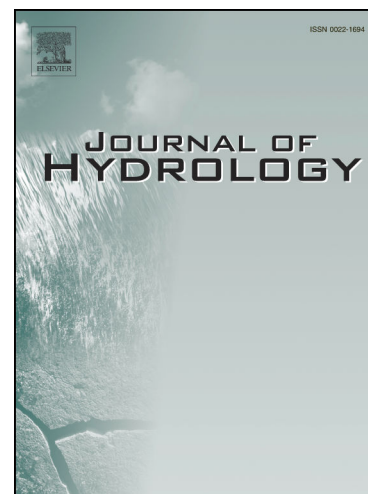
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1 **A French hydrologist's research for sustainable agriculture**

2

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13 Abstract

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

21 Introduction

22 As a hydrologist at the French agricultural research institute INRAE¹, Chantal Gascuel-
23 Odoux has always conducted research with an interdisciplinary dimension, embedded
24 in environmental sciences. In her research, hydrology intersects most often with soil
25 science and agronomy, the disciplines of her closest colleagues at her research unit,
26 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.

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

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

47 When Chantal started her career in the mid-1980s, publishing in English in
48 international journals was not an obvious choice for French researchers. It is
49 noteworthy that her first international article was published in French in the *Journal of*
50 *Hydrology*, before English became the dominant language of global scientific
51 communication (Gascuel-Odoux and Mérot, 1986)! Chantal was one of the first
52 researchers at SAS to disseminate her research in English, and we consider her
53 responsible for the internationalization of the unit, first as a researcher and then as unit
54 director. Subsequently, Chantal and her colleagues increasingly published their
55 research in international journals, including the *Journal of Hydrology*. The
56 internationalization of her research also led her to participate in European research
57 projects (e.g. COST actions) and to co-author many articles with international teams,
58 mainly in European countries facing similar problems with diffuse agricultural pollution,
59 such as the United Kingdom (UK), Ireland and the Netherlands. Her international

60 research career is also marked by two scientific visits, one to the French National
61 Research Institute for Sustainable Development (IRD) in Dakar, Senegal (1991-1992),
62 and the other to the University of British Columbia, Vancouver, Canada (2006-2007).
63 The Ph.D. students that Chantal supervises are certain to have the opportunity for a
64 short-term scientific visit to a foreign country to broaden their horizons!

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

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



87

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

90 1. Influence of soil and subsoil properties on hydrological processes

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

103 1.1. Spatial variability in infiltration and runoff

104 At the beginning of her career (including her PhD research 1981-1984), Chantal
105 investigated spatial variability in runoff and water infiltration at the field scale.
106 Knowledge of the spatial variability in soil physical properties was required to address
107 several agricultural issues, such as wetland preservation in agricultural areas. Three
108 main objectives governed her studies in this field: (i) quantifying spatial variability, (ii)
109 analysing correlation(s) between hydrological and soil factors and (iii) producing soil
110 maps. Chantal and colleagues used geostatistics and isotopic tracer methods such as
111 ^{18}O to study water movement, soil water content (Gascuel-Oudoux and Mérot, 1986),
112 soil properties (Gascuel-Oudoux, 1987; Gascuel-Oudoux and Merot, 1991) and the
113 rainfall rate (Mérot et al., 1989). Starting from in-situ measurements and sampling, both
114 methods improved mapping of water movement and soil characteristics (Gascuel-
115 Oudoux and Boivin, 1994; Gascuel-Oudoux et al., 1991). Chantal has promoted the use
116 of geostatistics to define appropriate strategies for soil sampling and the spatial
117 resolution of in-situ measurements. Chantal and colleagues also conducted early
118 research on the ability of a helicopter-borne C-band scatterometer radar to map the
119 extent of saturated areas (Brun et al., 1990). In particular, they demonstrated benefits
120 of using ERS-1 synthetic aperture radar backscatter to map these extents (Mérot et
121 al., 1994). These studies paved the way for using remote sensing to map saturated
122 areas and to limit parameter ranges of uncertainty in hydrological models such as
123 Topmodel (Franks et al., 1998).

124 With a fine knowledge of soil properties, Chantal and colleagues have used several
125 approaches to study runoff generation in rural contexts. From in-situ measurement of
126 overland flow in an agricultural field, they identified local microtopography, soil crusting
127 and the spatial distribution of soil patches with high hydraulic conductivity as the main
128 factors that control runoff (Gascuel-Oudoux et al., 1996). From experiments and
129 computer modelling, they showed that flow-path connectivity at the square-meter scale
130 depends on the ratio of the mean slope to random roughness, which controls transfers
131 within the soil surface and may change significantly over time during a storm event
132 (Darboux et al., 2002). While runoff may be triggered on the upper part of hillslopes,
133 sheet flow is low, and the runoff coefficient decreases as the slope length increases.
134 Infiltration and soil deposition are particularly active in concave parts of hillslopes,
135 regardless of the characteristics of storm events, and are enhanced by hedgerow

136 networks (Mérot et al., 1999). This result contradicts the intuitive model of downstream
137 amplification of runoff through aggregation in the drainage area. It also supports the
138 assumption of a threshold of spatial scale at which to define the head of channel
139 networks, at least in temperate regions such as Brittany. After this major observation,
140 Chantal and colleagues worked to improve maps of surface-flow connectivity using
141 digital elevation models (DEMs) by representing the influence of hedgerows and field
142 networks on the drainage area (Aurousseau et al., 2009; Gascuel-Odoux et al., 2011;
143 Tortrat et al., 2003).

144 1.2. Riparian wetland mapping

145 Because riparian wetlands in agricultural landscapes strongly influence hydrology,
146 water quality and biodiversity, their degradation in intensive agricultural landscapes is
147 of great concern. To address the need for reliable wetland mapping, Chantal and
148 colleagues developed a hydrological typology of wetlands (Durand et al., 2000; Mérot
149 et al., 2006). First, potential wetlands are defined by soil properties and topographic
150 data that can be derived from available databases and DEMs. Second, existing
151 wetlands are mapped from in-situ observation of soil water content and wetland
152 vegetation. Third, effective wetlands are defined for a variety of ecosystem services
153 related to hydrology, water quality and biodiversity. Mapping these three types of
154 wetlands requires different levels of investigation effort. This study was the basis for
155 the inventory of valley-bottom wetland maps currently used in Brittany (Gascuel et al.,
156 2009) and for the PEEW (Potential, Existing and Effective Wetlands) method, which
157 provides a framework for organizing knowledge about wetland management (Mérot et
158 al., 2006).

159 1.3. Characterization and modelling of shallow groundwater

160 Since the 1990s, Chantal and colleagues have assessed the ability of hydrological
161 models to predict spatial variability in groundwater levels in catchments. Attracted by
162 Topmodel's ability to capture with elegant simplicity the dynamics and dominant
163 controls of shallow groundwater hydrology in a semi-distributed form (Beven et al.,
164 2020), they considered this model as a reference. This led Chantal to collaborate with
165 Keith Beven to conduct one of the first studies of the influence of temporal and spatial
166 resolutions on model parameterization and simulations (Bruneau et al., 1995).

167 Specifically, she worked to determine the appropriate modelling approach for
168 predicting dynamics of the water table and stream runoff simultaneously in catchments
169 dominated by saturated subsurface flow (Gascuel-Oudoux et al., 2010b; Martin, 2003;
170 Martin et al., 2006; Molenat, 1999; Molenat et al., 2005). Chantal has always been
171 convinced that the spatial distribution of shallow groundwater must be predicted well
172 to simulate matter fluxes and travel times in catchments (section 2). Furthermore, she
173 showed that groundwater is the main component of stream flow during both base flow
174 conditions and storm events (Gascuel-Oudoux et al., 1999; Molénat et al., 1999). Her
175 research has made good use of the number and quality of water-table records in the
176 catchments of the AgrHyS observatory (“Agro-Hydro Systems”, Gascuel-Oudoux et al.,
177 2018). High-frequency records (< 1 h) from wells on transects extending down
178 hillslopes provided the data necessary to analyse the ability to simulate spatio-
179 temporal dynamics of shallow groundwater. In this regard, Topmodel’s assumptions
180 appear to work well for simulating stream flow and the water table in valley bottoms
181 but less well for simulating midslope and upslope areas. Relaxing two of Topmodel’s
182 assumptions – steady-state spatial subsurface flux and topographic assumptions –
183 significantly improve water-table simulations for these two areas (Molenat et al., 2005).
184 The question is then how much the representation of geometry (e.g. depth, thickness)
185 of the soil and subsoil, as well as the hydraulic properties of groundwater systems, can
186 be simplified while still achieving acceptable simulations of the water table, transit time
187 and solute fluxes. Spatial simulations of the water table were less sensitive to the
188 geometry of the subsoil than to the spatial distribution of hydraulic conductivity (Martin
189 et al., 2006). Consequently, Chantal analysed the relevance of considering
190 homogeneous hydraulic geometry (i.e. soil and subsoil thickness and depth) and
191 properties (e.g. hydraulic conductivity, drainable porosity). Using the HillVi model
192 (Weiler and McDonnell, 2004), she demonstrated that considering lateral variations in
193 hydraulic properties along the hillslope improves the spatial prediction of water tables
194 only slightly (Gascuel-Oudoux et al., 2010b). She concluded that i) there is some
195 incommensurability in comparing point observations to grid-averaged predictions and
196 ii) improving spatial simulations of water table requires fitting local transmissivity to
197 local water-table observations, which would require acquiring these observations.

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

199 Since the early 1990s, Chantal's research has focussed mainly on water, solute and
200 particulate transfer in agricultural catchments. She has considered the understanding
201 of processes that underlie these transfers as a key scientific challenge to preserve
202 and/or restore water quality in the face of high agricultural pressures and climate
203 change. In the context of the severe nitrate contamination of water that western France
204 was experiencing, Chantal advanced knowledge of the nitrogen (N) cycle and nitrate
205 transfer at the catchment scale. However, as water quality should be evaluated as a
206 whole, she collaborated with other colleagues, especially Gérard Gruau (CNRS,
207 France), Catherine Grimaldi (INRAE, France) and Aline Dia (CNRS, France), to
208 extended the study of matter transfer to carbon (C), P and suspended sediments. They
209 soon perceived the need for long-term and spatially distributed hydrological and
210 concentration time series, associated with the observation of agricultural practices. To
211 this end, she actively contributed to the development of the AgrHys research
212 observatory in Brittany (Figure 2; Fovet et al., 2018b). This long-term observatory has
213 focused since 1992 on headwater catchments (Kervidy-Naizin 5 km² and Kerbernez,
214 1.2 km²), and characterized by hard rock aquifers, an oceanic climate, and dominance
215 of agricultural land uses devoted to animal farming. The AgrHyS observatory is
216 dedicated to the investigation of the biogeochemical response times of catchments to
217 variations in climate and agriculture, with a focus on the following elements: water,
218 nitrogen, carbon and phosphorus. Chantal has (co-)supervised 11 PhD thesis that
219 have analyzed AgrHys observational data from (Gascuel-Oudoux et al., 2018). To
220 promote the observatory, develop scientific collaborations and investigate scientific
221 questions over a wider range of hydroclimatic conditions, Chantal has worked to
222 integrate the observatory into a national (OZCAR; (Gaillardet et al., 2018) and a
223 European network (eLTER). Through collaborations, her research has also benefited
224 from observations from research catchments outside of France (e.g. Ireland, Norway).
225 Extrapolation of results acquired in headwater catchments, associated with the needs
226 and requests of local and national water managers, have led her and colleagues to
227 extend the study of transfers to mesoscale catchments and national scales. To this
228 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).

246 How long does it take a solute to travel from the soil to a stream? This question was
247 initially motivated by water-management concerns. In a context of high nitrate
248 contamination of streams and rivers, several research teams and especially Chantal's,
249 were challenged by water-management agencies and public authorities to estimate
250 how much time it would take stream water quality to recover after implementing good
251 agricultural practices. Subsequently, Chantal and colleagues used a variety of
252 approaches to quantify groundwater travel time. Spectral analysis of long time series
253 of in-stream solute concentrations led to the conclusion that mean travel time in the
254 Kervidy-Naizin catchment (Brittany) exceeded 1.3 years (Molénat et al., 1999).
255 Computer simulations performed later with distributed physical-based groundwater
256 models predicted that travel times varied greatly across catchments, taking up to 3
257 years in the Kervidy-Naizin catchment (Molénat and Gascuel-Odoux, 2002) and 14
258 years in the Kerbernez catchments (Brittany) (Martin et al., 2006). Further research by
259 Chantal and colleagues confirmed the magnitude of previously estimated mean transit
260 times while emphasizing their high uncertainties. They did this by i) using spectral
261 analysis of stream-solute-concentration time series and gaseous tracers (CFCs and
262 SF₆), in collaboration with Luc Aquilina (Univ. of Rennes 1), to calibrate a groundwater
263 model (Molénat et al., 2013) and ii) applying a conceptual compartment-based model
264 calibrated with long time series of solute concentration (Fovet et al., 2015). The results
265 of these studies were in line with those of other studies of catchment transit times (e.g.
266 (Kirchner et al., 2000; McGuire et al., 2002; Stewart and Fahey, 2010).

267 Chantal has also extensively studied the influence of groundwater dynamics on stream
268 nitrate concentrations. She began from observations that stream water concentrations
269 varied not only in the short term due to storm events but in the long term, at seasonal
270 and annual scales. Understanding low-frequency variations requires understanding
271 nitrate groundwater transfer and interactions between groundwater and surface water.
272 One main advance of Chantal and colleagues was to develop a conceptual model
273 based on the connectivity of hydrological compartments in a catchment to explain
274 seasonal dynamics (Molenat et al., 2008). Stream nitrate concentration in most
275 agricultural catchments with shallow groundwater was shown to follow an annual cycle,
276 with the highest concentrations in winter and the lowest in summer (Aubert et al.,
277 2013b; Martin et al., 2004; Molénat and Gascuel-Odoux, 2002). Meanwhile, a steady-
278 state spatial distribution of nitrate concentration in groundwater, with a decreasing

279 pattern from upslope to downslope, was revealed as a common characteristic of the
280 two catchments in the AgrHys observatory (Martin et al., 2004; Molénat and Gascuel-
281 Odoux, 2002). High nitrate concentrations in upslope areas behave as an infinite pool
282 at the multi-annual scale (Ruiz et al., 2002). Chantal and colleagues showed that
283 riparian zones, where the water table rises to the soil surface, are hot-spots of
284 denitrification that result in nitrate concentrations near zero (section 3). With these
285 elements, the concept of connectivity assumes that stream nitrate concentration
286 depends on the connection of hydrological compartments (i.e. high-nitrate groundwater
287 upslope, a nitrate-free riparian zone and low-nitrate deep groundwater), with the
288 connection and disconnection of these compartments controlled by temporal dynamics
289 of the groundwater level along the hillslope. Ocampo et al. (2006a, b) in the Susannah
290 Brook catchment (Australia), and Wriedt and Rode (2006) in the lowland Schaugraben
291 catchment (Germany) also demonstrated the ability of hydrological connectivity to
292 explain variations in stream nitrate concentration. The connectivity assumption has
293 also been confirmed since then by the study and modelling of long-term (> 10 years)
294 stream nitrate concentration (Aubert et al., 2013a; Strohmenger et al., 2021). The
295 connectivity concept has also helped guide the design of conceptual compartment-
296 based models to explore the response of stream water quality to climatic and
297 anthropogenic forcing (section 2.3).

298 2.2. Influence of riparian wetland dynamics on sediment and phosphorus transfer

299 Unlike nitrate, suspended sediments and P forms are transferred mainly via surface
300 and shallow-subsurface flowpaths (Lefrançois et al., 2007; Vongvixay et al., 2010).
301 Consequently, they are transferred mainly during short storm events, which implies
302 specifically monitoring and analysing them during these events. Chantal and
303 colleagues, particularly Catherine Grimaldi, analysed the shape and direction of
304 concentration-discharge hysteresis loops to differentiate events with a proximal source
305 (in- or near the stream: clockwise hysteresis) from those with a more distal source
306 along the hillslope (anticlockwise hysteresis). In a grassland catchment in which cattle
307 had access to the stream, Lefrançois et al. (2007) showed that suspended sediments
308 originated mainly from the stream channel and banks, either by hydraulic erosion or
309 cattle trampling. The high seasonal availability of suspended sediments during the
310 grazing season (Lefrançois et al., 2007) and the sharp decrease in suspended-
311 sediment fluxes after construction of watering troughs (Vongvixay et al., 2018)

312 confirmed the crucial role of bank degradation by cattle in the suspended-sediment
313 dynamics of this catchment. In contrast, an arable catchment with supposedly higher
314 potential for hillslope erosion but the presence of woody vegetation or grass buffer
315 strips along the stream had one-fifth the suspended-sediment fluxes (Vongvixay et al.,
316 2018). In this catchment, stream protection limited the delivery of eroded soil from
317 arable fields during most (but not the largest) storm events.

318 Chantal and colleagues' research on suspended sediment paved the way for research
319 on particle-associated contaminants, specifically forms of P. Results for the Kervidy-
320 Naizin catchment showed, however, that a large percentage of P (13-48% of annual
321 load) is transferred in dissolved forms (Minaudo et al., 2017) and that storm dynamics
322 of dissolved P are not synchronous with those of particulate P (Dupas et al., 2015b).
323 Dupas et al. (2015b) concluded that particulate and dissolved P forms have different
324 spatial origins in the landscape and are transferred by different mechanisms.
325 Particulate P originates from resuspension of streambed sediments, bank erosion and
326 occasionally from erosion on hillslopes. In contrast, dissolved P originates from riparian
327 soils when fluctuations in the shallow groundwater level connect them to the stream.
328 Monitoring P concentration in the soil water of the riparian zone revealed that
329 alternating dry and wet phases in these zones fosters P solubilisation (Dupas et al.,
330 2015c). It is therefore essential not to rely only on riparian buffers to limit P transfer to
331 streams, as the P that they retain may be remobilized. Management efforts should
332 therefore limit erosion at its original source, place buffer features (e.g. grass strips,
333 hedgerows) upslope of riparian wetlands and extract P from these hydrologically
334 connected zones (Dupas et al., 2017).

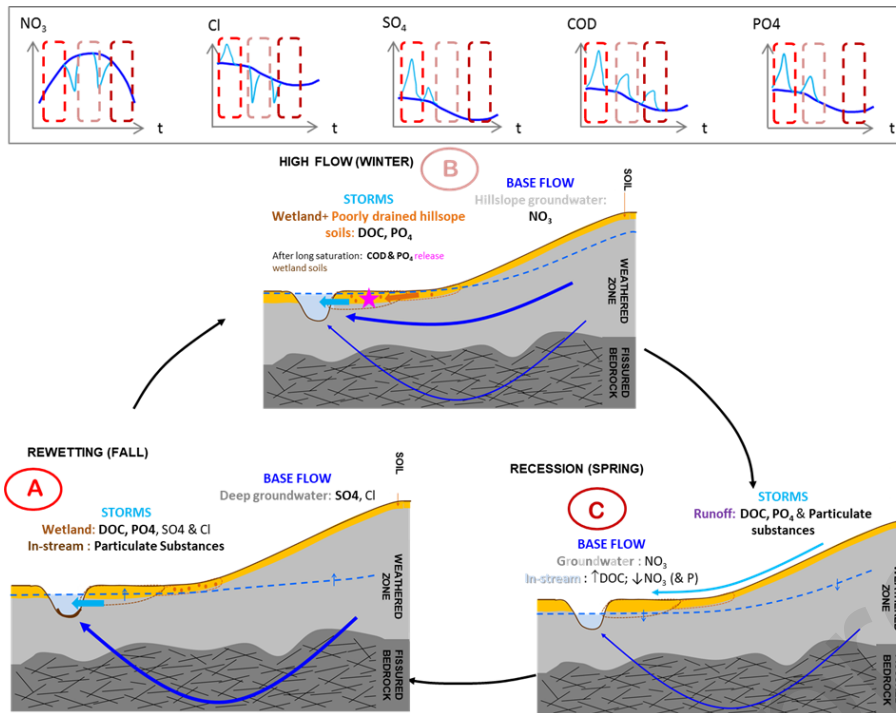
335 2.3. Development of an integrated conceptual model of solute and particulate 336 transfer in headwater catchments

337 In the 2010s, Chantal and colleagues have developed conceptual models of solute and
338 particulate transfer in agricultural headwater catchments that went beyond earlier
339 disjointed work on nitrate and phosphorus exports (Gascuel-Oudoux et al., 2018). The
340 work relied strongly on long-term and high-frequency monitoring of the concentrations
341 of multiple constituents in the Kervidy-Naizin catchment (i.e. daily since 2000 and, for
342 several parameters, sub-hourly since 2011) (Fovet et al., 2018b). Water-quality
343 monitoring at the outlet of the 5-km² catchment is supplemented with measurements

344 in several other environmental compartments, such as the soil, groundwater and
345 atmosphere. To interpret these data, Chantal and colleagues conceptualized a
346 catchment as a set of compartments, each with static chemical signatures (Aubert et
347 al., 2013b). Concentration dynamics at the outlet are then conceptualized as a mixing
348 of compartment contributions (Figure 3). To add complexity, one can also consider
349 dynamic chemical signatures, when biogeochemical reactions or agricultural
350 management modifies concentrations (Aubert et al., 2013a). Chantal and colleagues
351 have applied this representation of a catchment to develop perceptual models, formal
352 end-member-mixing analyses (Durand and Juan Torres, 1996) and FLEXIBLE mixing
353 reservoir models (Fovet et al., 2015; Hrachowitz et al., 2014; Strohmenger et al., 2021).

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

376 In addition to studying individual chemical elements in a disjointed manner, Chantal
377 played a pioneering role in developing joint conceptual models C-N-P cycles and their
378 interactions in agricultural landscapes. This evolution from a focus on nitrate (section
379 2.2) to coupled C-N-P cycles accompanied a change in water managers' concerns
380 from drinking water production (often with nitrate standard not being met) to reaching
381 a good ecological status of surface water in contexts with a high risk of eutrophication
382 (Le Moal et al., 2019). Joint understanding of C-N-P cycles and transfer is crucial to
383 understand how the concentration of each element is controlled by that of the others
384 and how their relative concentrations influence aquatic ecosystems. This work is also
385 motivated by the necessity to identify potential risks of pollution swapping when dealing
386 with one element without considering the others. Strohmenger et al. (2020) showed
387 that dynamics of nitrate and DOC concentrations are opposite at annual, seasonal and
388 storm-event scales, while P dynamics are independent of those of the other two. The
389 ratios of pairs of elements may vary more when dynamics of the elements are
390 asynchronous or out-of-phase and vary less when their dynamics are in-phase.
391 Guillemot et al. (2021) confirmed these results using data from 180 headwater
392 catchments in Brittany and found that the temporal opposition between nitrate and
393 DOC (and the independence of P) is also spatially valid across Brittany. Minaudo et al.
394 (2019) also found temporal opposition between nitrate and forms of P at the seasonal
395 and storm-event scales, and attributed it to different dominant sources for both
396 nutrients: diffuse sources for N and a combination of diffuse and point sources for P.



397
 398 **Figure 3. A conceptual framework for carbon, nitrogen and phosphorus transfer**
 399 **in headwater catchments during baseflow and stormflow conditions, developed**
 400 **by Chantal Gascuel-Oudou and colleagues. Inspired by Fovet et al. (2018a)**
 401 **(modified).**

402 2.4. Retrospective and prospective analysis of the influence of climate on water
 403 quality

404 The influence of climate change on surface water quality in agricultural catchments
 405 greatly concerns the scientific community and water managers. Analysis of 16 years
 406 of meteorological data from the Kervidy-Naizin catchment revealed an increase in
 407 temperature but no overall trend in annual discharge, although winters tended to
 408 become wetter and summers tended to become drier (Strohmenger et al., 2020).
 409 These observations of recent trends are consistent with predictions of climate models
 410 for the region, although the predicted trend in annual rainfall is uncertain (Mérot et al.,
 411 2014). Predicting responses of hydrological systems to these changes is challenging
 412 due to the complexity of the processes involved, the many feedback loops that exist
 413 and potential interactions with changes in land management (Blöschl et al., 2019).

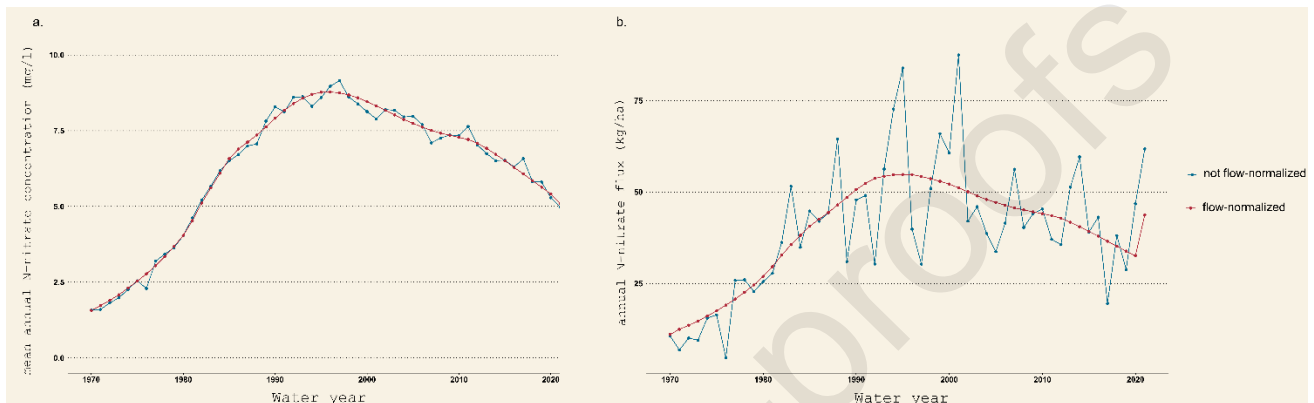
414 Chantal's contributions to understanding the influence of climate variability on water
 415 quality have relied mainly on retrospective analysis of long-term monitoring data
 416 (Dupas et al., 2018; Gascuel-Oudou et al., 2010a; Mellander et al., 2018; Strohmenger

417 et al., 2020). Disentangling the influence of climate from that of changes in land
418 management is especially challenging, especially for regions whose agriculture has
419 changed greatly the past several decades (Dupas et al., 2016; Strohmenger et al.,
420 2020). Using public water-quality data from Brittany, Gascuel et al. (2010a) and Dupas
421 et al. (2018) highlighted the existence of mesoscale (2-6 year) variations in discharge
422 that drive synchronous variations in nitrate concentrations and fluxes (Figure 4). Here,
423 discharge is taken as an integrative indicator of several climatic variables: rainfall and
424 evapotranspiration, itself influenced by temperature. These mesoscale variations may
425 mask improvements in land management in certain years or exaggerate these
426 improvements in other years; thus, water quality must be observed for more than 5-10
427 years to reliably assess effects of improved land management on water-quality trends.

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

446 Finally, Chantal also participated in prospective studies that used the integrated agro-
447 hydrological model TNT2 (Salmon-Monviola et al., 2013) (section 3.1). Salmon-
448 Monviola et al. (2013) simulated the influence of temperature, rainfall and increased
449 atmospheric carbon dioxide on water and N cycles in the Kervidy-Naizin catchment,

450 and highlighted the importance of understanding how the functioning of riparian
 451 wetlands would respond to climate change. Overall, the synergetic effect of increasing
 452 temperature, decreasing rainfall and increasing carbon dioxide concentration is
 453 predicted to decrease N loads in the catchment's stream, but uncertainties remain
 454 about how farming practices will respond to climate change (and other incentives) and
 455 then interact with the direct effects of climate change to influence water and N cycles.



456
 457 **Figure 4. Long-term (1970-2021) mean and flow-normalized mean annual nitrate**
 458 **concentration (a) and flux (b) at the outlet of the Elorn catchment, western**
 459 **France (260 km²). The data was obtained through WRTDS modelling with**
 460 **monthly data of concentration monitoring and daily discharge (Hirsch et al.,**
 461 **2010). The gap between the mean and flow-normalized mean estimations of**
 462 **concentrations or fluxes shows the influence of 5-10 years interannual climatic**
 463 **variations, which may interfere with the estimation of long-term trends when**
 464 **using too short time-series. This figure is inspired by Gascuel-Odoux et al.**
 465 **(2010a).**

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

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

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

483 3.1. Integrating hydrology with other disciplines

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

495 For example, she worked with a local Chamber of Agriculture to assess, based on field
496 experiments, effects of maize-cropping techniques (e.g. a mixed weeding strategy, no-
497 tillage) on herbicide transfer by surface runoff. Results showed that compared to
498 conventional chemical weeding, a mixed weeding strategy reduced herbicide
499 concentrations by ca. 75% and fluxes by up to 90%. They also observed that no-tillage
500 increased soil infiltrability by a factor of 5-10, which greatly reduced surface runoff and
501 herbicide transfer (by up to 90%) compared to those of conventional tillage (Heddadj
502 and Gascuel, 2001). To explore agricultural practices to reduce N transfer to streams,
503 Chantal helped Patrick Durand (INRAE) and other colleagues develop integrated agro-
504 hydrological models (Moreau et al., 2012). Whereas field experiments are complex and
505 costly, particularly at the landscape level, integrated modelling can predict whether
506 changes in agricultural practices are likely to reach a targeted reduction in nitrate

507 concentrations in groundwater or streams. They used the spatially distributed agro-
508 hydrological model TNT2 (Beaujouan et al., 2001), which couples a crop model
509 (Brisson et al., 1998) with a hydrological model (based on Topmodel (Beven, 1997)) to
510 predict the ability of introducing cover crops (i.e. fast-growing crops that are grown
511 between successive main crops) to reduce N losses at the catchment scale (Durand
512 et al., 2015).

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

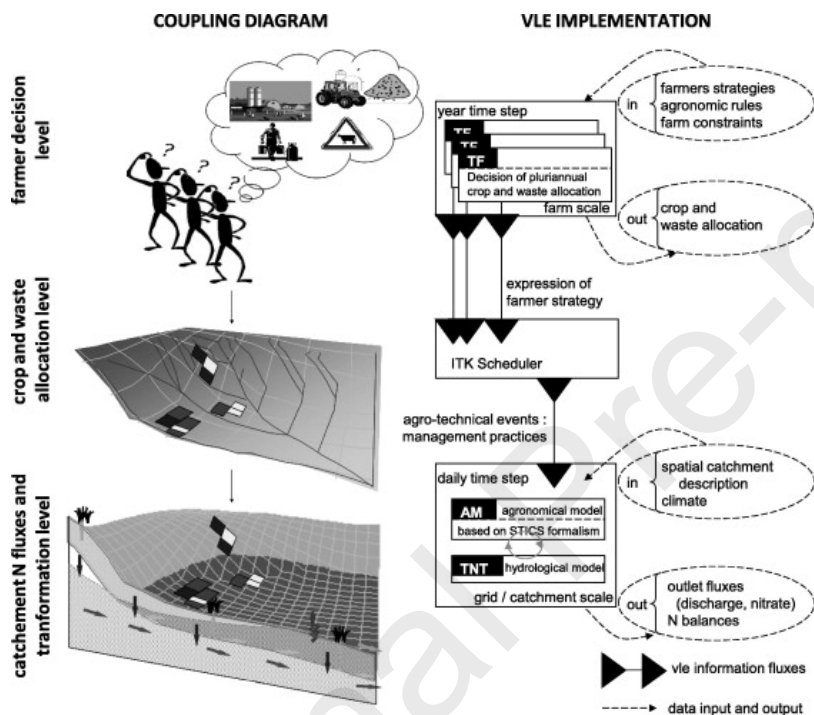
530 3.2. Integrated catchment modelling

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

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

556 Many biophysical models, such as SWAT (Arnold et al., 1998), SHETRAN (Birkinshaw
557 and Ewen, 2000), TNT2 (Beaujouan et al., 2001, 2002) and DNMT (Liu et al., 2005),
558 operate at the catchment scale and simulate effects of agricultural practices on N
559 transfer and transformation. However, they do not represent consistent farming
560 systems because they do not explicitly represent farmer decisions. This is particularly
561 critical for mixed farming systems, in which processes such as fodder production and
562 manure spreading of cropping and livestock systems are closely related. In other
563 words, when a model simulates large changes in the cropping system, there is no
564 guarantee that it will simulate production of enough forage for animals or that the
565 amount of manure applied in the model will equal the amount of manure produced
566 (Durand et al., 2015). To address this gap and assess effects of different dairy farming
567 systems on catchment N dynamics, Patrick Durand, Chantal and colleagues
568 developed the Casimod'N model (Figure 5), which couples a farmer-decision model
569 with the TNT2 model (Moreau et al., 2013). Casimod'N simulates farming systems
570 explicitly through production strategies and farmer decisions, and translates these
571 decisions into management practices. Representing these strategies when simulating

572 management practices ensures that i) simulated fodder production matches livestock-
 573 feed requirements, ii) livestock-feeding and manure-management strategies are
 574 consistent with each other and iii) specific farm constraints (e.g. distances between
 575 fields) are met. Applying Casimod'N to the Yar catchment (Brittany) in a project co-led
 576 by Chantal and Laurent Ruiz (INRAE) demonstrated that such models can be powerful
 577 and relevant tools to redesign farming systems (Durand et al., 2015; Gascuel et al.,
 578 2015; Moreau et al., 2013). Here, she made a decisive contribution by building a
 579 multidisciplinary research group.



580
 581 **Figure 5. Diagram of the CASIMOD'N model and its implementation in the Virtual**
 582 **Laboratory Environment (VLE) CC-BY-CA Moreau et al. (2013)**

583 3.3. Integrating hydrological sciences with non-academic stakeholders

584 The international research agenda of the 2000s and 2010s, as described in the
 585 Prediction in Ungauged Basins (Hrachowitz et al., 2013) and Panta Rhei (Montanari et
 586 al., 2013) initiatives, challenged the scientific community to make progress in
 587 transferring knowledge about well-known research sites to poorly gauged, monitored
 588 or documented catchments for which societal issues are strong. In accordance with
 589 this agenda, Chantal co-led several projects to conceptualize farming systems in
 590 catchments affected by water pollution. In these projects, scenarios of agricultural
 591 practices at farming-system and catchment scales were co-built with local non-

592 academic stakeholders from the agricultural and/or water-management sector. This
593 co-building allows future scenarios to be explored, while the integrated models
594 described previously (section 3.2) can predict impacts of these scenarios on water
595 resources.

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

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

616 3.4. Making scientific knowledge accessible and relevant for water and 617 environmental managers

618 Chantal has promoted the development of methods to improve water management that
619 are scientifically sound and operational. For example, considerable effort was made to
620 transfer knowledge about critical source areas of pollutants into a decision support tool
621 called Territ’eau (Gascuel-Odoux et al., 2011; Gascuel et al., 2009). Territ’eau helps
622 stakeholders define action plans that include changes in agricultural practices and

623 systems as well as restoration and preservation of semi-natural areas in rural
624 landscapes.

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

636 4. Contributing to public policies and public debate

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

641 4.1. Contributions to joint scientific assessments

642 In France, Ministries can request joint scientific assessments on any subject which
643 summarize validated scientific knowledge in response to a complex question related
644 to a strong and urgent societal issue. In them, a group of experts analyses the
645 international scientific literature to inform public debate about the given question.
646 Chantal contributed to the joint scientific assessment “Pesticides, agriculture and the
647 environment: reducing the use of pesticides and limiting their environmental impact”
648 (Aubertot et al., 2007), which updated knowledge about and data on agricultural use
649 of pesticides, their contamination of environmental compartments and impacts on non-
650 target organisms and ecosystems. Chantal specifically contributed to the chapters
651 related to hydrological transfers (i.e. buffer zones, transfer indices and models),
652 examining pesticide drift in the environment and discussing crop management

653 strategies and spatial configurations to reduce it. Chantal co-led another joint scientific
654 assessment entitled “Causes, mechanisms, consequences and predictability of
655 eutrophication phenomena” (Le Moal et al., 2019; Pinay et al., 2018) that highlights the
656 general increase in N and P fluxes to oceans and agriculture’s increased contribution
657 to them during the 20th century. To predict eutrophication risk, nutrient transfer and
658 transformation processes need to be considered along with climatic variability and
659 ecological vulnerability of downstream ecosystems. Control strategies can
660 occasionally use engineered nutrient-removal techniques but will first require source
661 reduction.

662 4.2. Tools and expertise for public water policies

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

677 4.3. Contributions to scientific resource centres

678 Chantal took an active role in creating a resource centre with the National Office for
679 Water and Aquatic Environments for Drinking Water Protection to help local authorities
680 design more ambitious and effective action plans for managing water resources
681 (Menard et al., 2014). This resource centre aims to facilitate coordination among
682 stakeholders and to disseminate documents and methods. It provides case studies in
683 which (i) outputs from biophysical models are presented to stakeholders, as in Dupas

684 et al. (2015a), and (ii) local experts identified the critical role of crop rotations,
685 especially the periods between main crops, via participatory modelling. Another
686 resource centre called Creseb (Resource and Expertise Centre for Water in Brittany)
687 was created in 2011 to transfer up-to-date scientific knowledge to local and regional
688 water managers. Chantal was President of its scientific and technical board for four
689 years. During this period, she promoted the topics of hydromorphology, diffuse
690 agricultural pollutants, floods and support for transitions in territorial projects.

691

692 Conclusion

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

705

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

711

712 Chantal has helped define the directions of future research in landscape agroecology
713 necessary to design sustainable agricultural systems. She has paved the way for
714 young researchers to conduct high-quality research that meets societal needs. The
715 relative effects of human activities and the climate on C-N-P cycles and the eutrophying

716 impacts of major contaminants on aquatic ecology are among the research fields that
 717 Chantal has opened up and that we will be exploring in the years and decades to come.

718

719

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721

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1098 • Career contributions of Chantal Gascuel-Odoux in hydrology, soil science and
1099 agronomy

1100 • Influence of soil and subsoil properties on hydrological processes

1101 • Water, solute and particulate transfer at the catchment scale

1102 • Design of integrated approaches to landscapes and territorial management

1103 • Contributions to public policies and public debate

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