

# A French hydrologist's research for sustainable agriculture

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## Review papers

A French hydrologist's research for sustainable agriculture

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1	A French hydrologist's research for sustainable agriculture
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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 INRAE <sup>1</sup> , 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,

26 SAS (Soil, Agro- and HydroSystems, Spatialization). However, her collaborations and

<sup>&</sup>lt;sup>1</sup> 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.

29 This vast range of collaborations reflects Chantal's curiosity and embodies her conviction that collaboration is key to research. Above all, she considers that 30 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 requires understanding the societal context of Brittany, in western France, where she 34 has spent most of her career. Beginning in the 1960s, Brittany experienced rapid 35 development of intensive agriculture, particularly confined animal production. Because 36 of its temperate oceanic climate and shallow soils and aquifers, water pollution by 37 38 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 39 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 hydrological and biogeochemical processes in the Brittany region aims mainly to 42 understand the degradation of water quality and find solutions to improve the situation... 43 The impact of Chantal's research goes far beyond the regional context, however, as 44 she always endeavours to identify and highlight generic knowledge in every study, 45 46 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 47 international journals was not an obvious choice for French researchers. It is 48 noteworthy that her first international article was published in French in the Journal of 49 Hydrology, before English became the dominant language of global scientific 50 communication (Gascuel-Odoux and Mérot, 1986)! Chantal was one of the first 51 researchers at SAS to disseminate her research in English, and we consider her 52 responsible for the internationalization of the unit, first as a researcher and then as unit 53 54 director. Subsequently, Chantal and her colleagues increasingly published their research in international journals, including the Journal of Hydrology. The 55 56 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, 57 mainly in European countries facing similar problems with diffuse agricultural pollution, 58 such as the United Kingdom (UK), Ireland and the Netherlands. Her international 59

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, 65 66 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) 67 to federate research teams from several institutes (INRAE, CNRS, University of 68 Rennes) working on environmental sciences in Rennes, France. CAREN became 69 OSUR (Observatoire des Sciences de l'Univers de Rennes) in 2010 under the 70 leadership of Gilles Pinay (CNRS), and Chantal served as its vice-director. She was 71 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 returns ecology to the centre of agricultural system design (Caguet et al., 2020b; 75 Gascuel-Odoux et al., 2022; Gascuel and Magda, 2015). 76

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



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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.

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

91 Since the 1980s, Chantal and colleagues (particularly Philippe Mérot, INRAE) have analysed and modelled runoff generation and groundwater dynamics. Along with 92 colleagues from the SAS unit, she conducted research to identify the relevant scales 93 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 United States, Weyman (1970, 1973) in the UK and Cappus (1960) in France, runoff 96 97 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 98 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) guantifying 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 <sup>18</sup>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 112 113 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 Odoux and Boivin, 1994; Gascuel-Odoux 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 research on the ability of a helicopter-borne C-band scatterometer radar to map the 118 119 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 120 121 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-Odoux et al., 1996). From experiments and computer modelling, they showed that flow-path connectivity at the square-meter scale 129 130 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 131 132 (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. 133 134 Infiltration and soil deposition are particularly active in concave parts of hillslopes, regardless of the characteristics of storm events, and are enhanced by hedgerow 135

networks (Mérot et al., 1999). This result contradicts the intuitive model of downstream 136 amplification of runoff through aggregation in the drainage area. It also supports the 137 assumption of a threshold of spatial scale at which to define the head of channel 138 networks, at least in temperate regions such as Brittany. After this major observation, 139 140 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

Because riparian wetlands in agricultural landscapes strongly influence hydrology, 145 146 water quality and biodiversity, their degradation in intensive agricultural landscapes is of great concern. To address the need for reliable wetland mapping, Chantal and 147 colleagues developed a hydrological typology of wetlands (Durand et al., 2000; Mérot 148 et al., 2006). First, potential wetlands are defined by soil properties and topographic 149 150 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 151 152 vegetation. Third, effective wetlands are defined for a variety of ecosystem services related to hydrology, water quality and biodiversity. Mapping these three types of 153 154 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., 2009) and for the PEEW (Potential, Existing and Effective Wetlands) method, which 156 provides a framework for organizing knowledge about wetland management (Mérot et 157 158 al., 2006).

## 159 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 167 predicting dynamics of the water table and stream runoff simultaneously in catchments 168 dominated by saturated subsurface flow (Gascuel-Odoux et al., 2010b; Martin, 2003; 169 170 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 conditions and storm events (Gascuel-Odoux et al., 1999; Molénat et al., 1999). Her 174 research has made good use of the number and guality of water-table records in the 175 176 catchments of the AgrHyS observatory ("Agro-Hydro Systems", Gascuel-Odoux et al., 2018). High-frequency records (< 1 h) from wells on transects extending down 177 hillslopes provided the data necessary to analyse the ability to simulate spatio-178 179 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 180 181 but less well for simulating midslope and upslope areas. Relaxing two of Topmodel's assumptions - steady-state spatial subsurface flux and topographic assumptions -182 183 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) 184 185 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 186 187 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 188 189 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 only slightly (Gascuel-Odoux et al., 2010b). She concluded that i) there is some 194 195 incommensurability in comparing point observations to grid-averaged predictions and ii) improving spatial simulations of water table requires fitting local transmissivity to 196 local water-table observations, which would require acquiring these observations. 197

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

Since the early 1990s, Chantal's research has focussed mainly on water, solute and 199 200 particulate transfer in agricultural catchments. She has considered the understanding of processes that underlie these transfers as a key scientific challenge to preserve 201 202 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 guality should be evaluated as a whole, she collaborated with other colleagues, especially Gérard Gruau (CNRS, 206 France), Catherine Grimaldi (INRAE, France) and Aline Dia (CNRS, France), to 207 208 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 this end, she actively contributed to the development of the AgrHys research 211 212 observatory in Brittany (Figure 2; Fovet et al., 2018b). This long-term observatory has focused since 1992 on headwater catchments (Kervidy-Naizin 5 km<sup>2</sup> and Kerbernez, 213 214 1.2 km<sup>2</sup>), and characterized by hard rock aguifers, an oceanic climate, and dominance of agricultural land uses devoted to animal farming. The AgrHyS observatory is 215 216 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, 217 218 nitrogen, carbon and phosphorus. Chantal has (co-)supervised 11 PhD thesis that have analyzed AgrHys observational data from (Gascuel-Odoux et al., 2018). To 219 220 promote the observatory, develop scientific collaborations and investigate scientific questions over a wider range of hydroclimatic conditions. Chantal has worked to 221 222 integrate the observatory into a national (OZCAR; (Gaillardet et al., 2018) and a European network (eLTER). Through collaborations, her research has also benefited 223 224 from observations from research catchments outside of France (e.g. Ireland, Norway). 225 Extrapolation of results acquired in headwater catchments, associated with the needs and requests of local and national water managers, have led her and colleagues to 226 227 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.



229 230

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

231

Papillon.

232 2.1. Groundwater nitrate transfer: from estimation of travel time to connectivity 233 analysis

Chantal and colleagues have addressed groundwater nitrate transfer in agricultural 234 catchments for the past 30 years. It is useful to recall the scientific context in the 1990s, 235 236 when she began this research. Most studies focussed mainly on storm events to 237 understand the main hydrological and biogeochemical processes that control 238 dynamics of solute concentrations and fluxes in stream water. In addition, solute transfer times in headwater catchments with shallow groundwater were assumed to be 239 240 short, due to the shallow groundwater and short travel distances along hillslopes from 241 the soil to a stream. In this context, Chantal and Philippe Davy explored two topics: i) 242 estimating travel times in shallow groundwater systems and ii) exploring relationships 243 between the dynamics of shallow groundwater and stream nitrate concentration at 244 seasonal and annual scales. The objective of this research was to better understand 245 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 initially motivated by water-management concerns. In a context of high nitrate 247 contamination of streams and rivers, several research teams and especially Chantal's, 248 249 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 of in-stream solute concentrations led to the conclusion that mean travel time in the 253 Kervidy-Naizin catchment (Brittany) exceeded 1.3 years (Molénat et al., 1999). 254 Computer simulations performed later with distributed physical-based groundwater 255 models predicted that travel times varied greatly across catchments, taking up to 3 256 257 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 Chantal and colleagues confirmed the magnitude of previously estimated mean transit 259 260 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 261 262 SF<sub>6</sub>), 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 263 264 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. 265 266 (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 varied not only in the short term due to storm events but in the long term, at seasonal 269 270 and annual scales. Understanding low-frequency variations requires understanding nitrate groundwater transfer and interactions between groundwater and surface water. 271 272 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

pattern from upslope to downslope, was revealed as a common characteristic of the 279 two catchments in the AgrHys observatory (Martin et al., 2004; Molénat and Gascuel-280 281 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 denitrification that result in nitrate concentrations near zero (section 3). With these 284 285 elements, the concept of connectivity assumes that stream nitrate concentration depends on the connection of hydrological compartments (i.e. high-nitrate groundwater 286 287 upslope, a nitrate-free riparian zone and low-nitrate deep groundwater), with the 288 connection and disconnection of these compartments controlled by temporal dynamics of the groundwater level along the hillslope. Ocampo et al. (2006a, b) in the Susannah 289 290 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) stream nitrate concentration (Aubert et al., 2013a; Strohmenger et al., 2021). The 294 295 connectivity concept has also helped guide the design of conceptual compartmentbased models to explore the response of stream water quality to climatic and 296 297 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 (Lefrancois 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 (in- or near the stream: clockwise hysteresis) from those with a more distal source 305 306 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 cattle trampling. The high seasonal availability of suspended sediments during the 309 310 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-Naizin catchment showed, however, that a large percentage of P (13-48% of annual 320 load) is transferred in dissolved forms (Minaudo et al., 2017) and that storm dynamics 321 322 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 323 324 spatial origins in the landscape and are transferred by different mechanisms. Particulate P originates from resuspension of streambed sediments, bank erosion and 325 326 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. 327 Monitoring P concentration in the soil water of the riparian zone revealed that 328 alternating dry and wet phases in these zones fosters P solubilisation (Dupas et al., 329 330 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 331 332 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 333 334 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-km<sup>2</sup> catchment is supplemented with measurements

in several other environmental compartments, such as the soil, groundwater and 344 atmosphere. To interpret these data, Chantal and colleagues conceptualized a 345 catchment as a set of compartments, each with static chemical signatures (Aubert et 346 347 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 dynamic chemical signatures, when biogeochemical reactions or agricultural 349 350 management modifies concentrations (Aubert et al., 2013a). Chantal and colleagues have applied this representation of a catchment to develop perceptual models, formal 351 352 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). 353

354 In addition to dividing a catchment into compartments, Chantal and colleagues also divided time into characteristic time scales: long-term (multi-annual), seasonal (intra-355 356 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 357 358 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 inorganic C depended on each year's mean weather conditions (hot/cold vs. dry/wet). 360 Martin et al., (2004) showed that seasonal nitrate cycles can even reverse (i.e. winter 361 362 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 363 364 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, 365 366 chloride, DOC and sulphate) depend on antecedent hydrological conditions. Dupas et al. (2015d) used dynamic time warping techniques and showed that P-transfer 367 dynamics during spring storms differ from those during autumn and winter storms, 368 highlighting the risk of incidental P losses after spreading animal waste in spring. More 369 370 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 also be observed in intensive agricultural catchments (Aubert et al., 2014). 375

In addition to studying individual chemical elements in a disjointed manner, Chantal 376 played a pioneering role in developing joint conceptual models C-N-P cycles and their 377 interactions in agricultural landscapes. This evolution from a focus on nitrate (section 378 379 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 a good ecological status of surface water in contexts with a high risk of eutrophication 381 382 (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 383 and how their relative concentrations influence aquatic ecosystems. This work is also 384 motivated by the necessity to identify potential risks of pollution swapping when dealing 385 with one element without considering the others. Strohmenger et al. (2020) showed 386 387 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 DOC (and the independence of P) is also spatially valid across Brittany. Minaudo et al. 393 394 (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 395 396 nutrients: diffuse sources for N and a combination of diffuse and point sources for P.



397

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).

402 2.4. Retrospective and prospective analysis of the influence of climate on water403 quality

The influence of climate change on surface water quality in agricultural catchments 404 405 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 become wetter and summers tended to become drier (Strohmenger et al., 2020). 408 409 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., 410 411 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).

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 417 418 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 improvements in other years; thus, water quality must be observed for more than 5-10 426 427 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 concentration data from France, Ireland and Norway, Mellander et al. (2018) 430 431 hypothezised 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 available only during an upward trend in the NAO index (2010-2016), future analysis 434 435 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-436 437 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 NAO or ENSO index. Their results highlighted the joint influence of changes in climate 440 441 and land management on long-term trends in nitrate (decreasing), P (decreasing) and DOC (increasing). They also highlighted effects of extreme climatic conditions, whose 442 443 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.

Finally, Chantal also participated in prospective studies that used the integrated agrohydrological model TNT2 (Salmon-Monviola et al., 2013) (section 3.1). SalmonMonviola et al. (2013) simulated the influence of temperature, rainfall and increased
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.



Figure 4. Long-term (1970-2021) mean and flow-normalized mean annual nitrate 457 concentration (a) and flux (b) at the outlet of the Elorn catchment, western 458 459 France (260 km<sup>2</sup>). The data was obtained through WRTDS modelling with 460 monthly data of concentration monitoring and daily discharge (Hirsch et al., 2010). The gap between the mean and flow-normalized mean estimations of 461 concentrations or fluxes shows the influence of 5-10 years interannual climatic 462 463 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. 464 465 (2010a).

466 3. Integrating hydrology into the design of integrated approaches to landscapes and467 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;

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

## 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 evolved towards more interdisciplinary perspectives (McCurley and Jawitz, 2017) to 486 487 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 water-energy-food nexus (Montanari et al., 2015; Wagener et al., 2010). Through 489 490 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 need to combine thorough understanding of catchment hydrology with that of 493 494 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 conventional chemical weeding, a mixed weeding strategy reduced herbicide 498 499 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 and Gascuel, 2001). To explore agricultural practices to reduce N transfer to streams, 502 503 Chantal helped Patrick Durand (INRAE) and other colleagues develop integrated agrohydrological models (Moreau et al., 2012). Whereas field experiments are complex and 504 505 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 barriers that prevent efficient data processing, only daily flux and concentrations at the 515 catchment outlet are usually analysed, even though higher temporal or spatial 516 517 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 of herbicide sinks or sources and factors that explained herbicide transfer along the 524 525 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 agricultural practices on N emissions at multiple spatio-temporal scales by providing 528 529 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 the management of rural areas. Using these models has facilitated dialogue among 532 533 local stakeholders around land-management scenarios, for example by exploring exante simulations of impacts of changes in agricultural practices on water quality 534 535 (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.

With computer scientist Frederic Garcia (INRAE), Chantal led a study of interactions 539 540 between farmers' technical decisions and biophysical systems in the development of 541 the decision-oriented Sacadeau model (Gascuel-Odoux 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 crop-phenology submodel and a submodel of water and chemical transfer within 546 547 agricultural catchments. In the transfer submodel, Chantal developed an innovative approach to modelling surface drainage networks that determines surface water 548 connectivity by considering the topography between and within farm fields, hedgerows, 549 550 roads and ditches (Aurousseau et al., 2009; Gascuel-Odoux et al., 2011). This 551 "landscape drainage network" considers both farming systems and landscape features, unlike a traditional drainage network extracted from DEM data alone. The 552 553 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.

Many biophysical models, such as SWAT (Arnold et al., 1998), SHETRAN (Birkinshaw 556 557 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 558 559 transfer and transformation. However, they do not represent consistent farming systems because they do not explicitly represent farmer decisions. This is particularly 560 561 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 562 563 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 564 565 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 systems on catchment N dynamics, Patrick Durand, Chantal and colleagues 567 568 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

management practices ensures that i) simulated fodder production matches livestock-572 feed requirements, ii) livestock-feeding and manure-management strategies are 573 consistent with each other and iii) specific farm constraints (e.g. distances between 574 fields) are met. Applying Casimod'N to the Yar catchment (Brittany) in a project co-led 575 576 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., 577 2015; Moreau et al., 2013). Here, she made a decisive contribution by building a 578 579 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 Prediction in Ungauged Basins (Hrachowitz et al., 2013) and Panta Rhei (Montanari et 585 586 al., 2013) initiatives, challenged the scientific community to make progress in transferring knowledge about well-known research sites to poorly gauged, monitored 587 588 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-

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.

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 symbolic-learning techniques were applied to model predictions to identify situations 601 602 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 agriculture – especially dairy farming – with coastal activities in areas affected by 605 coastal eutrophication (Gascuel et al., 2015). Thus, researchers, farmers, local 606 607 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).

616 617 3.4. Making scientific knowledge accessible and relevant for water and 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-Odoux 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 prediction of wetland extents in hydrosystems controlled by subsurface groundwater 632 633 (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

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).

641 4.1. Contributions to joint scientific assessments

In France, Ministries can request joint scientific assessments on any subject which 642 643 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" (Aubertot et al., 2007), which updated knowledge about and data on agricultural use 648 of pesticides, their contamination of environmental compartments and impacts on non-649 target organisms and ecosystems. Chantal specifically contributed to the chapters 650 651 related to hydrological transfers (i.e. buffer zones, transfer indices and models), examining pesticide drift in the environment and discussing crop management 652

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

662 4.2. Tools and expertise for public water policies

Chantal led several national studies to help the French National Office for Water and 663 Aquatic Environments (ONEMA from 2006-2016, now merged with other agencies into 664 665 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 modelIING), which uses a statistical approach to estimate nutrient loads from multiple variables, including N and P surpluses and 669 670 catchment characteristics. Dupas et al. (2013) compared national and regional calibrations of the Nutting-N model in two regions of France. Regional models generally 671 672 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 connectivity, respectively. 676

## 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

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.

691

## 692 Conclusion

693 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 694 695 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

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.

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.
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1093 1094 1095 1096	
1097 1098 1099	<ul> <li>Career contributions of Chantal Gascuel-Odoux in hydrology, soil science and agronomy</li> </ul>
1100 1101	<ul> <li>Influence of soil and subsoil properties on hydrological processes</li> <li>Water, solute and particulate transfer at the catchment scale</li> </ul>
1102	<ul> <li>Design of integrated approaches to landscapes and territorial management</li> </ul>
1103	<ul> <li>Contributions to public policies and public debate</li> </ul>
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