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Authors

Mathis Loïc Messager*, Hervé Pella, Thibault Datry[†]

Laboratoire EcoFlows, Unité de Recherche RiverLy, Département AQUA
Institut National de Recherche pour l'Agriculture, l'Alimentation, et l'Environnement (INRAE)
Centre Lyon-Grenoble Auvergne-Rhône-Alpes
5 rue de la Doua, CS 20244
69625 Villeurbanne Cedex, France
Contacts: * mathis.messager@inrae.fr, [†]thibault.datry@inrae.fr

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Abstract

Even the most stringent environmental law cannot protect a river if its tributaries remain exposed to pollution and other threats upstream. Excluding a subset of watercourses from legal protection therefore threatens to alter freshwater ecosystems across entire river networks and the services they provide, like drinking water and flood regulation. Considerable attention has been devoted to defining the scope of environmental laws protecting watercourses. Yet how these definitions are implemented through regulatory mapping, the cartography of waterbodies that legally qualify as watercourses and are thus protected, has not been examined outside of the United States. Here, we demonstrate the consequences of regulatory mapping on the extent of river networks that are protected, using France as a case study. By assembling the first map of France's watercourses protected under the Water Law, we estimate that a quarter of previously mapped hydrographic segments were excluded from protection, and found stark geographical variations in the extent of protected ecosystems. Headwater and non-perennial segments are disproportionately excluded by 28% compared to their prevalence (67%) in the overall hydrographic network, with potentially far-reaching implications for biodiversity and people. We expect regulatory frameworks in most countries to be equally susceptible to local interpretation of legal definitions.

Synopsis : Uneven implementation of environmental laws through regulatory mapping of watercourses can lead to critical gaps in the protection of rivers and streams, threatening vulnerable ecosystems and their contributions to human well-being.

Introduction

Rivers and streams make up the very fabric of human societies, and vice versa. Societal structures evolved from and are still entwined with river networks[1–3]. To this day, flowing waters are essential to meet basic human needs and enable people's well-being, livelihoods and cultures[4–6]. At the same time, rivers and streams are hybrid features of the landscape, both social and natural[7,8]. No watercourse on Earth is free from the effects of climate and land use change, river regulation, channelization, water pollution or nonnative species, among other human impacts[9,10]. And what people perceive as a watercourse is not just the fruit of climate or geology but also reflects local history, culture and politics[8,11,12].

The complex nature of rivers and streams is well illustrated by the protracted disputes that follow attempts to define them from a legal standpoint[13–16]. In the United States for example, what water bodies are protected by the Clean Water Act (CWA, 1972), the primary federal instrument for protecting freshwater ecosystems in the country[13], still remains intensely debated half a century after its enactment. The CWA is the environmental policy that led to the most US Supreme Court cases[17], and successive changes to its jurisdictional scope (four in the past 18 years) have figured prominently in the scientific literature[14,18,19]. Similar debates around the legal definition of watercourses take place across the world[15,16], yet the implications of these definitions and their interpretation on the effectiveness of environmental policies have not been examined outside of the United States.

Legally defining what is a watercourse involves trade-offs and can have far-reaching consequences for the hydrology, physico-chemistry and biology of freshwater ecosystems and the essential services they provide to society, including clean drinking water and flood regulation[5]. In most countries, once a linear depression legally qualifies as a watercourse, numerous activities in and around it become subject to regulation (e.g., bank modifications requiring authorizations) or banned altogether (e.g., pesticide application within a buffer). Excluding a watercourse from legal protection, on the contrary, exonerates riparian landowners and other users from most regulation. Subjecting even a limited subset of the river network to degradation can substantially impact water quality and ecosystems elsewhere in the basin[20–22]. Indeed, nearly all network segments are hydrologically connected, either longitudinally with downstream flow or vertically with groundwater[23,24]. A narrow definition of watercourses hence risks exposing a large swath of river networks to degradation, threatening the resilience of entire river networks and the people that depend on them[23,25]. In the United States, for example, a 2020 White House rule deregulated over a million stream kilometers and 30% of freshwater bodies around drinking-water sources[19]. Being too inclusive in the definition of watercourses, on the other hand, can result in a high administrative burden on regulators and the regulated community, as well as a contested reduction in suitable land for conventional agriculture, real estate development and other intensive land uses[16,26]. To alleviate the burden associated with the European Union Water Framework Directive (WFD), for instance, member states were allowed to exclude headwater streams with a catchment area under 10 km^2 from their River Basin Management Plans[27]. What legally counts as a watercourse hence reflects both cultural perceptions[16] and the balancing of multiple, sometimes conflictive, societal values ascribed to rivers and streams[28].

Regulatory definitions of watercourses have two main elements in common across jurisdictions globally: (i) the presence of an active channel, usually of natural origin (even if subsequently modified), and (ii) flowing water at least part of the year (**Supplementary Table 1**). To the authors' knowledge, no academic study to date has systematically compared regulatory definitions of watercourses across multiple countries (but see [15]). However, a cursory review of legal definitions across continents (see **Supplementary Table 1** for a sample of transcriptions) suggests that human-made ditches, pipes, canals, and ephemeral streams that flow only after precipitation events, do not qualify as watercourses protected under environmental policies in most countries[14,16,18]. For example, the Queensland Water Act in Australia stipulates that "*a watercourse is a river, creek or other stream,* […]*, in which water flows permanently or intermittently, regardless of the frequency of flow events (a) in a natural channel, whether artificially modified or not; or (b) in an artificial channel that has changed the course of the stream* […]*. However, a watercourse does not include a drainage feature*"[29], which is "*a natural landscape feature, including a gully, drain, drainage depression or other erosion feature that (i) is formed by the concentration of, or operates to confine or concentrate, overland flow water during and immediately after rainfall events; and (ii) flows for only a short duration after a rainfall event, regardless of the frequency of flow events; and (iii) commonly, does not have enough continuing flow to create a riverine environment*"[30]. Whether a depression is an active channel and where its upstream limit is may be debatable[31], but disagreements more often arise about what "natural" means, and how often water must be present in a channel for it not to be considered ephemeral. Humans have modified water drainage directly (e.g., diversion, channelization, piping, burying, infilling) or indirectly (e.g., land-use and climate change) for hundreds to thousands of years in many regions, re-shaping entire riverscapes[32]. For example, 100,000 water mills had been built along French rivers by the end of the 18th century[33]; 97.8% of total stream length in Denmark has been channelized[34]. Therefore, maps of the pre-transformation "natural" hydrography of most regions do not exist and, regardless, would give an erroneously static view of continuously shifting landscapes[32]. Furthermore, every river network includes intermittent and ephemeral segments[24] that provide valuable ecosystem services, but most are undifferentiated, miscategorized or absent on topographic maps[35–37]. Consequently, ascertaining whether a body of flowing water is intermittent or ephemeral requires field visits to observe flow multiple days after the last rainfall during a wet period of the year[38] (though proxies of flow duration are commonly used[39]). In short, both criteria – of naturalness and flow permanence – leave room for interpretation and often require a field visit.

The aim of this study was to examine the implications of the legal definition and regulatory mapping of watercourses on the extent of river networks protected under environmental laws, using France as a case study. Regulatory mapping involves creating a cartographic inventory that identifies which waterbodies, regardless of their presence on previous topographic maps, legally qualify as watercourses and are thus subject to legal protection. We present the first regulatory map of watercourses that fall under the Water Law in France, quantitatively show that the associated mapping strategy led to inconsistent protection of watercourses, and explore the potential socio-environmental factors influencing these geographic differences in regulatory watercourse maps. We then demonstrate how regulatory watercourse maps in France disproportionately exclude non-perennial and headwater streams, which we collectively refer to as vulnerable waters due to their susceptibility to degradation (following [25,40–42]). In light of the scientific literature, we discuss how exposing vulnerable waters to degradation can alter the ecological condition of freshwater ecosystems (i.e., their physical, chemical, and biological characteristics and processes) and their contribution to people across entire river networks. Finally, we compare our findings to analyses conducted in the US, the only other country where a similar assessment exists, and advocate for research in other countries to examine the implementation of regulatory frameworks for watercourse protection and its implications for ecosystem and human health.

Materials and Methods

1.1. Case study context : regulatory mapping of watercourses in France

The Water Law represents a cornerstone of environmental policy for the protection of freshwater ecosystems in France. Once a watercourse is protected under the Water Law, all installations, structures, works, or activities on or near this watercourse are subject to environmental authorization if they may pose risks to public health and safety, impede the free flow of water, diminish the water resource, markedly increase the risk of flooding, or seriously harm the quality or diversity of the aquatic environment (Article L.214-3 of the Environmental Code). Yet what characterizes a watercourse in the eyes of the Water Law was undefined until recently. Only in 2015 did a government directive provide a formal definition[43] (translated in **Supplementary Methods Section 1**), now legally inscribed in the French Environmental Code: a body of flowing water legally qualifies as a watercourse if it meets three criteria: 1. having a channel of natural origin (i.e., even if subsequently modified), 2. being fed by a source other than precipitation alone, and 3. carrying "sufficient flow most of the year" – flow can be intermittent, considering local hydroclimatic conditions (Article L.215-7-1 of the Environmental Code; **Supplementary Table 1**). This codification was meant to appease rising tensions between water law enforcement, farmers, municipalities, and environmental organizations that frequently led to court cases and appeals, with overlapping and sometimes contradictory rulings[38,43,44]. Beyond defining watercourses, the 2015 directive tasked decentralized government authorities of the second smallest administrative division level in France (departments) to draw comprehensive maps of watercourses across their jurisdiction[43]. Based on the newly minted national definition, each department was to devise and implement a mapping protocol in collaboration with local stakeholders to differentiate watercourses from ditches, canals and ephemeral streams. The objective of this decentralized process was to promote a local "pragmatic" approach ensuring stakeholder buy-in and addressing variations in geography, climate and water uses among regions[43]. Since then, multiple governmental and journalistic reports have anecdotally mentioned large portions of the river network being disqualified as "non-watercourses" in some departments[45,46]. However, departmental regulatory maps of watercourses have never been merged, including by the national government, such that no national map exists and a comprehensive assessment of the implications of this cartography is still lacking.

The 2015 government directive established general guidelines to frame departments' mapping protocols (see **Supplementary Methods Section 1** for a translation), and several groups of departments (i.e., administrative *regions*) jointly refined those guidelines to seek coherence in their application to the regional context. Across France, departments first compiled existing sources of hydrographic data and identified watercourses whose status was either obvious (e.g., major rivers and tributaries) or consensual (e.g., established through other regulations). Then, they determined which remaining uncategorized hydrographic segment qualified as a watercourse – this process is still ongoing in many departments. Departments used cartographic methods and field visits to evaluate the legal criteria defining watercourses, often in collaboration with governmental agencies and stakeholders. We compiled all official and publicly available information about this process for each department, but the amount of documentation of this process differs vastly among departments and the degree of involvement of these various actors (e.g., training and supervision from governmental agencies) is seldom detailed. Mapping usually progressed in regular consultation with stakeholders to validate and publicize intermediate maps. Legal action cannot be taken against the resulting maps, but requests can be made to verify or edit them.

In plain language, the term *watercourse* usually refers to all bodies of flowing water. From here on, however, we differentiate the terms *rivers and streams*, *hydrographic segment*, and *watercourse* for the sake of clarity: *rivers and streams* refers to all flowing water bodies of natural origin regardless of their legal status; *hydrographic segments* includes all flowing water bodies represented on topographic maps regardless of their legal status and naturalness (i.e., including rivers and streams as well as canals, ditches, etc.); *watercourse* refers exclusively to those rivers and streams determined to be protected under the Water Law in France. *Watercourse* is the literal translation of *cours d'eau* in French (the term used in the Water Law), but also a common legal term used in environmental policies across many English-speaking countries (e.g., Canada, Australia, South Africa; **Supplementary Table 1**). The scope of the Water Law differs from several other laws regulating flowing waters in France (**Supplementary Table 1**). Nonetheless, this new cartography will eventually replace or complement the maps used to enforce several other laws. Throughout, we use the term "department" for both the administrative body and the geographic extent of a department.

1.2. Assembling the first national map of watercourses under the Water Law

To assemble a national map of watercourses that fall under the Water Law, we first compiled 91 individual regulatory watercourse maps in the form of GIS vector layers produced by the cartographic service of each department across mainland France (**Figure 1**). As of November 2023, all departments but one provided a regulatory map of watercourses online, and 74 (79%) provided online access to underlying data; 20 fully excluded non-watercourses from the maps. Therefore, we individually contacted departments to either request the entire dataset (if it was unavailable online), only excluded segments, or to confirm the currency of the dataset (see **Supplementary Methods Section 2** for more details on this compilation process).

Departmental datasets of watercourses protected under the Water Law came in widely differing formats, level of detail in metadata, and content, so we individually inspected, quality-controlled and harmonized all datasets before merging them. Datasets which differed in geometric type (some included watercourses as polygons representing buffers around each segment), projected coordinate system, character encoding, file naming, and file format (e.g., .TAB, .shp) were all converted into a common set of formats. Corrupt and invalid geometric records were identified and removed. If two records were fully overlapping geographically, we kept the record with the most amount of attribute information (i.e., ancillary information associated with each line in the digital maps), and the other one was deleted. The attributes associated with the data varied as well, with a total of 733 unique attribute names across all datasets. We harmonized attribute names for a limited set of essential attributes for subsequent analysis, like the status assigned to the hydrographic segment under the Water Law, the flow permanence status of the segment (i.e., perennial or intermittent) and the method of characterization of the segment (e.g., cartography, field expertise). Finally, because the different categories within each of these attributes were not consistent across datasets, we created a harmonized set of possible values for each attribute following formatting guidance provided to the departments by the National Office of Biodiversity (OFB) and the National Institute of Geographic and Forest Information (IGN)[47]. For the attribute describing the status of the hydrographic segments under the Water Law, for example, a total of 139 unique category names existed across the departmental maps, which we converted to 5 possible categories: watercourse, non-watercourse (i.e., not qualifying as a watercourse under the Water Law), uncategorized, inexistent and outside of the department. After removing all lines located outside of the department to which they were associated, we merged all departmental maps to produce a single national map. We did not include the Paris region (0.1% of the area of mainland France) in subsequent analyses because it represents an outlier, with more than 90% impervious cover and minimal surface drainage.

1.3. Comparison with other sources of data

We assessed the consistency of the regulatory maps of watercourses among and within departments by comparing the length of watercourses per unit area (i.e., drainage density) in these maps to the main hydrographic basis used by departments for mapping watercourses. Prior to the mapping of watercourses by departments for the purpose of the Water Law, two main hydrographic datasets already existed in France: BD TOPO and BD Carthage. Neither was officially considered to be a national reference for legal purposes because they were not exhaustive enough (omitting an estimated 10-30% of the drainage network depending on the area)[47]. They also did not enable a complete assessment of the watercourse identification criteria through cartographic analysis. Notably, no dataset consistently differentiated watercourses from ditches or canals, or intermittent from ephemeral features (the latter regime being disqualifying). Nevertheless, BD TOPO was used by departments as the starting point for the cartography of watercourses, to be completed by BD Carthage and case-by-case analysis with other cartographic sources (i.e., scanned topographic maps, current and historical cadastral maps) and field expertise. We provide a description of the characteristics and limitations of these datasets in **Supplementary Methods Section 3** and in the discussion section *Limitations and uncertainties*.

We quantified the difference in drainage density between the departmental watercourse maps and BD TOPO (version 151 of 2015)[48] as the ratio in drainage density between the two (excluding sub-basins with missing data, totaling 3.4% of the country's area; see **Supplementary Methods Section 4** for details on identifying these sub-basins). We focused on this drainage density ratio (DDR) because 36 (40%) departments provided either no or partial data on non-watercourses (i.e., some or all hydrographic segments present on source maps deemed not to qualify as watercourses were removed from the resulting regulatory map rather than labeled as "non-watercourse") and because drainage density naturally varies among regions[49], so we did not expect constant drainage densities across and within departments. DDR also provides a scale-agnostic metric to compare departments or sub-basins regardless of differences in total network length –thus representing a measure of deviation rather than absolute network length. We conservatively assumed in our main results that uncategorized segments by departments would be considered as watercourses. To understand variations in DDR at multiple scales, we analyzed DDR both across departments (average area: 6 x 10^3 km^2) and among consistently sized sub-basins within departments (average area: 67 km^2). Therefore, DDR for a given sub-basin or department (excluding incompletely mapped sub-basins) was simply computed as:

$$DDR = \frac{\sum segment\ length_{watercourse} + \sum segment\ length_{uncategorized}}{\sum segment\ length_{BD\ TOPO}}$$

1.4. Analyzing socio-environmental correlates of drainage density ratio

We quantified the relationships between DDR and various socio-environmental factors with regression models at our two scales of analysis: among departments, and among sub-basins within departments (see **Supplementary Methods Sections 5 to 7** for a full description of this workflow). Our goal was to understand potential mechanisms driving the observed differences in DDR among departments, and the different ways that the identification criteria were applied to identify watercourses across departments. For example, a strong negative relationship between aridity and DDR among sub-basins of a department would imply a particular emphasis in that department on the flow permanence criterion for differentiating watercourses from non-watercourses (and likely a pronounced gradient in aridity across the department). Strongly contrasting relationships among departments suggest a potential difference in the application of that criterion.

To conduct this analysis, we first extracted 20 variables for each sub-basin, describing anthropogenic land covers (i.e., agriculture, impervious area), irrigation, population density, barrier density, soil texture, slope, and aridity. **Supplementary Table 2** details the source of each dataset and **Supplementary Methods Section 5** describes each dataset and how it was pre-formatted to compute summary statistics for each sub-basin. These datasets were selected for two reasons. First, because we hypothesized that the associated variables could influence the proportion of hydrographic features deemed as non-watercourses, and second because of their availability at a sufficient resolution and consistency across France. We used socio-environmental variables rather than all variables potentially explaining absolute drainage density across the landscape because our focus was on deviations in drainage density from the reference hydrographic dataset BD TOPO. We particularly focused on factors which could affect the criteria used in identifying watercourses: naturalness of the channel and flow permanence. Therefore, we selected variables reflecting the degree of alteration of the riverscape (land cover, irrigation, barrier and population density) as well as the relative prevalence of non-perennial rivers and streams (aridity, slope, predicted prevalence of flow intermittence, soil water storage capacity, irrigation and water withdrawals; **Supplementary Table 2**).

To examine the relationship between DDR and socio-environmental factors across departments, we developed a single regression model. To analyze DDR among sub-basins within departments, we developed regression models for groups of departments. We first examined the Spearman's rank correlation coefficients between every socio-environmental variable and drainage density ratios across sub-basins in each of the 90 departments (**Figure 3**). We then statistically identified groups of departments that displayed similar correlation coefficient values across all predictor variables. Finally, we developed a regression model for each of those groups. This grouping was meant for us to get a general understanding of the different sets of relationships present in the dataset, considering the large number of departments (90), sub-basins (6523) and variables (20), and to look for possible geographic patterns in those relationships. It also enabled us to neither develop 90 tailored models for individual departments nor build a single model for all departments (see **Supplementary Methods Section 7** for additional discussion on this modeling approach). For each model, we tested department-specific intercepts as well as fixed-effect interactions between departments and predictors to allow for department-specific coefficients. Regression models were developed through manual forward model selection and standard diagnostics[50,51] (**Supplementary Methods Sections 6 and 7**).

1.5. Evaluating implications for river network structure

We analyzed the potential impacts of excluding segments from watercourse maps on the structure of river networks in two ways. First, we estimated the proportion of headwater and non-perennial segments excluded from maps. Here, we define headwater segments as hydrographic segments of Strahler order one (i.e., first-order reaches). Non-perennial segments were identified based on attributed information from the departmental watercourse maps, BD TOPO, and BD Carthage. Substantial processing was required to conduct these analyses and some uncertainty remains about those results; see **Supplementary Methods Sections 3, 8, and 9** for the detailed description of this analysis. We then computed *representativeness* as a measure of the over- or under-representation of certain types of segments in non-watercourses. The representativeness of first-order segments among non-watercourses was calculated as the ratio between the percentage of non-watercourse length that is of first order and the percentage of the total network length that is of first order. The representativeness of non-perennial segments among non-watercourses was calculated as the ratio between the percentage of non-watercourse length with a defined flow permanence status that is intermittent over the total percentage of network length with a defined flow permanence status that is intermittent. Finally, the representativeness of vulnerable waters among non-watercourses was calculated as the ratio between the percentage of non-watercourse length that is either intermittent or of first order (or both) over the total percentage of network length that is either intermittent or of first order (or both).

Second, we analyzed potential network fragmentation resulting from non-watercourses and uncategorized segments by identifying individual segments surrounded by other segments of a different category – for example, watercourses surrounded by non-watercourses (i.e., isolated segments), or non-watercourses surrounded by watercourses (i.e., fragmenting segments). Due to the limitations of the geometric networks in terms of missing non-watercourse data and topology (see **Supplementary Methods Section 8**), this analysis was possible for only a subset of the segments. In addition, we excluded all isolated or fragmenting segments that were within 10 m of a standing waterbody. Indeed, many departmental maps assigned the same category to all segments going through or near a standing waterbody (some departments classified them all as uncategorized or all as watercourses, etc.) regardless of the surrounding segments, even though these hydrographic segments do not correspond to an actual channel on the ground and regulatory maps of standing waterbodies are distinct from watercourse maps.

Results and Discussion

1.6. A complete yet inconsistent regulatory map of watercourses

The regulatory cartography of watercourses in France represents a monumental undertaking by departments. As of 2023, the national map of watercourses covers 93% of mainland France and includes 2.2 million segments totalling 6.8 x 10^5 kilometres (**Figure 1**). As a comparison, the global river network HydroRIVERS[52] includes 6.2 million segments. Although most hydrographic segments were classified through cartographic analysis, the amount of field expertise required to follow governmental guidelines was substantial (**Supplementary Methods Section 1**)– in one department alone, over 55,000 segments were expertized through field visits.

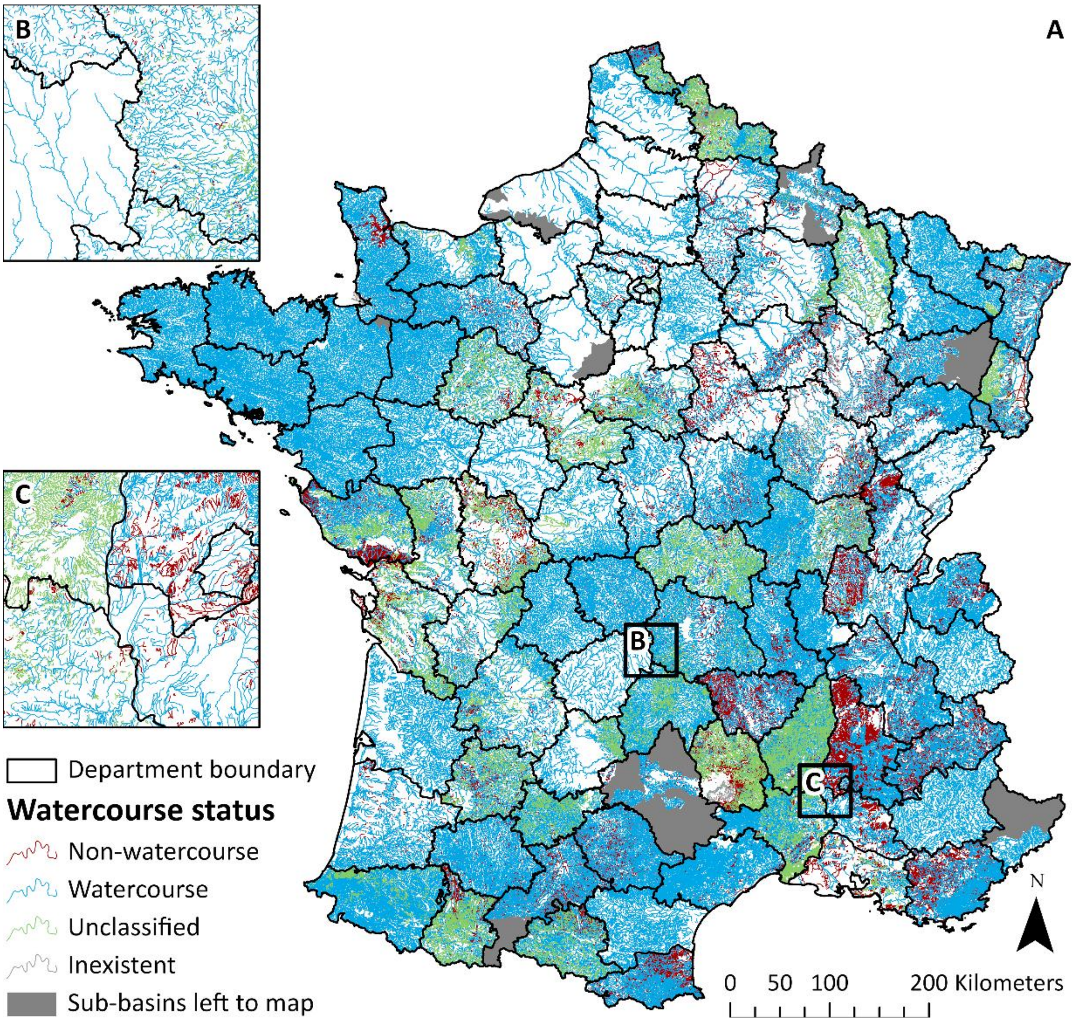

Figure 1. National map of watercourses protected under the Water Law in mainland France as of 2023. The insets (**B and C**) are illustrative cases of discontinuities in drainage density or watercourse status distribution across neighboring departments. Grey areas show sub-basins where the legal status of hydrographic segments is either still actively being assessed by departments or individually determined only upon request by a stakeholder.

Despite the apparent comprehensiveness of the map, our assessment reveals diverse and inconsistent interpretations across France of the same definition of watercourses (**Figure 2**). We estimate that about a quarter of previously mapped hydrographic segments, by length, were disqualified as non-watercourses (i.e., excluded from protection under the Water Law; based on an assessment spanning 84% of the country's area; **Table 1**; **Supplementary Methods Section 9**). DDR varied considerably, both between departments (mean departmental DDR ± SD = 0.82 ± 0.26) and within a given department (average range in DDR among sub-basins within a department ± SD range = 1.24 ± 1.54; excluding sub-basins under 10 km^2; **Figure 2**). Neighboring department maps could have starkly different drainage densities (**Figure 1B-C**). Eighteen departments were particularly inclusive and complemented BD TOPO with alternative sources of hydrographic data in mapping watercourses, so that their department-wide drainage density exceeded that of BD TOPO. By contrast, 15 departmental maps exhibited a DDR under 0.5, indicating that vast swaths of the hydrographic network were disqualified as non-watercourses.

Table 1. Summary statistics of regulatory maps of watercourses by Strahler stream order (SO) based on a subset of 68 departments with sufficient data[1].

SO	Length (10^3 km | %)			% length w flow regime	Representativeness among non-watercourses	
	Total analyzed	Non-watercourses	Non-perennial		Stream order	Non-perennial
1	270	83.0 | 31%	188 | 80%	87%	1.3	1.1
2	113	21.0 | 19%	69 | 65%	94%	0.8	1.3
3	47	4.5 | 10%	20 | 43%	97%	0.4	1.8
4	17	0.8 | 5%	4 | 25%	98%	0.2	2.3
5	3	0.1 | 4%	0.5 | 16%	99%	0.2	3.2
NA	190	38.0 | 20%	62 | 35%	94%	0.9	1.5
Total	**639**	**147 | 23%**	**344 | 59%**	**91%**	**1.0**	**1.3**

[1] spanning 84% of the country's mapped area; see **Supplementary Methods Section 9** for details on identifying departments with sufficient data.

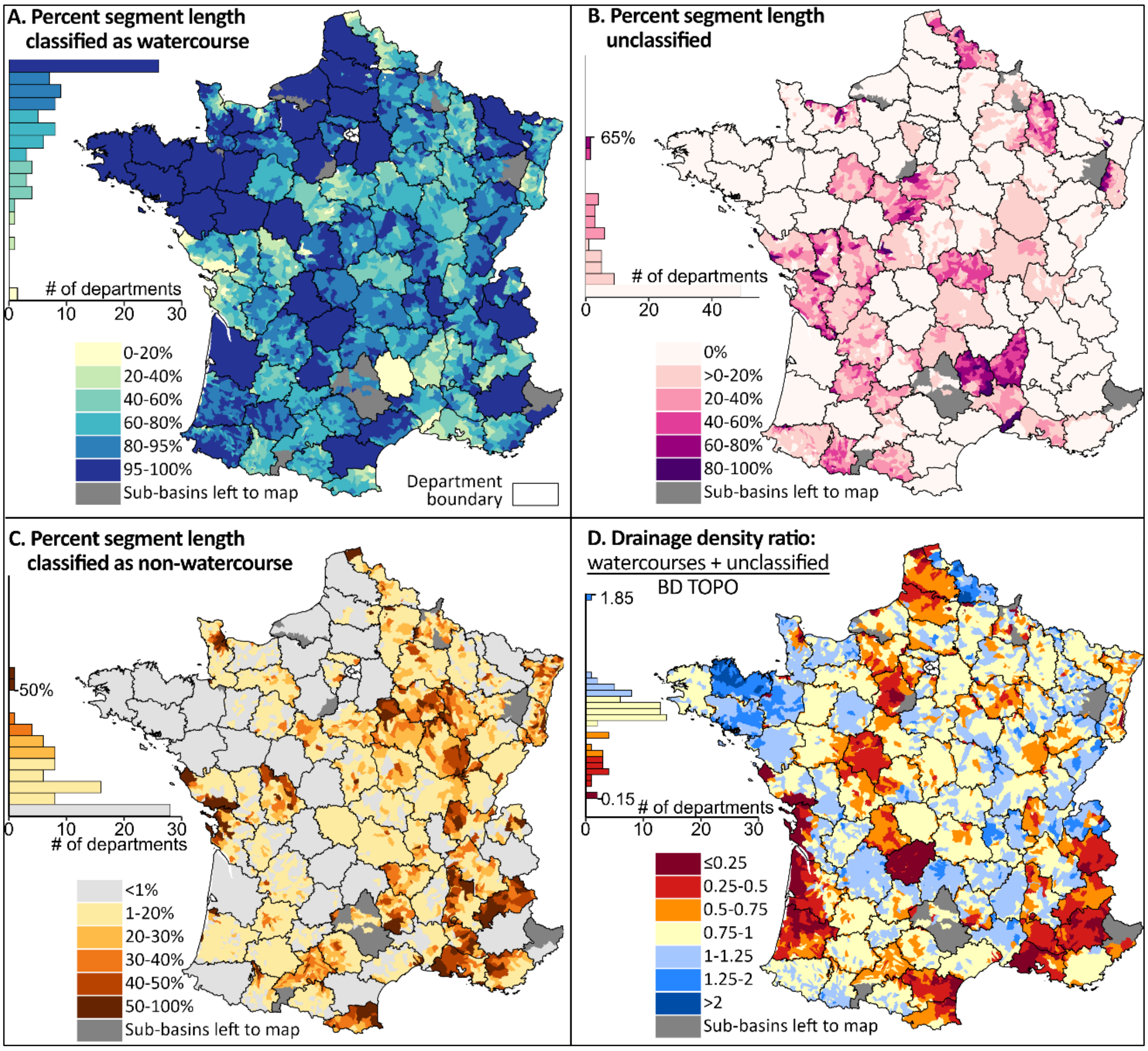

Figure 2. Relative prevalence of categories in departmental maps of watercourses under the Water Law in France (A-C) and drainage density ratio (DDR; D) between the regulatory maps of watercourses and reference hydrographic data from BD TOPO.

Maps show statistics by sub-basin whereas histograms show the distribution of statistics by department; the average area of sub-basins (after intersection with departments) is 67 km^2. DDR was computed assuming that unclassified segments in watercourse maps would by default be considered watercourses unless otherwise expertized.

1.7. Correlates of drainage density ratio daylight uneven mapping criteria

Whereas differences in DDR among departments were weakly correlated (|Spearman's ρ|≤ 0.4) to socio-environmental variables (**Supplementary Table 3**), within-department differences in DDR (i.e., among sub-basins) were moderately to strongly correlated to several socio-environmental factors (**Figure 3**). A widespread pattern was for DDR to be lower in drier basins with greater cultivated cover (**Figures 3 and 4**, **Supplementary Table 4**). The extent of winter crops (straw cereal and winter and spring oilseeds), in particular, was commonly associated with lower DDR. Those relationships significantly varied among departments, however, further demonstrating that the official criteria defining watercourses were unevenly implemented across the country. Moreover, there was limited geographic clustering in which factors were associated with DDR variations across France (**Supplementary Figure 1**).

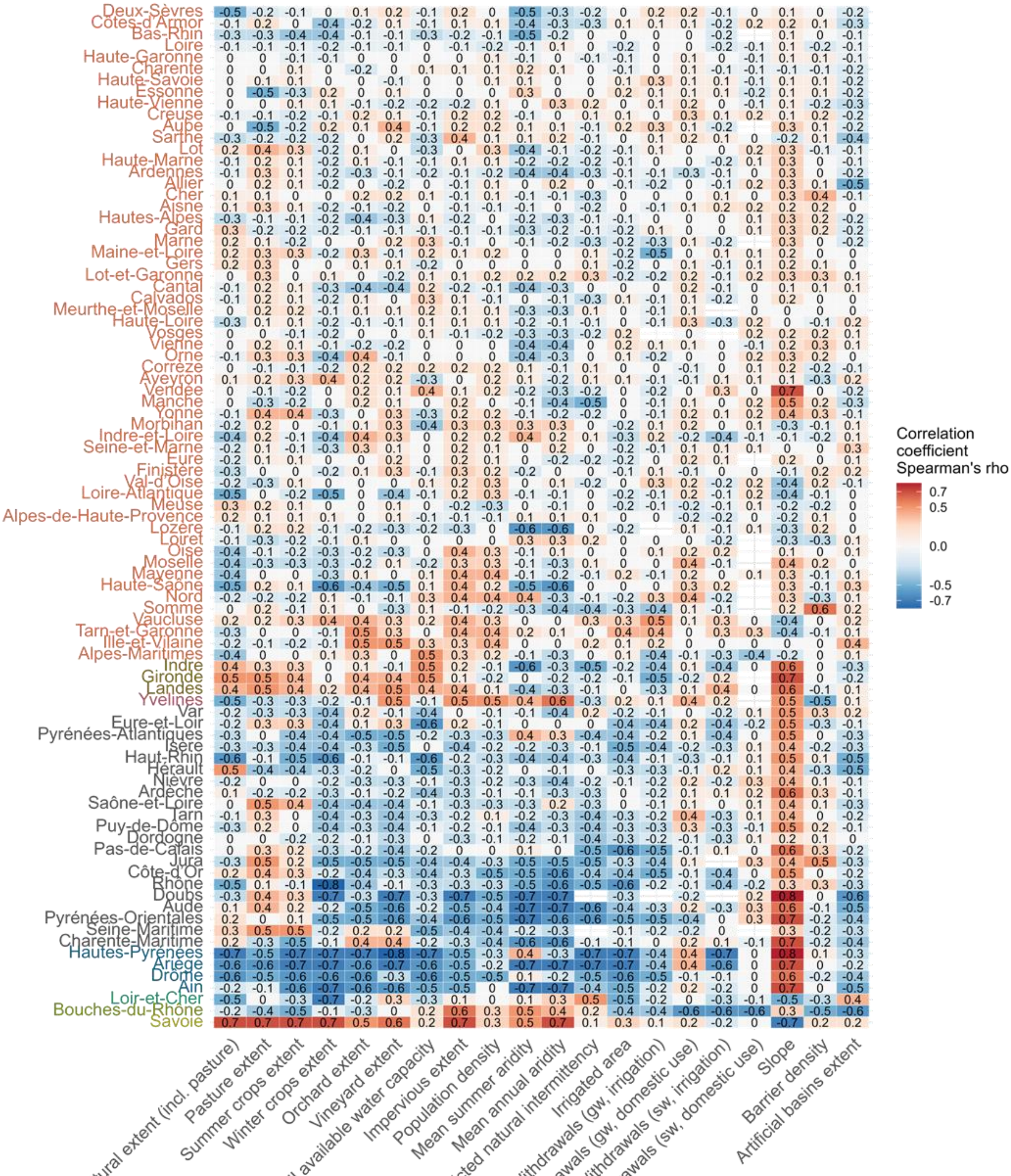

Figure 3. Heatmap of Spearman's correlation coefficients between socio-environmental variables and within-department variations in drainage density ratio (DDR). For a given department (row), a negative correlation (blue color) means that an increase in that variable (column) translates to a decrease in DDR – the ratio of the length of watercourses deemed to be protected by the Water Law and the total length of hydrographic segments mapped in BD TOPO in that department. Departments are grouped to minimize the dissimilarity in correlation coefficients between adjacent rows, and the colors of the department names correspond to groups of departments that displayed similar correlation coefficient values across all predictor variables (see Methods section *Analyzing socio-environmental correlates of drainage density ratio*).

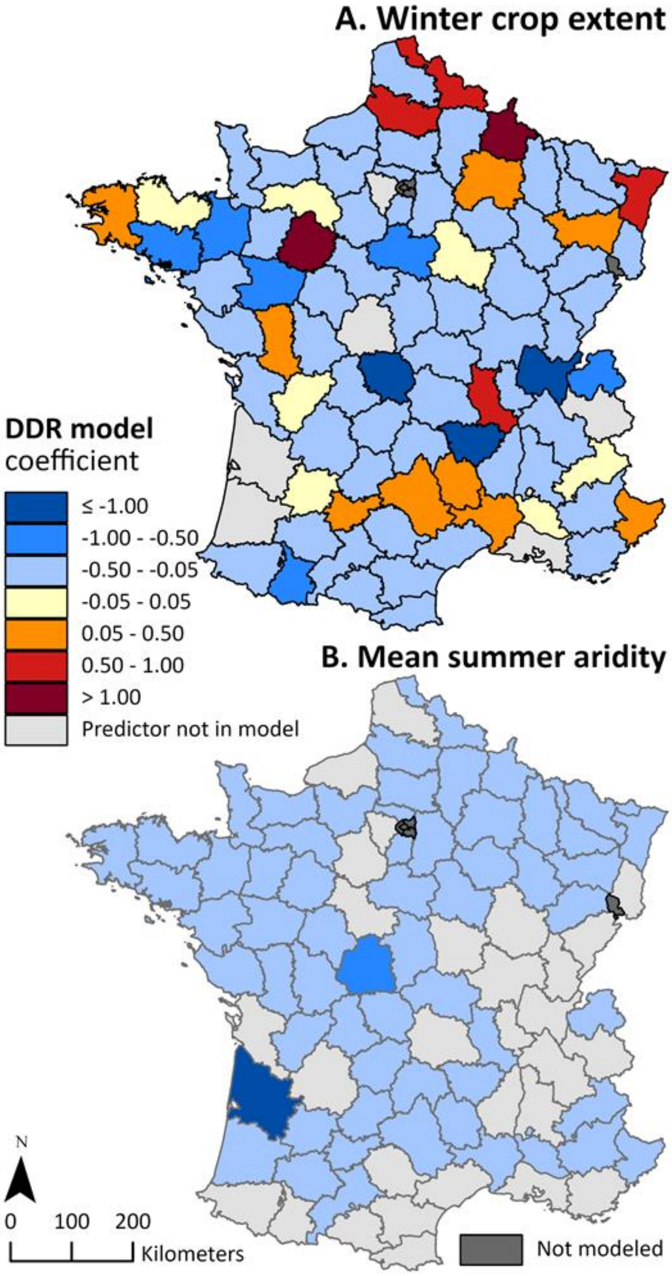

Figure 4. Distribution of coefficients from regression models of drainage density ratio (DDR) across sub-basins within departments for two socio-environmental variables. LSummer aridity was computed as the long-term ratio between potential evapotranspiration and precipitation from June to August. Winter crop extent (as a percentage of sub-basin area) was square-root transformed. For B, a coefficient of -0.5 for a given department means, all things being equal, that a 10% increase in summer aridity from one sub-basin to the next is associated with a mean decrease of 5% in watercourse length compared to BD TOPO (i.e., a 0.05 decrease in DDR). Departments with five sub-basins or less were excluded from the analysis. See **Supplementary Table 2** for data sources, **Supplementary Table 4** for model specifications and **Supplementary Methods Section 7** for details on the modeling approach.

1.8. Vague definitions put vulnerable waters at risk

The definition of watercourses under the Water Law disproportionately exposes headwater and non-perennial segments – already vulnerable ecosystems[42,53] – to human alteration. We estimate that non-perennial segments comprise nearly 60% of the mapped hydrographic network length but make up about 80% of hydrographic segments which have been disqualified as non-watercourse (**Table 1**). Similarly, first-order segments represent at least 42% of the national hydrographic network length but 56% of disqualified segments in watercourse maps. Taken together, non-perennial and first-order segments are overrepresented in non-watercourses by 28% compared to their prevalence (67%) in the overall hydrographic network (**Table 1**, **Figure 5**).

The apparent dismissal of headwater and non-perennial streams in this cartography is unsurprising considering the ambiguous stipulation in the new definition that a channel must carry "sufficient" flow from a spring most of the year to qualify as a watercourse[43]. The definition also specifies that "flow can be intermittent, considering local hydrological and geological conditions"[43], leaving ample room for interpretation. In a survey of 25 government employees responsible for mapping watercourses in 12 departments of eastern France, respondents considered flow duration to be both the most common criterion for disqualifying segments as non-watercourses, and the most challenging to evaluate[54]. Considering ongoing and future changes in flow intermittence due to climate change across France[55,56], this criterion is likely to become increasingly difficult to appraise. It is not our goal to evaluate which classified segments we would ourselves deem to be non-watercourses or to critique specific departmental maps. Nonetheless, considering differences among departments in representativeness of vulnerable waters (**Figure 5**) and geographic variability in socio-environmental correlates of DDR (**Figures 3 and 4**, **Supplementary Table 4**), it is probable that numerous ecologically valuable, yet sensitive streams now lack protection under the Water Law.

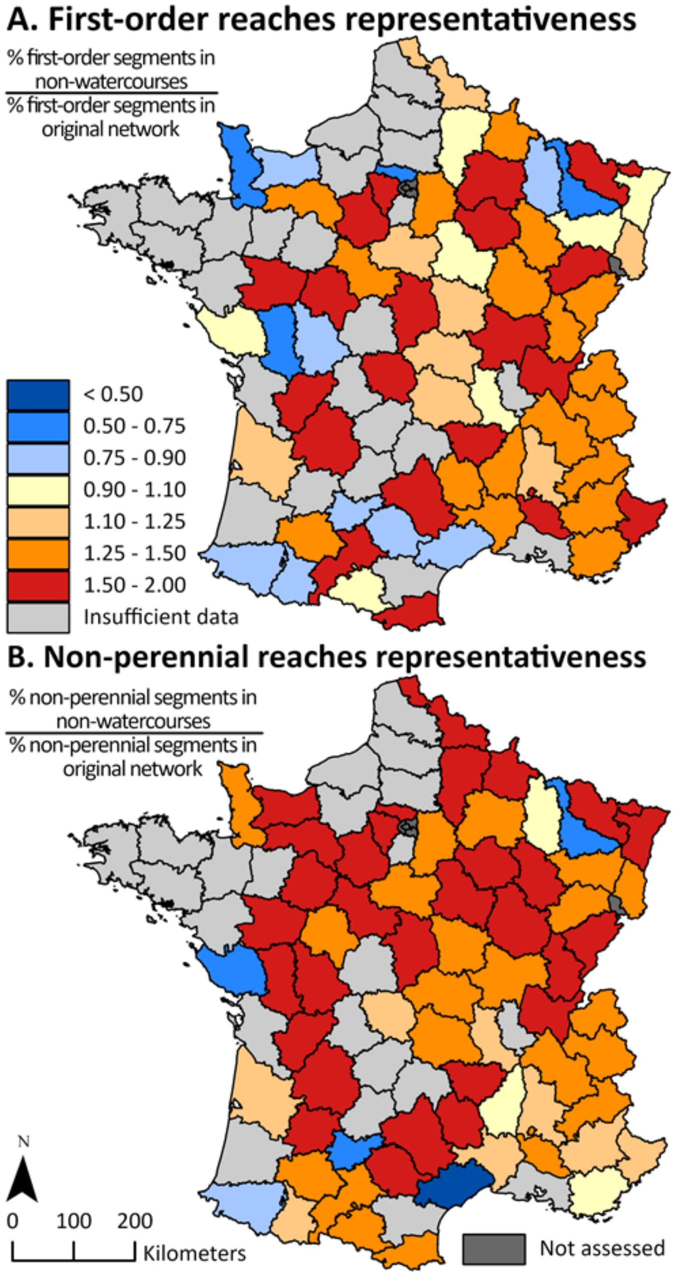

Figure 5. Representativeness of first-order and non-perennial segments among non-watercourses in departmental maps. Positive values indicate departments where headwater and non-perennial segments are disproportionately classified as non-watercourses (i.e., overrepresented) compared to their prevalence in the original hydrographic network. For A, in a department where first-order segments make up 60% of network length, a value of 1.5 means that 90% of non-watercourses are first-order streams. Departments where data on non-watercourses were incomplete and where less than 90% of the network could be matched to BD TOPO segments were not analyzed (see **Supplementary Methods Section 9** for details on the analytical approach).

The widespread disqualification of headwater and non-perennial segments as non-watercourses threatens freshwater ecosystems already under pressure. The capillary network of streams at the interface between land and water is both fundamental to the water quality, biodiversity, and ecological conditions of the entire river network, and uniquely vulnerable[25,57,58]. Headwater streams are the main point of entry for water, solutes, mineral sediment, and particulate organic matter in the aquatic environment, provide habitat and refuge for diverse riverine and riparian species, and support essential ecosystem services[58,59]. The spatial and temporal dynamics of drying and rewetting in non-perennial segments, most but not all of which are small streams, is also a strong driver of local biotic communities, ecosystem processes and ecosystem services[24]. Because of their abundance and connectivity to the rest of the landscape, headwater and non-perennial segments are especially vulnerable to degradation[53]. And while the functional loss of a single watercourse may have marginal impacts on downstream waters (though not always[60]), widespread alteration of these vulnerable waters can cumulatively have network-scale consequences on the hydrology, biogeochemistry, and ecology of aquatic and terrestrial ecosystems[23,25]. Land cover alterations along headwater segments, for example, can impact water quality far downstream[20,61,62]. In an analysis of 68 watersheds of eastern Kansas (USA), water chemistry parameters in downstream segments were more closely correlated to riparian land cover along first-order streams than the riparian cover nearby (two and four kilometers upstream) or across the whole watershed[20]. Such longitudinal connectivity also affects ecosystems services: the domestic water supply of the City of Albuquerque (New Mexico, USA) was interrupted for 66 days following a forest fire spanning less than 2% of the total watershed area, in tributary catchments about 50 km upstream[22].

Both headwater and non-perennial streams have been historically underappreciated and under-protected across the world, and many are already absent from hydrographic maps, despite comprising the majority of the river network[24,40,42]. As such, their disproportionate exclusion from many of the departmental maps of watercourses in France is only the continuation of a long-standing lack of recognition and protection that risks further deteriorating the ecological quality of entire river networks. Disqualifying hydrographic segments as non-watercourses in higher-order streams too can threaten the ecological conditions of river networks through fragmentation. If a non-watercourse is surrounded by watercourses or connected to groundwater, this unprotected segment may result in functional or physical disconnection of the network through unregulated water abstraction or physical alteration. Inversely, a watercourse surrounded by non-watercourses is functionally unprotected. We identified over 1500 such cases across France based on a preliminary analysis but expect that many more exist.

1.9. Hydrography is social and political

The mapping of watercourses over the past decade in France is remarkable for being decentralized and consultative, at least in theory. This approach aimed to smooth relationships between government agencies and stakeholders by including local expertise and establishing a common knowledge base of flowing waterbodies subject to regulation[43]. In most departments, the resulting maps reflect a massive cartographic and consensus-building effort on the part of multiple stakeholders. However, the consultation process has been tense and polarizing in other departments[44,45], and the amount of fieldwork required to diligently assess the criteria for identifying watercourses was not equally realistic across departments considering their respective resources. Unfortunately, the national outcome therefore lacks coherence, reflecting stark differences in the implementation of the definition of watercourses with potentially deleterious consequences.

The tendency for fewer hydrographic segments to qualify as watercourses in basins with greater agricultural cover may partly be the outcome of power asymmetries in consultation committees considering the strong documented mobilization of farmers' unions in this mapping process[44-46]. The enactment of the government directive defining watercourses in 2015 was received as a success by most agricultural unions, following years of advocacy on their part, and was followed by calls to mobilization of their members[63]; for example, the largest farmer's union in France published a "*Support guide for the identification of watercourses*"[63] a month after the decree, urging its members to get involved, drive and expedite the cartographic and consultation process, to limit and supervise field visits to minimize the use of ancillary criteria (e.g., the presence of aquatic organisms), and to ask departmental authorities to make the resulting cartography legally binding. In Seine-et-Marne for example, where cultivated areas cover nearly 60% of the department, environmental NGOs were not initially included in the mapping process, the department received nearly 500 requests to classify a hydrographic segment as a non-watercourse, and conflicts between stakeholders eventually led the governmental agency in charge of supervising the cartography to fully remove itself from the process of field expertise, so that it would no longer "be held responsible for a downgrading decision"[64].

Recent decades have witnessed a growing scholarly recognition of the intricate relations between humans and water[2,8,11,12,65] and, more broadly, an awareness of the hydro-social cycle, the "socio-natural process by which water and society make and remake each other over space and time"[12]. Based on our analysis, we argue that the regulatory definition and mapping of watercourses, in France and elsewhere (**Supplementary Table 1**), is a striking illustration of this cyclicity of human-water relations (**Figure 6**). On the one hand, rivers, streams and other hydrographic features as depicted on topographic maps represent a physical reality which results from the historical interaction between climate, geology, biogeography, and the local socio-political and cultural context – forming a hybrid hydrography. A blue line on a topographic map may not correspond to any remarkable feature in the landscape today because the watercourse that used to be there has long been diverted or buried; a historically perennial stream may have become intermittent or ephemeral due to water withdrawals and climate change. On the other hand, we contend that watercourse mapping crystallizes a selective perception of the riverscape; this perception is the outcome of specific social relationships and power asymmetries[8,12,64]. The resulting maps in turn legitimize this perception[66]. They shape the relations between people and the riverscape (e.g., by determining what people can and cannot do), social interactions mediated through these relations, and eventually, the riverscape itself. The erasure of a watercourse on a regulatory map can translate to its actual erasure from the landscape by making it vulnerable to filling, ditching, damming, or water withdrawals.

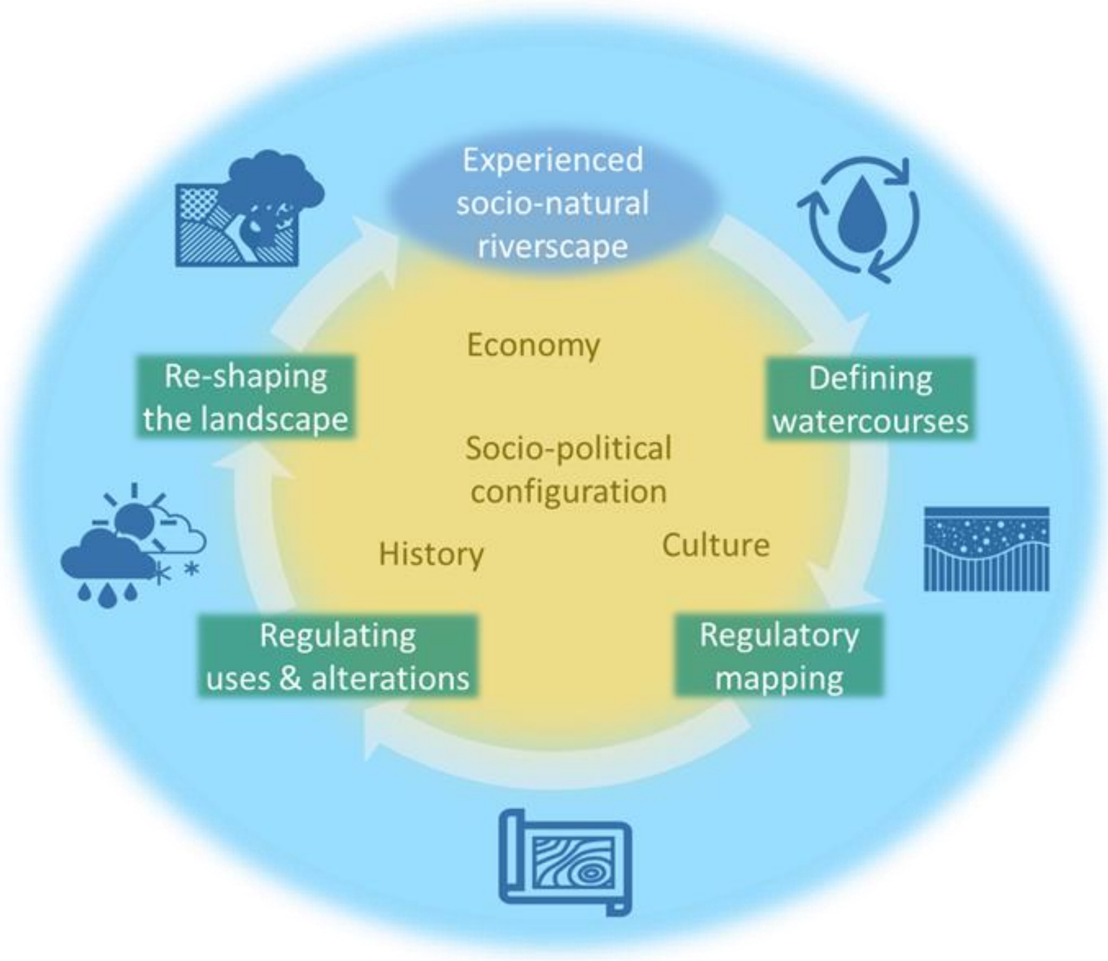

Figure 6. Mapping watercourses is part of a broader hydro-social cycle.
Current riverscapes result from the interaction of natural and societal factors. The boundary between these factors is porous -- societies are shaped by and shape their environment. The legal definition of watercourses stems from people's experience of this hybrid riverscape. For example, that ephemeral streams are not watercourses in their own right from a regulatory standpoint in many states of Australia comes from a Eurocentric legal heritage and does not match the reality of local ecosystems[16,67]. Once watercourses are defined and criteria are established to differentiate them from non-watercourses, our study demonstrates that the process of applying these criteria during mapping cannot be considered purely technical or abstracted from the local natural and socio-political context either. Regulatory maps define what features of the landscape are subject to regulation, which in turn governs humans in shaping or re-shaping the landscape, thus starting the cycle again. Credit for soil/lithology logo: Andy Miranda.

1.10. Limitations and uncertainties

Our analyses of DDR, socio-environmental correlates of DDR, and the representativeness of headwater and non-perennial segments come with several limitations and uncertainties. First, while BD TOPO was the official cartographic basis used by departments in mapping watercourses, it is not uniform nationally, which may partly explain the observed variability in DDR. For example, drainage density in BD TOPO is known to be underestimated in forested areas due to a reliance on aerial imagery[47], and many artificial segments and headwater streams are missing as the underlying topographic maps were historically drawn for army intelligence[47,68]. Second, non-watercourses were omitted from nearly a third of departmental watercourse maps, not all segments could be matched between watercourse maps and other hydrographic datasets, and there were numerous geometric artefacts (e.g., erroneously disconnected or looping segments, inaccurate flow direction) and complexities (e.g., multithreaded channels) in the digital river networks. These limitations entail uncertainty in our results (e.g., in the analysis of first-order streams; **Supplementary Methods Section 8**), constrained our analysis to the scale of sub-basins rather than individual river segments, and precluded the calculation of network-wide properties like connectivity. Third, the flow regime of many hydrographic segments was undetermined (**Table 1**) and is notoriously uncertain in topographic maps[37]. Ongoing efforts by national government agencies to quality-check and integrate the departmental maps of watercourses in a new national hydrographic dataset with improved topological integrity and attribute accuracy will enable those analyses in the future. Finally, the precise structure and coefficient values of the regression models presented here were selected through a structured approach, but each represents one of multiple valid alternative models to represent these relationships, owing to collinearity among socio-environmental correlates. Furthermore, the direction of causality between socio-environmental correlates and DDR cannot be conclusively presumed. For example, lower DDRs in sub-basins with a higher prevalence of winter crops may be simultaneously attributed to two main mechanisms: pressure from agricultural stakeholders to disqualify hydrographic segments as artificial non-watercourses in intensively farmed areas, and a stronger imprint by humans on these landscapes manifesting as a higher share of genuinely artificial drainage lines (and thus, a lower share of actual watercourses).

1.11. Lessons from France and the United States for the world

While we use France as a case study, inconsistent regulatory mapping and the associated exclusion of non-perennial and headwater segments is likely widespread beyond France and the United States (the only other country in which large-scale assessments of the extent of protected watercourses have been conducted[18,19,35]), as suggested by our cursory review of legal definitions across continents (**Supplementary Table 1**). In the case of the United States, a critical development in clarifying the definition of the "waters of the United States" protected under the Clean Water Act came with the 2006 Supreme Court's decision in *Rapanos v. United States*. This nationwide ruling temporarily led to the inclusion of water resources with a "significant nexus" to navigable waters (implying a biological, chemical, or physical connection)[13] by regulatory agencies. The significant nexus criterion, which has been discarded by the most recent Supreme Court's decision in *Sackett v. Environmental Protection*

Agency, was a rare acknowledgement of the connectedness of freshwaters and shifted the definitional focus from the characteristics of individual waterbodies to their role as part of a whole river network[23,40]. Despite representing a significant advancement at the time, this concept nonetheless had been instrumentalized to exclude large swaths of the country's river networks, with inconsistent implementations among administrative units[19,35]. Indeed, predictive models of the jurisdictional status of water bodies trained on approved jurisdictional determinations by the US Army Corps of Engineers following the *Rapanos* ruling performed better when political boundaries were included as a predictor[19]. Accordingly, we argue here that social, cultural, and political forces not only influence the definitions of watercourses but also shape the implementation of these definitions in previously underappreciated ways (**Figure 3**). A predictive model could similarly be developed to estimate what watercourses fall within the scope of the Water Law in France, but we expect that such an approach would not gain buy-in from stakeholders. Instead, we propose that quantitative methods should go hand in hand with political ecology to examine the complex relations at the core of water governance and seek decision-making structures that can transparently support the implementation of legal definitions of watercourses in France and beyond.

Regulatory mapping may seem technical and uncontroversial compared to other contentious issues of water governance like water allocation to different uses, barrier removal and restoration[8,33]. However, defining what features of the riverscape are protected by environmental regulations has major implications for the health of entire watersheds and the people that depend on them[14,25]. Excessive water withdrawals, pollution and direct alterations of river channels compromise drinking water quality, species diversity, nutrient cycling, flood regulation, and recreational activities, among other services which are essential for human well-being[5]. Watercourse mapping in France presented us with a natural experiment to quantitatively evaluate a cartographic expression of the hydro-social cycle playing out in over 90 individual departments. This case study, which echoes similar assessments in the United States[18,19,35], has broad and novel relevance. It distinguishes itself from the definitional disputes in the US[13] and Australia[16] because the physical criteria to differentiate watercourses from non-watercourses are firmly established at the national level. In France, we contend that the lack of a consistent framework governing the decentralized implementation of these criteria largely contributed to the observed inconsistencies. We hypothesize that this lack of governance structure enabled local power dynamics among stakeholders to translate into a selective perception of what counts as a watercourse in some departments. Here we took an innovative approach to daylight the implications of this specific process that can inform regulatory mapping elsewhere. We expect that regulatory frameworks for watercourse protection are similarly vulnerable to local interpretation yet equally unexamined in most countries, thus putting freshwater ecosystems and their critical contributions to people's well-being at risk.

Supplementary information

Additional results and methods, including examples of legislation on watercourses across continents, detailed data sources, statistical model results, and supplementary technical information on methods (PDF): https://pubs.acs.org/doi/10.1021/acs.est.4c01859.

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Centre Center Lyon-Grenoble - Auvergne-Rhône-Alpes
5 rue de la Doua, CS 20244
69625 Villeurbanne Cedex, France

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