Historical and future patterns of streamflow intermittence in Europe

Dynamiques historiques et futures de l'intermittence dans les cours d'eau d'Europe

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RÉSUMÉ

Même dans les climats humides, les petits cours d'eau peuvent s'assécher périodiquement, et dans les régions plus sèches, l'écoulement peut cesser pendant de longues périodes dans des grandes rivières. Le changement climatique est susceptible d'augmenter la prévalence des assecs, un phénomène structurant pour les écosystèmes et les services associés, mais les dynamiques temporelles et spatiales de l'intermittence restent mal connues. Dans cette étude, nous avons combiné un modèle hydrologique global, des observations de débit provenant de 3706 stations de gaugage, et un modèle de machine learning pour estimer les dynamiques spatiotemporelles passées et futurs de l'intermittence dans les cours d'eau d'Europe, sur plus de 1,5 million de segments de rivière. Entre 1981 et 2019, 17 % des segments ont connu au moins un jour sans débit. Les projections futures, basées sur cinq modèles climatiques et deux scénarios (RCP2.6 et RCP8.5), indiquent une augmentation des mois non-pérennes. Selon le scenario le plus pessimiste, 4,9 % des mois de rivière seront intermittentes d'ici les années 2080, contre 3,6 % en 1985–2014. Même les régions ou les précipitations annuelles sont amenées à augmenter pourraient voir des rivières historiquement pérennes devenir non-pérennes (2,7 % sous RCP8.5). La réduction des émissions (RCP2.6) pourrait limiter ces effets, mais l'augmentation saisonnière de l'intermittence, surtout en fin d'été, pourrait persister. Cette étude fournit des informations essentielles pour la gestion des écosystèmes aquatiques face au changement climatique.

ABSTRACT

Even in wet climates, small streams can seasonally dry up. In drier regions, large rivers may lack flow for extended periods. Climate change is expected to exacerbate these drying patterns, making streamflow intermittence—a critical factor for ecosystems and water supply—more widespread. However, its temporal and spatial dynamics remain poorly understood. Here, we combined a global hydrological model, streamflow observations from 3706 gauging stations, and machine learning to estimate historical and future patterns of streamflow intermittence in Europe across over 1.5 million river segments. For 1981–2019, we found that 17% of segments experienced at least one day without flow. Future projections, based on five climate models and two scenarios (RCP2.6 and RCP8.5), indicate an increase in non-perennial months under both scenarios, with 4.9% of all reach-months expected to experience no-flow days by the 2080s under RCP8.5, up from 3.6% in 1985–2014. While areas with reduced precipitation are most affected, even regions with increased rainfall may see shifts from perennial to non-perennial reaches (2.7% under RCP8.5). Mitigating greenhouse gas emissions under RCP2.6 could largely limit these effects, though seasonal increases in intermittence, particularly in late summer, may persist. This study provides a groundbreaking understanding of streamflow intermittence dynamics at a continental scale, offering critical insights for managing freshwater ecosystems under changing climate conditions.

KEYWORDS

river drying, climate change impacts, hydrological modeling, machine learning, large-scale modeling

assèchement des rivières, impacts du changement climatique, modélisation hydrologique, machine learning, modélisation large échelle

1 INTRODUCTION

Most streams and rivers on Earth periodically cease to flow or dry (Messager et al., 2021). While streamflow intermittence is most prevalent in semi-arid and arid regions of the globe, it is also widespread in humid regions. In France, for example, 25-60% of the river network is predicted to be non-perennial (Messager et al., 2024; Snelder et al., 2013). The recurring cycles of flowing, non-flowing, and dry phases in non-perennial rivers and streams are the primary determinant of ecosystem structure and functioning in these ecosystems (Crabot et al., 2021; Datry et al., 2014). Changes in streamflow intermittence due to climate change are thus expected to strongly affect freshwater biodiversity, ecosystem functions, and ecosystem services (Datry et al., 2023). Therefore, understanding future patterns of streamflow intermittence is critical for adapting water resource management to meet the needs of both society and ecosystems. However, we still lack quantitative estimates of climate change impacts on flow cessation at both the resolution and scale required for coordinated planning. Generally, we know that reductions in mean annual or monthly streamflow will lead to decreased low flows and more no-flow days, in particular as climate variability intensifies. Yet higher average streamflow might not systematically lead to decreased intermittence (Döll & Müller Schmied, 2012). Moreover, climate change is anticipated to cause complex seasonal shifts in streamflow intermittence, mainly due to corresponding changes in precipitation and runoff timing (Sauquet et al., 2021).

Most hydrological models struggle to accurately simulate intermittence patterns (Shanafield et al., 2021). Even with physically based approaches, hydrological models imperfectly capture the small-scale processes causing no-flow conditions, such as water losses from the river to the underground or variations in groundwater contribution (Mimeau et al., 2024; Shanafield et al., 2021). At even larger spatial scales, hydrological model predictions are too coarse to represent headwater streams, which are much more likely to be non-perennial than large rivers, especially in Europe. For instance, Döll and Müller Schmied (2012) used the global hydrological model (GHM) WaterGAP to predict where shifts between perennial and non-perennial river flow regimes may occur due to climate change. However, the low spatial resolution of the model (ca. 50 km) limited the scope of its projections. Here, we developed and applied a novel approach to estimate, for the first time, the temporal dynamics of streamflow intermittence across European rivers and streams, including small ones.

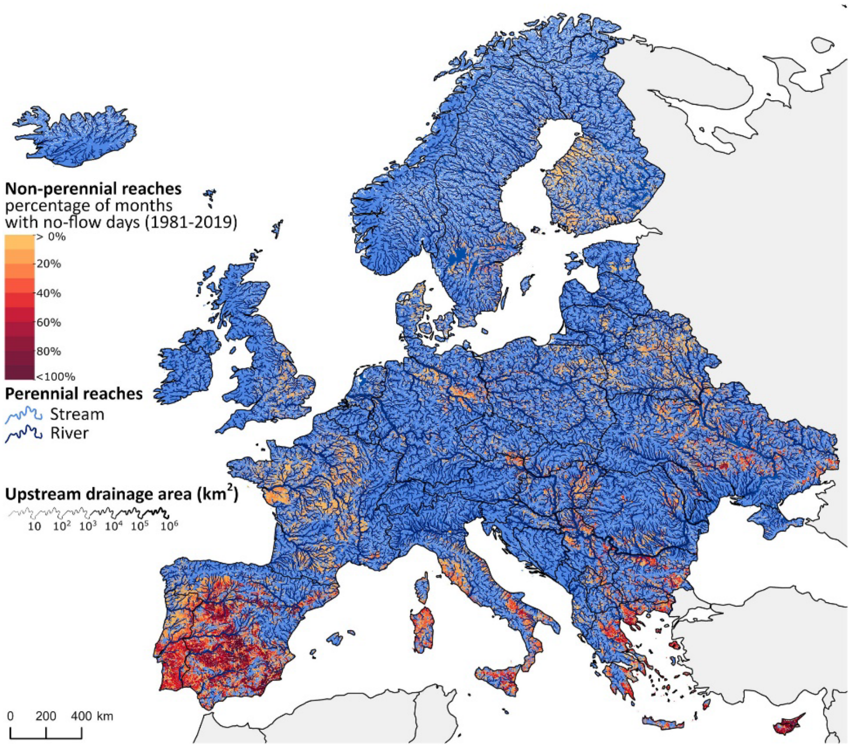
2. DATA AND METHODS

This hybrid approach combines the output of a GHM with streamflow observations and other data with a machine learning (random forest) model. We first refined the GHM model outputs available for 50-km cells to monthly streamflow in 500-m cells. We then applied a two-step random forest (RF) model to predict flow intermittence for over 1.5 million river segments as the number of no-flow days grouped into five classes (0, 1-5, 6-15, 16-29, 30-31 no-flow days) for each month from 1981 to 2019. The two-step RF model consisted of a first model predicting whether a month was perennial or non-perennial, and a second, for non-perennial months, classified the number of no-flow days into four categories (1–5, 6–15, 16–29, 30–31 days). A total of 23 predictor variables were employed, nine derived from the low-resolution global hydrological model (GHM) WaterGAP 2.2e and 14 from external sources describing climate, land cover, physiography, geology, and anthropogenic impacts. By incorporating human water use and reservoir effects, the model accurately reflected a range of river conditions, from natural to heavily influenced. We trained the random forest model with daily streamflow observations at 885 gauging stations with non-perennial and 2821 gauging stations with perennial flow conditions.

Building on this baseline, future projections were made for two climate change scenarios, RCP2.6 and RCP8.5, using outputs from five bias-adjusted global climate models (GCMs). Monthly streamflow simulations were downscaled to 500 m resolution, and changes between the historical period (1985–2014) and future periods (2041–2070 and 2071–2100) were quantified. In addition, we evaluated the applicability of our random forest approach for climate change impact modeling considering that future climatic conditions may lie outside of the predictor space used for model training.

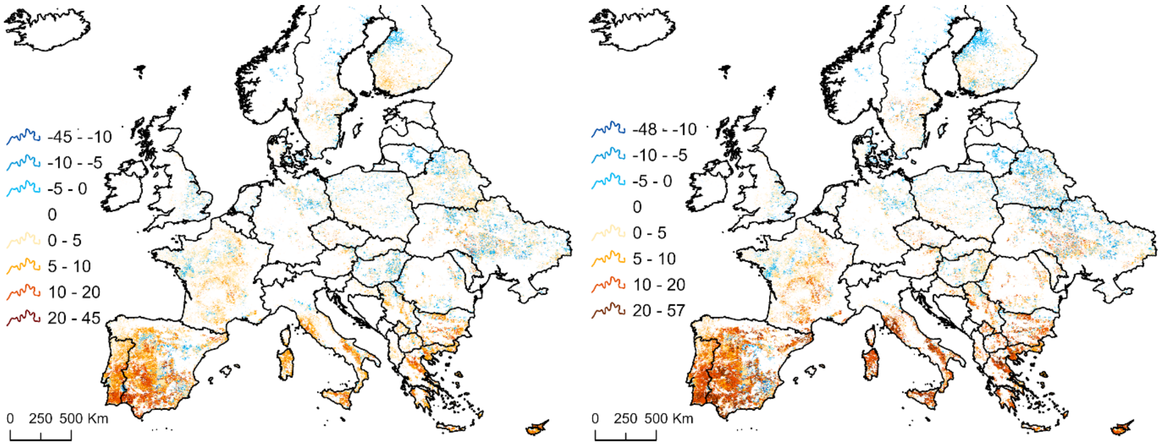
3. RESULTS

For 1981–2019, the model estimated that 17% of European river reaches experienced at least one no-flow day annually, predominantly in southern Europe. The RF approach achieved high classification accuracy, correctly identifying 98% of perennial and 86% of non-perennial months. This unprecedented high-resolution dataset provides a comprehensive historical baseline for assessing streamflow intermittence across Europe.



Percentage of months with at least one no-flow day for European stream reaches during the period 1981–2019.

Projections indicate an increase in non-perennial months under both scenarios, with 4.9% of all reach-months expected to experience at least one no-flow day by the 2080s under RCP8.5, compared to 3.6% in the historical period. While the Mediterranean region is most affected, even humid regions may see significant shifts from perennial to non-perennial conditions.



Ensemble median change in the percent of non-perennial months in 2041-2070 (left) and 2071-2100 (right) as compared to 1985-2014 [percentage points] under RCP8.5 (the most pessimistic climate change scenario) computed with the output of five Global Climate Models (GCMs).

The analysis also explored the spatial distribution of these changes across six aggregated climate zones. This zonal breakdown highlighted regional vulnerabilities, with Mediterranean and semi-arid areas experiencing the most significant increases in intermittence. Even under the moderate RCP2.6 scenario, late-summer drying is expected to intensify, emphasizing the need for climate change mitigation to reduce impacts on water-dependent ecosystems and human water use.

The study assessed the uncertainty induced by variability in predictions among global climate models using the signal-to-noise ratio, providing a robust framework for interpreting model projections. While uncertainties remain, the ensemble median results suggest that drastically reducing greenhouse gas emissions could largely prevent substantial increases in intermittence in most regions, though some seasonally increasing drying is likely unavoidable in summer.

This work advances our understanding of streamflow intermittence dynamics across Europe, offering critical insights for managing freshwater ecosystems and water resources under changing climate conditions. It underscores the need for integrated water management strategies to address the growing challenges posed by altered flow regimes.

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