XXVI SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

ASSESSING FLOW REGIME ALTERATIONS BY RESERVOIRS IN FRANCE THROUGH HYDROLOGICAL SIGNATURES

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Abstract: Reservoirs significantly alter the natural flow of rivers, with varying impacts depending on how they are used and managed. In France, the increasing demand for irrigation reservoirs highlights the need to better understand these impacts. Here we present the first national-scale assessment of reservoir impacts on hydrological regime in France, using a large set of 1107 catchments. We distinguished 190 regulated and 917 potentially unregulated catchments, based on the presence of reservoirs above 1hm3 or with a cumulated storage capacity equivalent to more than 10mm of rain over the catchment area. A set of hydrological signatures was applied to detect changes in flow regime, and in drought and flood characteristics between regulated and unregulated catchments. Overall, reservoirs change flow seasonality, reduce intensity and duration of floods and droughts, reduce flood frequency, while increasing drought frequency and inter-annual sensitivity to rain. When separating the catchments according to their reservoirs purposes, we observe varying impacts. Specifically, irrigation reservoirs reduce low-flow variability, increase inter-annual sensitivity to rain and drought frequency, and shorten their duration. Hydroelectricity reduces runoff inter-annual sensitivity to rain, alters runoff seasonality and flood duration, reduces flood and drought intensity and decreases drought duration. Multiple-use reservoirs have similar effects as on the national scale. Ultimately, the study allows us to better understand how reservoirs can affect regulated rivers, which is relevant for collective reservoir management in the frame of the ecological transition.

Keywords – Reservoirs influences; Regulated catchments; Hydrological indicators of changes.

Resumo: Os reservatórios alteram significativamente o regime natural dos rios, com impactos variados conforme seu uso e manejo. Na França, a crescente demanda por reservatórios de irrigação destaca a necessidade de compreender melhor esses efeitos. Apresentamos aqui a primeira avaliação em escala nacional dos impactos dos reservatórios no regime hidrológico da França, com base em um conjunto de 1107 bacias hidrográficas. Identificamos 190 bacias reguladas e 917 potencialmente não reguladas, considerando a presença de reservatórios com volume superior a 1 hm³ ou com capacidade acumulada equivalente superior à 10 mm de precipitação sobre a área da bacia. Aplicamos indicadores hidrológicos para detectar mudanças no fluxo e nas características de secas e cheias entre bacias reguladas e não reguladas. Em geral, os reservatórios alteram a sazonalidade do fluxo, reduzem a intensidade e duração de secas e cheias, diminuem a frequência de cheias, mas aumentam a frequência de secas e a sensibilidade interanual à precipitação. Quando separadas conforme o uso dos reservatórios, observamos impactos distintos. Reservatórios de irrigação reduzem a variabilidade das vazões mínimas, aumentam a sensibilidade interanual à chuva, elevam a frequência de secas e encurtam sua duração. Para hidreletricidade reduzem a sensibilidade interanual, alteram a sazonalidade do fluxo e a duração das cheias, além de diminuir a intensidade de secas e cheias. Reservatórios de usos múltiplos apresentam efeitos similares aos observados em escala nacional. Este

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estudo contribui para uma melhor compreensão dos impactos dos reservatórios e para a gestão coletiva no contexto da transição ecológica.

INTRODUCTION

The development of reservoirs since the 1950s, leaded to increase in the worldwide number of large dams and water consumption (Steffen et al., 2015). In France, there is a growing pressure for the development of reservoirs for irrigation, with the aim of protecting or extending agriculture production capacities (FNSEA, 2012). This, reinforces the need to better understand how reservoirs can affect hydrological regimes in the country. Multiple studies have shown that reservoirs can modify natural flow regimes, affecting flow variability and seasonality, as well as flood and drought events (Ferrazzi et al., 2019; Brunner, 2021; Salwey et al., 2023; Bai et al., 2024). These hydrological impacts are linked to the operation of dams and to the ponding effect of the reservoirs themselves (McCully, 2021). Regulation rules can vary between countries and hydro- climatic contexts, and depending on the purposes of the reservoirs such as irrigation, hydropower, water supply, flood control, recreation, or a combination of these functions (Lehner et al., 2011; Brunner et al., 2019a). For example, in flood protection, reservoirs need to be empty to accommodate incoming precipitation, while for water supply, they are maintained near full capacity, ensuring water availability throughout the year (Margat & Andréassian, 2008).

However, assessing these impacts presents several challenges. First, most reservoirs lack publicly available data on their operational rules, such as the timing and volume of water storage and release, which significantly limits the comprehension of their local effects (Brunner, 2021). Second, the influence of reservoirs is often intertwined with other processes, i.e climate change and urbanization (Dey & Mishra, 2017).

Several methods have been proposed to quantify the hydrological alterations caused by reservoirs, mostly relying on large-sample analysis of discharge statistics. Large samples offer several advantages: they increase statistical robustness, capture a broader range of hydrological variability, and provide a more comprehensive understanding of alterations of flow regimes (Addor et al., 2020; Janssen & Ameli, 2021). One of the key challenges in these analyses is establishing a reference discharge that reflects 'natural' conditions, unaffected by reservoir operations. To derive this reference discharge, different strategies can be employed (Terrier et al., 2020), including pairing regulated and hydrologically similar natural catchments, comparing streamflow upstream and downstream of reservoirs, or analyzing changes before and after dam construction. In the United States, Brunner (2021) assessed the impacts of reservoirs on hydrological extremes, by comparing relative changes between paired catchments located upstream and downstream of reservoirs. In the United Kingdom, Salwey et al. (2023) developed a set of hydrological signatures to detect the influence of reservoir regulation on river flow at the national scale, using comparisons between unregulated conditions and regulated catchment samples. These hydrological signatures were also used at the global scale by Bai et al. (2024) within an improved paired-catchment approach.

In France, to our knowledge, no study has yet assessed the impacts of reservoirs on river flow at the national scale. Moreover, most reservoirs are older and few hydrological series are available before their construction, which limits the choice of methodological approaches. In addition, establishing reliable catchment pairs is often challenging and could significantly reduce the number of catchment pairs eligible for analysis: Bai et al., (2024) could identify only 177 pairs worldwide.

In this study, we ask how reservoir regulation affects flow regimes at the national scale in France, and how this effect relates to the reservoir purpose, by using hydrological signatures. To answer these questions, we used a suite of hydrological signatures that capture the effect of reservoirs on river regimes and can be computed with the data publicly available in France. In order to compare the expected “natural” flow behavior with the flow influenced by reservoirs, we identify unregulated and regulated catchments. We expect a) at the national scale, to see differences in the hydrological signatures of benchmark and regulated catchments, reflecting reservoirs effects and b) to distinguish the types of influence different reservoirs functions can have on river flow.

METHODOLOGY

To detect the influence of reservoirs on the flow regimes, we used a sample of catchments distributed across France, with hydrometeorological and reservoir data. We defined two groups: a set of potentially unregulated catchments, called here “benchmark”, and a set of regulated catchments, based on the presence within their boundaries of reservoirs above 1hm3 (one million cubic-meters). The differences in flow regimes between the groups were characterized using hydrological signatures.

Reservoirs data

We compiled information on reservoir in France from multiple sources: the national pond, lake and reservoirs registry Inventaire National des Plans d'Eau (INPE v1, 2023), a national database of large reservoirs Metropolitan Area Dams (MADAM, Delaigue et al., 2025), the database of flow obstacles BDOE (OFB, 2023), and the international large reservoir database Global Dam Watch (GDW) (Lehner et al., 2024). From this combined dataset, we selected only reservoirs with storage capacity greater than 1 hm^3, after Salwey et al. (2023) and Brunner (2021). We retained only reservoirs, as opposed to natural lakes, even if some may have a level regulation, and only reservoirs whose functions can have a significant hydrological impact, after Bai et al. (2024): hydroelectricity, irrigation, water supply, flood control. This left us with a selection of 468 reservoirs across France, 388 of which with known purpose (hydroelectricity, irrigation, water supply, flood control, or multiple uses) and 80 with unknown purpose (Fig. 1.b). Although our analyses focus on larger reservoirs, we also did a second selection of artificial reservoirs with known storage capacity, regardless of size (see Fig.1a). This selection of 3788 reservoirs was done with the purpose to exclude catchments with a cumulated storage capacity of reservoirs, each of them below 1hm3.

On Figure 1b we show the distribution of the reservoirs with capacity above 1hm3 across France. We observe that the largest reservoirs are mainly located in the East and North West. These are primarily used for water supply and hydroelectricity. The water supply reservoirs are more spread across the country while hydropower reservoirs are primarily located in mountainous areas, in central, east and southeastern France. In contrast, irrigation reservoirs are mostly smaller and more present in southwestern regions.

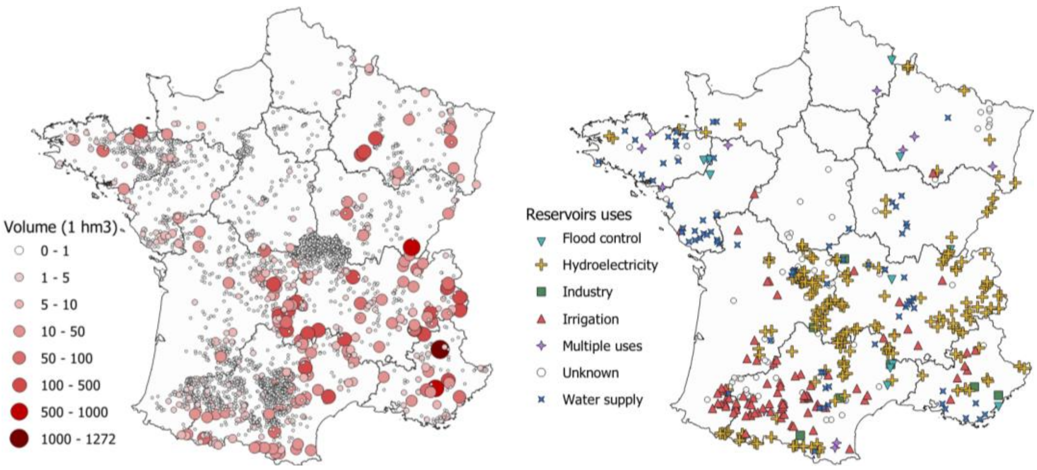


Figure 1: a) Distribution of the artificial reservoirs with known volume. b) Uses of reservoirs above 1hm3

Hydrometeorological data

Hydrological signatures were calculated using daily hydro-climatic data from the BDD-Hydroclim database of INRAE (Delaigue et al., 2023), which includes around 4,000 catchments across France. This dataset comprises 1) daily meteorological data from 1958 to 2022 that are derived from the SAFRAN atmospheric reanalysis (Quintana-Segui et al., 2008; Vidal et al., 2010) and 2) daily discharge time series for station-dependent periods spanning from 1958 to 2021 that were collected from the Hydroportail platform, (hydro.eaufrance.fr).

We only retained stations with a complete discharge time series for at least 30 years for robust statistical analyses (Delaigue et al., 2025). A year was regarded as complete if data are missing on less than five days of each month. Ultimately, 1107 catchments were selected with 30 years of data over the 1970–2021 period. Finally, we assume that all reservoirs were already built at the beginning of the study period, based on the available construction dates.

Identification of benchmark and regulated catchments

We regarded as regulated the catchments located downstream of reservoir exceeding a capacity of 1hm3. Two criteria were applied to identify benchmark (potentially unregulated) catchments. First, benchmark catchments must not contain reservoirs with capacity above 1hm3. Second, we calculated the total volume of reservoirs of all sizes within each catchment and divided it by the catchment area; this ratio had to remain below a threshold of 10 mm (Delaigue et al., 2025). Additionally, to ensure that reservoir influence is not counted multiple times across nested basins, we only retained in the regulated catchment sample the most upstream catchments when multiple catchments shared the same set of reservoirs. Finally, this left us with 917 benchmark and 190 regulated catchments.

For the second part of the analysis, we defined a main purpose for each regulated catchment considering the reservoirs within their area after Bai et al. (2024). We computed the proportion of reservoir capacity for each use: if the proportion for a functionality exceeded 60%, the catchment was categorized under that functionality and if the proportions for all functional types fell below 60%, the catchment was classified as having multiple functions.

Hydrological signatures

To assess the effect of reservoirs on flow regulation, we used a set of hydrological signatures linked to the effects of reservoirs. These signatures were selected based on two main criteria i) their potential to identifying reservoir-induced alterations according to literature (Bai et al., 2024; Salwey et al., 2023; Brunner, 2021) and ii) their applicability to our database for France. Subsequently, these signatures can be grouped into two categories. The first relates to flow variability in the year and between years, and includes: (a) low-flow variability (LFV), (b) changes in seasonal runoff coefficient (SWRR), and (c) runoff elasticity (E), which reflects the relationship between annual precipitation and streamflow (Salwey et al., 2023). The second group relates to the effects of reservoirs on extreme discharges, comprising: (a) 5-year return period minimum annual discharge (QMNA5, used in French regulation), (b) mean frequency and mean duration of floods and droughts and (c) average of the maximum flows recorded in a flood event.The Low-Flow-Variability (*LFV*), adapted from Salwey et al. (2023), was calculated by Eq. 1:

$$LFV = \frac{max_{m=1,\dots 12}\,(Q_{m,80}) - min_{m=1,\dots 12}\,(Q_{m,80})}{\bar{Q}} \quad (1)$$

where Qm,80 is a characteristic low flow rate, exceeded 80% of the time in a month m across all years, and $\bar{Q}$ is the interannual mean discharge. The value of this metric is positive, with a minimum of 0 for constant monthly low flow rates.

Deviations in seasonality patterns were calculated from Eq. 2, using the Summer-Winter-Runoff-Ratio ($SWRR$, Salwey et al., 2023):

$$SWRR = \overline{\left(\frac{Q_m}{P_m}\right)}_{summer} \Big/ \overline{\left(\frac{Q_m}{P_m}\right)}_{winter} \quad (2)$$

Where $Qm/\ Pm$ is the monthly runoff coefficient, averaged by season (summer; April to September and winter; October to March) and by year. In a river of pluvial regime, the runoff coefficient is lower in summer than in winter. On such a river, a high SWRR value suggests that reservoirs are redistributing water or receiving imports from other catchments.

Elasticity (E) describes the sensitivity of river flow to intra-annual precipitation variations (Sawicz et al., 2011) and can be calculated by Eq. 3:

$$E = median\left(\frac{\Delta Q_{year-on-year}}{\Delta P_{year-on-year}}\right) \times \frac{\bar{P}}{\bar{Q}} \quad (3)$$

$\Delta Q_{year-on-year}$ and $\Delta P_{year-on-year}$ represent the variations of annual precipitations and flow rate between successive years and $\bar{P}$ the interannual mean precipitation. A value of 1 of E indicates that changes in precipitation leads to equal changes in streamflow, while a value greater or respectively smaller than 1 would define the catchment as being elastic, i.e., sensitive to change of precipitation, or respectively inelastic, i.e., insensitive to a change of precipitation. This metric is associated with the function of reservoirs to store precipitation, reducing the sensitivity of downstream runoff to precipitation (Bai el al., 2024).

For the second group of metrics, we identified flood and drought events to assess the impact of reservoirs on hydrological extremes. Flood events were defined when river flow overpasses the median of the annual maxima and are separated by a minimum period of 10 days to ensure independence (Diederen et al., 2019 and Brunner et al., 2020a, 2020b). For drought events, in order to minimize the risk of identifying dependent events, we smoothed the discharge time series with a 30-day running average (Van Loon and Laaha, 2015), Droughts events were identified when the discharge was below a day-in-the-year threshold, the 15th percentile of the smoothed discharge series (Brunner, 2021). After Brunner (2021), we determined for each catchment the mean duration of extreme events, their mean frequency (number of events per year), and for floods the mean of the maximum peak flow rate of each events. Finally, we also calculated the mean annual minimum monthly flow rate with a 5-year return period (in mm/month, used as reference low flow in French regulation, and noted QMNA5).

In order to detect differences in the signatures between benchmark and regulated catchments, we analyzed their distributions with two statistical tests. We applied the Student t-test to assess differences in the means of metrics that either follows approximately a normal distribution or with a sample size of more than 30 catchments. Additionally, we used the Kolmogorov–Smirnov test (KS) to test whether the distributions of benchmark and regulated groups differ significantly. The type of and degree of hydrological alterations in river flow are related to the reservoir functions and operational regulation (Bai et al., 2024). Therefore, we made comparisons between the benchmark and regulated samples at the national scale not only by pooling all reservoirs together, but also for each reservoir function, using the national sample of benchmark catchments as a reference in both cases.

RESULTS AND DISCUSSION

Reservoirs cause alterations of the flow regime at the national scale

Reservoirs regulation can alter flow characteristics at the national scale, with significant differences in the signatures between benchmark and regulated catchments, despite the high hydrological variability across the country (Fig. 2). Highly significant differences in the mean values (p-values≤ 0.001) are in the flood frequency and the mean peak discharge, and both flood and drought mean durations. Other metrics exhibit less significant differences: elasticity, drought frequency and QMNA5. The Kolmogorov–Smirnov test confirms that these significant differences in the means correspond to significant differences between the distributions.

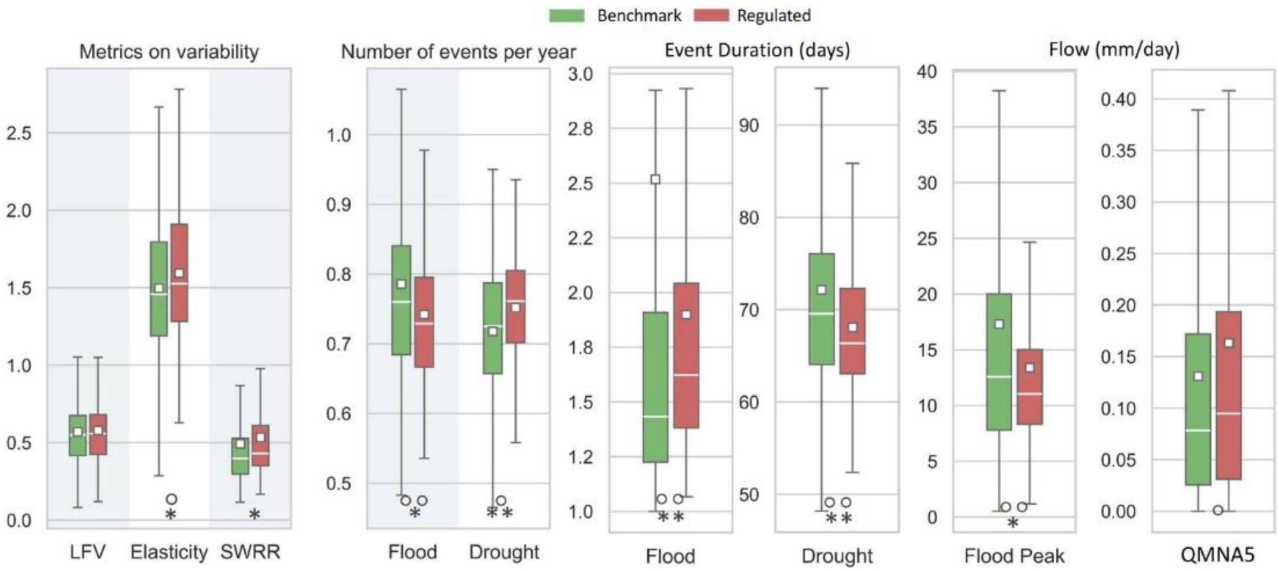


Figure 2. Distributions of hydrological signatures for the 917 benchmark and 190 regulated catchments. In the boxplots, the limits indicate the 1st and 3rd quartiles, white lines the medians, white squares the means; whisker length is 1.5 times the interquartile range; for readability, outliers were omitted. Circles ("○","○○") indicate p-values for the t-test, with p-values ≤ 0.05 and ≤ 0.001 respectively. Asterisks ("*", "**") indicate statistical significance levels of the KS test, with the same thresholds.

Reservoirs modify flood events. They reduce mean flood frequency, by approximately 0.04 events per year (i.e. 1.2 fewer flood events over a 30-year period), flood peak discharge and flood duration by 4 mm/day and 0.6 days, respectively. All these changes in signature means are highly significant. This indicates that flood events are less frequent, shorter and less intense in regulated catchments than in benchmark catchments. This relation was also observed in the United States (Brunner, 2021), although with higher differences than what we found for France. Drought events are also affected by reservoir regulation. The QMNA5 shows that there is an increase in the minimum monthly flows in regulated catchments. The frequency and duration of droughts are also affected, with an increase by 0.03 events per year and a reduction of 4 days. This means that droughts are less severe and shorter, but more frequent. These results highlight that hydrological extremes are damped by the presence of reservoirs.

Reservoirs seem to increase flow elasticity in France, namely the sensitivity of streamflow to intra-annual precipitation variability. However, Salwey et al. (2023) for the United Kingdom and Bai et al. (2024) in a global assessment reported the opposite effect and attributed it to the damping effect of interannual storage. The reasons behind an increased elasticity in France are not yet fully clear.

Reservoirs can alter seasonal flow patterns, as reflected by the significant difference in their distributions. This indicates that reservoirs change the runoff ratio during the summer months in comparison with the winter months. In the context of France, with seasonal patterns of low flows in summer and high flows in winter, this may indicate that reservoirs redistribute water between winter and summer or receive large imports during summer. Similar results were found in the UK (Salwey et al, 2023).

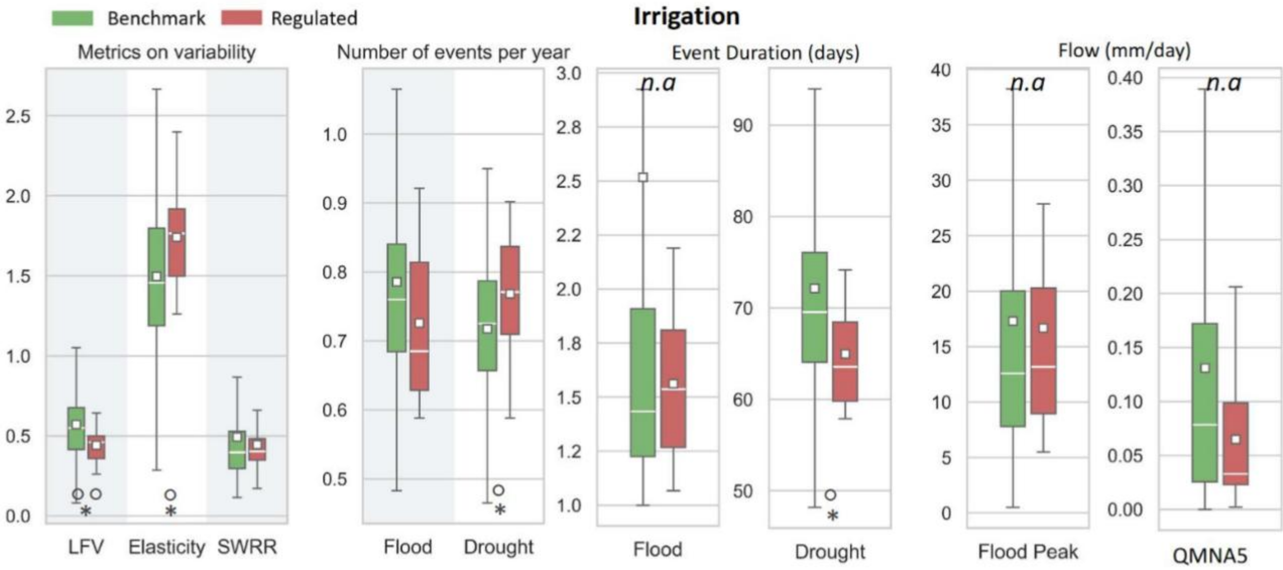
Reservoirs functions can cause different effects on flow regime

Figure 3 shows the differences in hydrological signatures between benchmark and regulated catchments, categorized by their main use. For each metric, we highlight the uses that presented significant differences. Industrial reservoirs were excluded from the analysis due to insufficient data, and catchments with unknown reservoir uses were omitted because their impacts could not be clearly attributed. In addition, we found significant statistical differences neither for flood control nor for water supply, therefore they are not shown here.

We can observe that reservoir impacts vary, depending on their main use. Irrigation reservoirs cause a highly significant reduction in low-flow variability, due to the required minimum ecological flows resulting in a more controlled variability. Similar findings were observed at the global scale for Bai et al. (2024). And lastly, we observe an increase in the frequency of droughts and a reduction in drought duration. The effects on low flows could be attributed to the abstraction of water for irrigation that is transformed into evapotranspiration and doesn't return to the streamflow, intensifying droughts events. Besides, irrigation reservoirs increase elasticity, meaning that river flows become more sensitive to variations in intra-annual precipitation. This result, similar to what we found at the national scale for all uses pooled together, is surprising and might be due to other factors that we do not consider in this analysis.

Hydropower reservoirs can reduce flow elasticity, contrary to most other uses, suggesting a strong separation of downstream flow from precipitation patterns. This aligns with the expected buffering effect of large storage reservoirs (Bai et al., 2024), where flow regime is more influenced by energy generation needs than by climatic conditions. In addition, they can reduce the drought event duration and reduce the severity of low flows, by augmenting the QMNA5. This effect could be attributed to the regulation of hydropower reservoirs, which require a constant release of water for electricity generation throughout the year.

Both hydropower and multiple uses reservoirs have common impacts: they change the seasonality of flows (SWRR), such as already observed for all purposes pooled together, and they change floods duration. For the effects of multiple uses they are similar to what was found at the national scale, with some metrics having higher significance. This is to be expected, since different types of operations at the same reservoirs can have different effects on rivers, depending on climatic conditions and the demand of human activities.



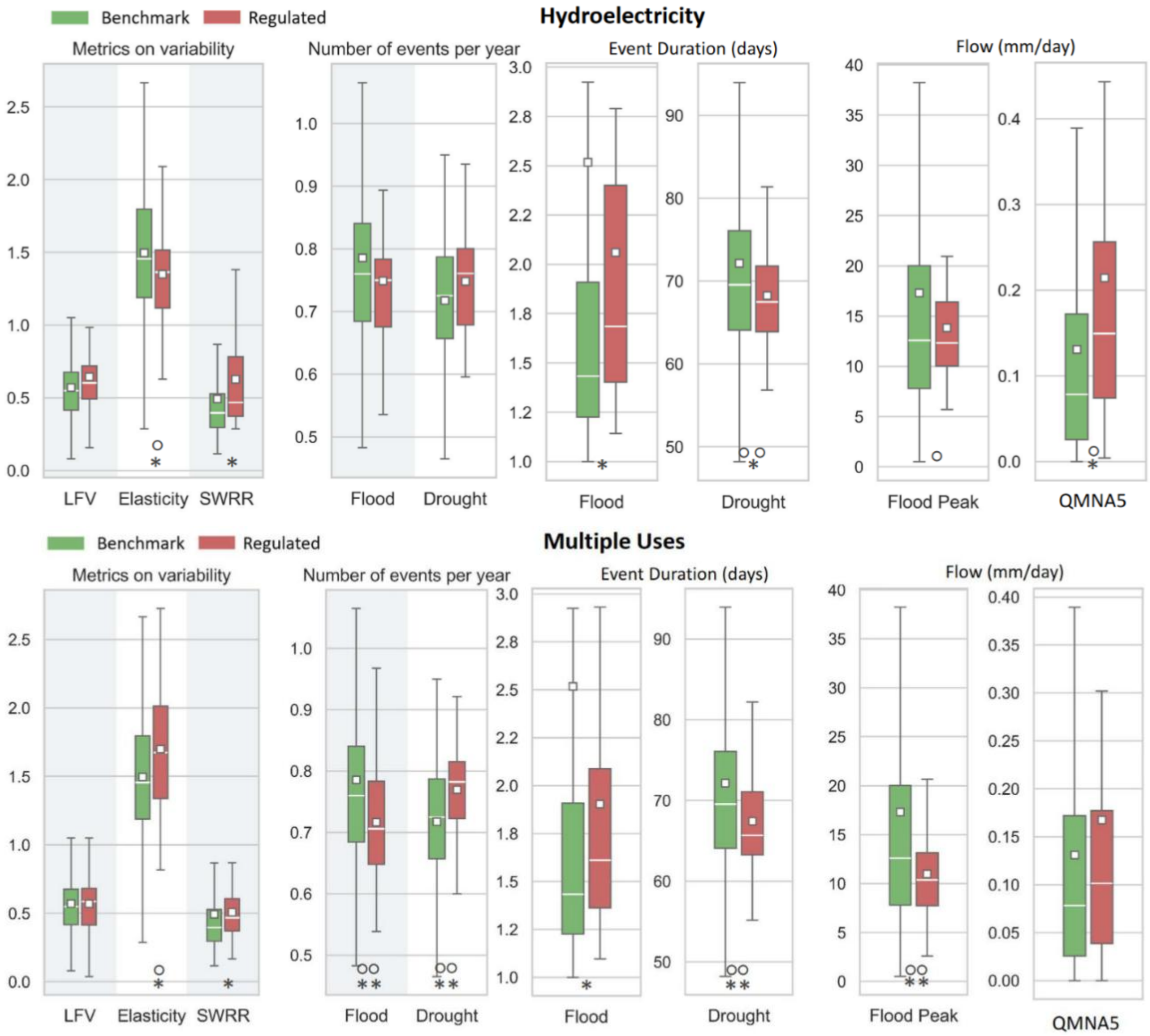


Figure 3. Distribution of the hydrological signatures for the 917 benchmark catchments and regulated catchments separated by main use of their reservoirs: a) irrigation (19 catchments) b) hydroelectricity (36) and c) multiple uses (61). *N.a* means that the t-test was not applied due to having neither normal distribution nor more than 30 catchments.

It important to note that insignificant differences in some metrics do not necessarily imply that reservoirs do not influence river flow. Rather, it may reflect limitations in the choices of the metric and how we analyze them, particularly at a national-scale where hydrological variability can obscure the effects of reservoir regulation. Secondly, although our database contains the main use of each reservoir, reservoirs are generally exploited for multiple uses. In addition, a catchment can b impacted by more than one use. Thus, this may understate specific impacts of each functionality of the flow.

CONCLUSIONS

Our results show the effects of reservoirs in river flow, for the first time at the national scale for France. Reservoir regulation can cause effects on seasonality, increase flow sensitivity to changes in precipitation, making both flood and droughts less severe, flood events less frequent and shorter, but droughts events shorter and more frequent. Among the different reservoir functions, irrigation worsens droughts and decreases minimum flow variability. Hydropower, reduces runoff elasticity, changes seasonal runoff and flood duration, reduces drought duration and the intensity of droughts and floods. Multiple-use reservoirs displayed similar impacts to all uses gathered at the national scale. The differences in hydrological signatures between unregulated and regulated catchments highlight the influence of reservoir operations and demonstrate how different reservoir uses affect differently river flow. We also remark the importance of extending this analysis by considering the different hydro-climatic variability in France, as well as catchment and reservoir attributes that could explain the variability of flow regimes. Characterizing flow alterations by reservoirs should contribute to a better reservoir management and support actions to mitigate their negative impacts, reinforcing the role of collective reservoir management in the ecological transition and the protection of river ecosystems.

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