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LETTER

# Contrasting signatures of distinct human water uses in regulated flow regimes

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## Abstract

In the last century, about 50,000 dams have been constructed all around the world, and regulated rivers are now pervasive throughout the Earth's landscapes. Damming has produced global-scale alterations of the hydrologic cycle, inducing severe consequences on the ecological and morphological equilibrium of streams. However, a recognizable link between specific uses of reservoirs and their impact on flow regimes has not been disclosed yet. Here, extensive hydrological data are integrated with a physically-based model to investigate hydrological alterations downstream of 47 isolated dams in the Central Eastern U.S. Our results reveal a strong connection between the anthropogenic use and the hydrological impact of dams. Flood control reduces the temporal variability and spatial heterogeneity of river flows proportionally to the specific capacity allocated to mitigate floods (i.e., capacity scaled to the average inflow). Conversely, water supply increases the relative variability and regional heterogeneity of streamflows proportionally to the relative amount of withdrawn inflow. Accordingly, downstream of our multipurpose reservoirs the impact of regulation on streamflow variability is smoothed due to the compensating effect of flood control and water supply. Nevertheless, reservoirs with high storage capacity and overlapping uses produce regulated hydrographs that increase their unpredictability for larger aggregation periods and, thus, resemble an autocorrelated red noise. These findings suggest that the increase of freshwater demand could redefine the cumulative effects of dams at regional scale, reshaping the trajectories of eco-morphological alteration of dammed rivers.

## 1. Introduction

Dams and impoundments have long been designed in response to the ubiquitous imbalance between water needs for anthropogenic uses and the variability of river flows. Over the course of the 20th century, population and economic growth caused a significant increase in global-scale construction and operation of engineering projects aimed at promoting social development by modulating water fluxes for flood control, water supply, irrigation, hydropower production, recreation or a combination of such purposes [1]. Overall, by the end of the century, more than 45,000 large dams were constructed in over 140 countries around the world, inducing a significant fragmentation of fluvial systems and worldwide alterations of the hydrologic cycle [2]. Anthropogenic modifications of natural flow regimes through dams and reservoirs, combined with their tendency to capture almost the entire sediment load of rivers, profoundly disrupt the equilibrium between water flow and patterns of erosion and sedimentation, leading to a general rearrangement of channel and floodplain morphology throughout entire river networks [3, 4]. Additionally, as a result of profound hydrological alterations, river regulation affects aquatic ecosystems and riverine biodiversity, often creating new thermo-chemical regimes and habitat conditions to which native species are poorly adapted [5, 6]. Accordingly, the perception of socio-economic benefits provided by dams has grown along with an increased awareness of the harmful effects connected to flow regime alterations. This brought to light the need to conceive new strategies for a sustainable management of water resources, and to acquire deeper understanding of the nature of anthropogenic modifications of flow regimes [7, 8]. A large body of literature exists describing the hydrological impact of individual dams, while a consistently smaller number of studies focuses on the spectrum of downstream effects produced by dams and reservoirs at regional to global scales. Existing large-scale investigations have revealed that river impoundments affect the magnitude, frequency and timing of both high and low flows with an intensity that is modulated by the storage capacity of reservoirs and the mean annual runoff [9–11]. These alterations are believed to generate a general reduction of daily streamflow variability and, consequently, an enhanced homogenization of regional river dynamics [12–14]. However, the correlation between regulation impacts and specific reservoir functions across multiple time scales has not been disclosed yet, and a number of key questions remain unresolved. Are there distinctive patterns of river regime alterations associated to specific water uses? May possible shifts in anthropogenic water uses alter observed trends of flow regime modifications in the future? To address these questions, we investigate the relationship between three different water uses, including related reservoir characteristics, and regional alterations of river regimes. We analyze the differences between flow regimes upstream and downstream of different isolated dams, grounding on extensive hydrological data and a physically-based model designed to predict natural flow regimes in ungauged settings. The approach eliminates the confounding effect of climate change, which is typically superimposed to that of regulation in pre-impact versus post-impact comparisons [15]. Moreover, the method exploits model predictions to overcome the lack of synchronous discharge records upstream and downstream of reservoirs, which are seldom available. The analysis is conducted by investigating the impact of river regulation on a number of flow statistics, including the mean discharge, the coefficient of variation of daily flows, the integral scale and the frequency stability. These hydrological indexes retain important information about the extent of ecological and morphological alterations of regulated rivers (*sensu* Richter *et al* [16]). In particular, mean and variability of river flows identify the magnitude and rate of change of hydrological conditions, that underlie habitat availability, ecological communities composition and life strategies (see *Methods* and references therein) [17–19]. Frequency stability and autocorrelation analyses quantify streamflow temporal patterns and rate of change, that in turn control life cycles, adaptation strategies and population dynamics (see *Methods* and references therein) [20–23]. The approach is applied to 47 isolated dams, spanning the range of hydro-climatic settings typical of the Central-Eastern United States and three different water uses, namely flood control, urban water supply and hydropower production.

## 2. Methods

### 2.1. Dam selection and hydro-climatic data

This study investigates the downstream effects of an illustrative selection of structures evenly distributed throughout the Central-Eastern United States. Selected dams meet the following methodological criteria. First, dams must impound poorly engineered rivers (i.e., rivers poorly affected by human regulation), so as to avoid the overlapping of possibly contrasting effects produced by multiple hydraulic devices operating in cascade. Second, reservoirs must be characterized by a minimum storage capacity of $10^6$ $m^3$, in order to produce a visible impact on downstream hydrology [9, 11]. Third, dams must be located upstream of, at least, one flow gauge providing sufficiently long records of regulated streamflows (i.e., with a minimum duration of 15 years). Overall, we detected 47 isolated dams with non-overlapping contributing areas meeting the above criteria, among which 25 with available streamflow time series both upstream and downstream of the reservoirs (see table S1). To associate the observed regulation impact to each of the analyzed functions, dams were divided into three different classes: (i) dams primarily operated for flood control [24, 25]; (ii) dams only operated for urban water supply; (iii) dams operated for hydropower production [25, 26]. Information about dams and reservoirs were found in the technical reports and websites of the corresponding operating agencies, while daily streamflow records were acquired through the stations belonging to the U.S. Geological Survey (USGS) [27]. Climatic and geomorphological information required for the analytical characterization of flow regimes were obtained by the American National Oceanic and Atmospheric Administration (NOAA), the Consortium for Spatial Information (CGIAR-CSI) and the U.S. Geological Survey (USGS) [28–30].

Reservoirs in the Western U.S., that host the large majority of irrigation dams, were not included in this analysis because of: (i) lack of homogeneity of information available on reservoir functions and operational criteria (e.g. unknown capacity allocated to different functions) as compared to the Eastern U.S.; (ii) inherent difficulty in deriving reliable sample statistics during seasons with no discharge, or in case of significant inter-annual climatic fluctuations, that prevent from fulfilling the ergodicity conditions (e.g., dry seasons in the Southwest or snow-dominated regimes).

### 2.2. Analytical characterization of flow regimes

The approach used to evaluate natural flow regimes upstream of the dams where discharge records are not available is a mechanistic stochastic method, which represents daily streamflow dynamics by describing the temporal evolution of the catchment water storage [31, 32]. The dynamics of the catchment storage are assumed to result from the superposition of evapotranspiration losses and stochastic increments triggered by precipitation, that is assimilated to a spatial uniform marked Poisson process with frequency $\lambda_P$ and exponentially distributed depths with mean $\alpha$ [33]. When the soil water deficit created by evapotranspiration is filled by precipitation, the catchment water storage can exceed the field capacity and the excess of water is drained from the catchment according to a non-linear storage discharge relationship, ultimately contributing to streamflow. In this framework, the sequence of rainfall events that trigger the hydrological response of a catchment is a suitable subset of the overall rainfall and, thus, it is approximated by a marked Poisson process with frequency $\lambda < \lambda_P$ [34] (see SI available online at stacks.iop.org/ERC/1/071003/mmedia). Accordingly, daily streamflow dynamics result from sudden discharge increments during streamflow-producing rainfall events and non-linear recessions in between events [35–37]. The resulting relation for streamflow temporal dynamics is [38]:

$$\frac{dQ(t)}{dt} = -KQ(t)^a + \xi_Q(t) \tag{1}$$

where $\xi_Q$ represents the sequence of stochastic jumps induced on $Q$ by streamflow-producing rainfall events, while $K$ and $a$ are the coefficient and exponent of the power-law decays representing non-linear streamflow recessions. The resulting equation for the steady-state pdf of streamflows derives from the solution of the master equation associated to equation (1) [38]:

$$p(Q) \propto Q^{-a} \exp\left(-\frac{Q^{2-a}}{\alpha K(2-a)} + \frac{\lambda Q^{1-a}}{K(1-a)}\right) \tag{2}$$

Equation (2) relies on four parameters, whose values can be obtained empirically based on a geomorphological recession flow model and a physically-based stochastic model of soil moisture dynamics. Parameter estimation is performed seasonally exploiting climatic (rainfall and evapotranspiration) and geomorphological (DEMs) data [33, 39] (see SI). Overall, the approach proved to be reliable in reproducing the major features of natural flow regimes in the case studies where discharge time series upstream of the dam were available. Upon calibration of a single parameter (i.e., the root zone depth), the Mean Square Relative Error of estimated $CV_Q$ is 0.08 (see figures S1 and S2).

### 2.3. Characterization of flow regimes in regulated and unregulated settings

The impact of regulation on river flow regimes has been first investigated by comparing the mean and the coefficient of variation of synchronous natural and regulated daily flows for each combination of site and season, thereby leading to 376 couples of values that represents the effect of dams on water resources. Analyzing the effect of regulation at the seasonal time scale is necessary to capture the seasonality of natural flows [40] and the associated patterns of hydrological alterations by dams, possibly amplified by the adoption of climate-dependent regulation strategies. The mean discharge, $\overline{Q}$, and the coefficient of variation of daily flows, $CV_Q$, provide a reliable measure of the mean water availability and relative hydrological variability, which are main drivers of ecological and geomorphological instream processes [41–43]. Any alteration of these attributes with respect to natural conditions can potentially threaten the eco-morphological equilibrium of rivers [6]. In unregulated settings, $\overline{Q}$, is a complex function of catchment area and climatic conditions [44], which is modulated by vegetation and soil properties through the partitioning of precipitation into evapotranspiration and drainage [33, 45]. On the other hand, $CV_Q$ depends on the sequence of flow pulses (sudden flow increments and recessions) experienced by a river reach, in turn related to important climatic and landscape attributes of the contributing catchment. The value of $CV_Q$ allows an objective and fundamental distinction between highly variable 'erratic' ($CV_Q > 1$) and more stable 'persistent' regimes ($CV_Q < 1$) that are characterized by diverse eco-morphological regimes and flooding potential [40, 46, 47]. Overall, the degree of alteration of $\overline{Q}$ and $CV_Q$ influences a large number of processes, including ecosystem size, macro-invertebrates grazing rates, riparian vegetation dynamics, microbial co-occurrence networks, sediment transport and erosion rates [47–53]. In the 25 fully gauged catchments, calculations of $\overline{Q}$ and $CV_Q$ have been based on long-term synchronous streamflow records. Conversely, in catchments where data are only available for reservoir release, the mean and the coefficient of variation of natural streamflows have been evaluated based on equation (1) (see SI).

The impact of dams and reservoirs on the temporal trajectory of downstream releases has been also analyzed across a broad range of time scales (from daily to yearly) [54–57]. Temporal patterns of streamflows are critical for population dynamics and life cycle stages, and their modifications might impact adaptation strategies by creating adverse conditions for fish movement and reproduction [58–60]. In particular, the frequency stability

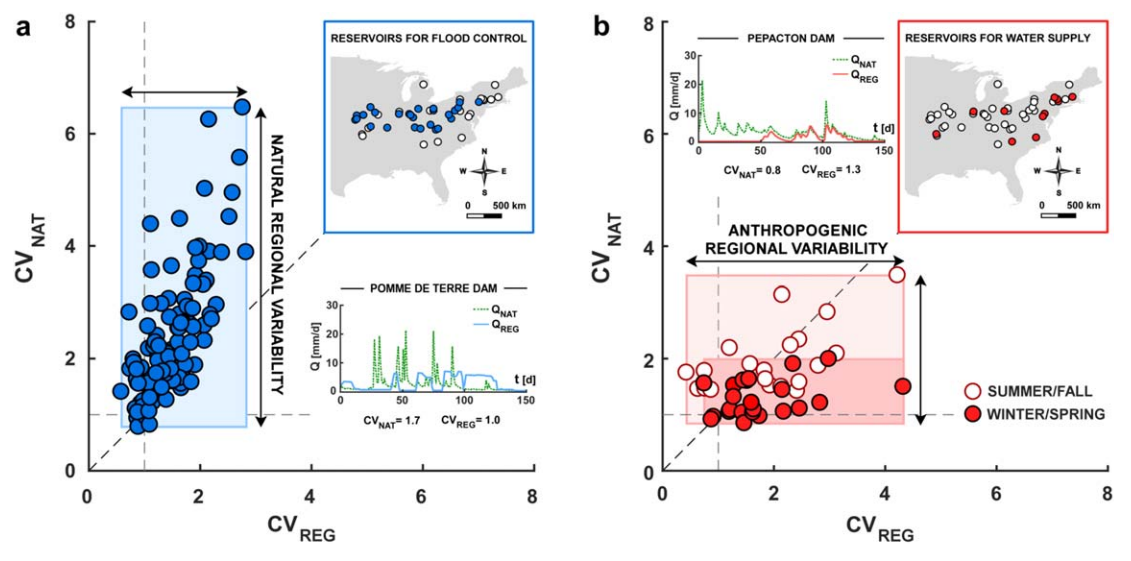


**Figure 1.** Seasonal coefficient of variation of natural river flows, $CV_{NAT}$, plotted against the corresponding value associated to regulated flows, $CV_{REG}$, for all the flood control and water supply dams considered in this study, properly stratified according to their main function. (a) Decrease of daily discharge variability and regional homogenization of flow regimes downstream of 26 reservoirs primarily used for flood control. (b) Increase of daily discharge variability and inter-catchment heterogeneity downstream of 11 reservoirs solely used for water supply. The insets show the geographical location of the selected dams and the typical behaviour of river flow dynamics upstream (dotted line) and downstream (solid line) of flood control and water supply reservoirs.

and the temporal autocorrelation analyses have been implemented to investigate the memory and fractal properties of unregulated and regulated flow patterns (see SI). The frequency stability analysis has been performed in the time domain, as it ensures more robust estimates in case of non stationary time series and large averaging times, $\tau$, as compared to the frequency domain [61, 62]. The approach exploits the one to one correspondence between the slope of the Allan deviation curve, $\alpha$, in a log-log plot and specific noise color ($\alpha = -0.5$ implies a White Noise, $\alpha = 0.0$ identifies a Pink Noise and $\alpha = +0.5$ corresponds to a Red Noise). Concurrently, temporal autocorrelation functions, $\rho(\tau)$, have been evaluated both upstream and downstream of each dam and then integrated up to the first zero crossing of $\rho$, to calculate the integral scale $\overline{T}$, representing a simple measure of the persistence of flow patterns.

All the analyses have been carried out stratifying the 47 selected reservoirs on the basis of their main function, the regulation capacity and the reservoir exploitation (see *Results* and caption of figure 2).

## 3. Results

Flow regimes upstream of the flood control structures selected in this study are extremely heterogeneous in space and time. Most cases are characterized by erratic regimes (i.e. $CV_Q > 1$). These regimes are commonly found throughout the entire Central-Eastern United States, though an enhanced erraticity ($CV_Q > 3$) emerges in the Eastern Great Plains, especially during summer and fall seasons. Nevertheless, persistent regimes (i.e. $CV_Q < 1$) are also observed, particularly in Northeastern catchments during spring and winter. During high flow events, flood control dams store water that is then released during low flow periods with the goals of preserving the storage capacity of reservoirs and conveying water downstream for secondary uses, such as irrigation, navigation or wildlife preservation. Accordingly, regulation for flood control does not alter substantially the mean river discharge (figure S3(b)). On the other hand, flood mitigation reduces the intra-seasonal variability of river flows during all seasons, and strongly lowers (by more than 60%) regional-scale differences typical of unregulated regimes (figure 1(a)). These results comply with the findings reported by previous studies [12–14], though these studies do not explicitly address the role of distinct reservoir functions.

Hydrological regimes upstream of the selected urban water supply reservoirs are relatively homogeneous: most cases are weakly erratic ($1 < CV_Q < 2$), especially during winter and spring seasons, when many intermediate regimes ($CV_Q \approx 1$) are observed. Regulation for urban water supply is intended to intercept river flows and feed aqueduct systems. As a result, the mean seasonal discharge downstream is reduced proportionally to the relative amount of water withdrawn or diverted from reservoirs (figure S3(c)), whereas the variance of flows (that is more sensitive to high flows) is less impacted [63]. Accordingly, water supply reservoirs typically produce an increase of the relative streamflow variability downstream of the dam, with regulated regimes that generally exhibit a more erratic behaviour (larger $CV_Q$). Moreover, damming enhances inter-catchment

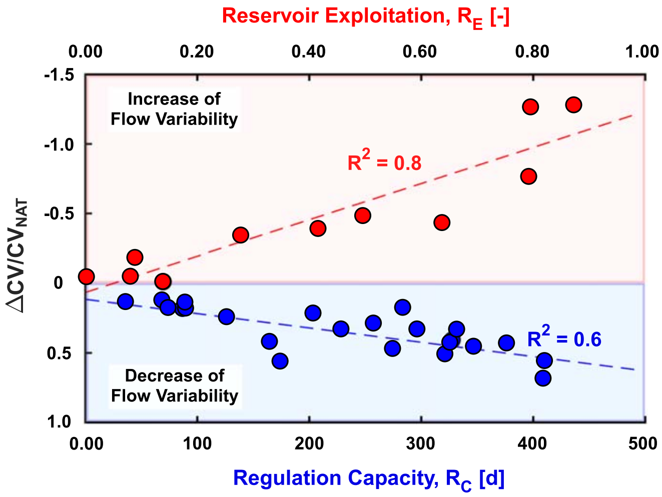


**Figure 2.** Reservoir regulation capacity and reservoir exploitation control the relative magnitude of flow regime alterations downstream of flood control and water supply structures, respectively. Blue dots suggest that the annual reduction of river flow variability downstream of flood control dams grows with the reservoir regulation capacity, $R_C$, here defined as the number of consecutive days for which the mean flow can be stored in the reservoir assuming no releases downstream. On the other hand, red dots suggest that the increase of streamflow variability observed downstream of water supply dams in spring and winter grows with the degree of exploitation of the reservoir, $R_E$ (i.e. the relative amount of inflows withdrawn from the corresponding lake).

heterogeneity of flow variability by almost 50% in response to diversified exploitation strategies across different reservoirs. During winter and spring, the increase of daily streamflow variability induced by dams and the effect of streamflow differentiation at the regional scale are more evident (red dots in figure 1(b)). In these two seasons, the inter-catchment heterogeneity of $CV_Q$ in dammed rivers is almost four times as large as that of unregulated regimes. This is due to the lower variability of natural flows from November to April, which conceals the unavoidable confounding effect of flood attenuation by dams during high flow events (figure 1(b)).

Differently from regulation for flood control and water supply, characteristic patterns in flow regime alterations prove difficult to find downstream of reservoirs used for hydropower production. These structures are generally managed for multiple purposes, including flood control. Accordingly, regulation typically decreases the variability of downstream flows, especially during summer and fall seasons, when river flow regimes display the highest erraticity (figure S3(a)). Though, the magnitude of regime alterations may be constrained by the reduced effective capacity of reservoirs, as implied by the compliance of a minimum stage (necessary to sustain the hydraulic head during hydropower production).

The reservoir main function and the natural streamflow variability are not the unique determinants of the extent of river flow regime alterations. Other quantitative descriptors can be introduced to better understand the link between anthropogenic water uses and hydrologic alterations by dams. Figure 1(a) suggests that the observed reduction of $CV_Q$ downstream of flood control dams is roughly proportional to the natural variability of discharges. However, the actual magnitude of flow regime alterations is also modulated by the regulation capacity of reservoirs, $R_C$ (i.e. the storage capacity allocated to flood control scaled to the mean annual inflow). As expected, the higher the regulation capacity, the more enhanced the reduction of streamflow variability (figure 2(bottom)). The downstream effect of water supply reservoirs, instead, depends on seasonal patterns of water consumption, particularly in seasons when the confounding effect of flood mitigation is not visible (i.e. winter and spring). This has been demonstrated empirically in figure 2(top), where the increase of relative streamflow variability downstream of water supply dams is shown to grow with the degree of exploitation of a reservoir, $R_E$ (i.e. the relative amount of inflows withdrawn from the reservoir).

Reservoirs for flood control increase downstream flow correlation consistently with their ability to store large amount of water through time. Storages with sufficiently high regulation capacity ($R_C > 150d$) are able to produce more persistent flow patterns up to seasonal and annual time scales, inducing an increase of the mean integral scale of flows, $\overline{T}$, greater than 130% (from 6.5 to 15.2 days; figure 3(a)). This is consistent with the reduction of streamflow variability operated by flood control dams, with higher low flows and smoothed peaks in regulated regimes. The frequency stability analysis (see *Methods*) reveals that the overall unpredictability of regulated streamflows is always reduced if compared to natural conditions, as inferred by the lower values of the Allan deviation (inset of figure 3(b) and SI). However, flood control reservoirs with a high regulation capacity induce a negative-positive transition in the slope of the log-log Allan deviation plot, $\alpha$, for averaging times up to 100 $d$ (see SI). Although the self-averaging behaviour of unregulated flows is slower than that of an ideal white noise ($\alpha = -0.5$), their unpredictability typically decreases over longer time intervals ($\alpha < 0$ in 95% of cases).

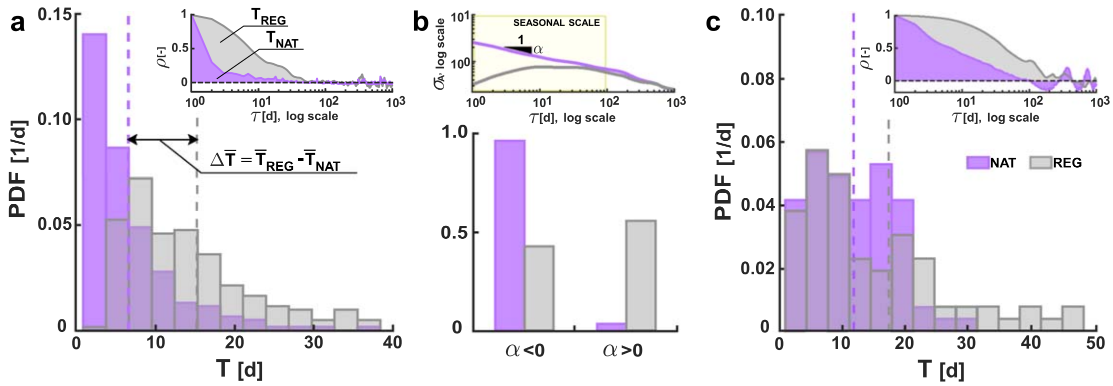


**Figure 3.** Streamflow memory and fractal properties alteration through dams. (a) and (c) Observed frequency distributions (PDFs) of the integral scale, $T$, characterizing river flow regimes upstream (lilac) and downstream (gray) of flood control ($R_C > 150d$) and water supply ($R_E > 0.5$) reservoirs. The insets show the typical behaviour of the autocorrelation functions upstream and downstream of dams. Regulation for flood control and water supply enhances daily streamflow correlation downstream, inducing an increase of the average value of $T$ from 6.5 to 15.2 days (flood control) and from 11.9 to 17.4 (water supply). (b) Negative-positive transition in the slope of the log-log Allan deviation plot, $\alpha$, induced by regulation for flood control ($R_C > 150d$) at the seasonal time scale, across all sites. The inset shows a typical example of the Allan deviation for unregulated (lilac) and regulated (gray) streamflows.

Instead, the unpredictability of regulated hydrographs downstream of large flood control structures ($R_C > 150d$) increases for longer time intervals up to the seasonal timescale ($\alpha > 0$ in 55% of cases), sometimes originating a red-noise signal (figure 3(b)). This behaviour is particularly evident downstream of large multipurpose structures, where sporadic though abrupt shifts of daily reservoir releases occur because of the variety of social and environmental requirements that must be fulfilled. The increase of flow unpredictability at the seasonal time scale is not evident downstream of water supply dams (figure S7). On the other side, when the amount of water withdrawn is relevant ($R_E > 0.5$), regulation for water supply is responsible for enhancing the correlation of downstream flows by 40% (figure 3(c)).

## 4. Discussion and conclusion

Our results reveal that reservoirs devoted to flood control and those operating for public water supply produce distinctive impacts on flow regimes. Flood control through dams does not alter the mean discharge downstream, but decreases the intra-seasonal variability of streamflows and, therefore, homogenize regional flow dynamics. Urban water supply, instead, reduces the mean discharge of regulated reaches but increases the relative streamflow variability, thereby enhancing the regional heterogeneity of discharge fluctuations.

Flow regime alterations through dams typically originate a lowered aquatic biodiversity. In particular, the flourishing of non-native organisms of fewer species has been often documented downstream of flood control structures [12, 64]. The case of the Upper Allegheny River Basin (table S1) is emblematic of the type of ecological impacts produced by flood control reservoirs. In this catchment, the reduction of river flow variability downstream of the Kinzua Dam ($\Delta CV/CV_{NAT} = 0.3$ on annual basis) was responsible for endangering native plant, mussel and fish species, concurrently promoting the settlement of nonnative riparian vegetation [65]. On the other hand, the negative impact of water supply dams on aquatic and riparian ecosystems has been documented in many regions of the U.S., including the New York State, where three reservoirs (Cannonsville, Pepacton and Neversink, see table S1) divert up to 85% of the annual inflow to supply the city of New York. Therein, the downstream reduction of mean discharge and the abrupt sporadic changes in flow magnitude have reduced the ecosystem size and have limited spawning and outmigration, leading to scarce and less diverse populations of fishes, benthic invertebrates and mussels [66, 67]. However, there is no evidence of the flourishing of invasive species in that river—a circumstance shared by all the regulated reaches downstream of water supply dams considered in this study.

Multipurpose structures partly devoted to water supply are, in most cases, primarily operated for flood control, and they have been classified accordingly also in this study [24]. Results from our analysis show that regulation through multipurpose reservoirs produces downstream patterns of discharge that differ from those observed downstream of reservoirs operated only to mitigate floods. The overall magnitude of flow regime alterations downstream of multipurpose dams is reduced by the distinctive, compensatory effect of water supply, that partly counterbalance the decrease of flow variability typical of flood control dams, especially during seasons with significant withdrawals and limited floods (see figure 4(a)). Accordingly, the relative reduction of $CV_Q$ induced by flood control decreases by 30% when reservoirs are also used for water supply (see SI). On the

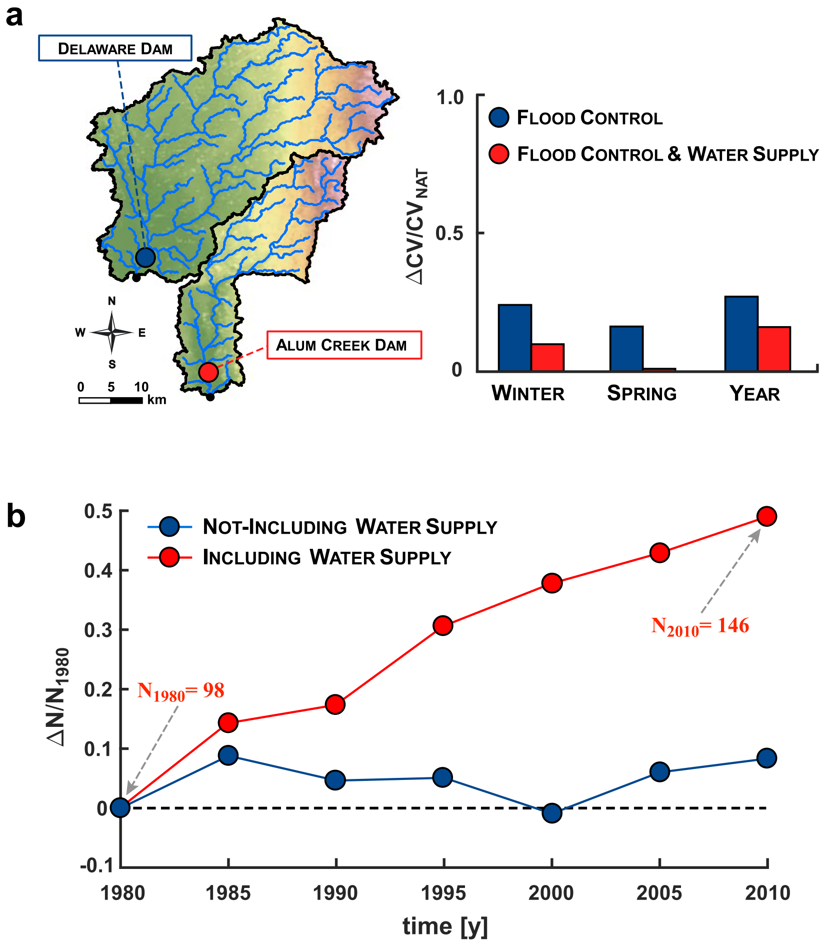


**Figure 4.** Impact of regulation on flow regimes and temporal patterns of public supply sources in the United States. (a) Comparison between the effects of regulation in two adjacent catchments. Alum Creek Dam (right) originates a multipurpose reservoir devoted to flood control and water supply, while Delaware Dam (left) is only designed for flood protection. The reduction of river flow variability observed downstream of the Alum Creek Dam is less significant than that observed downstream of the Delaware Dam (particularly in spring and winter), revealing that regulation for water supply partly counterbalance the decrease of flow variability due to flood mitigation. (b) Temporal trend in the number of reservoirs managed by the U.S. Army Corps of Engineers including and not-including water supply among their project functions.

other side, large multipurpose reservoirs are able to impact the autocorrelation structure of downstream flows beyond the timescale of single events. This implies that, at seasonal and annual time scales, regulated hydrographs behave more as an autocorrelated red noise rather than as an uncorrelated white noise—as some natural rivers do [56]. Discharge color, as well as its variability, is known to affect riverine ecosystems, exerting a significant impact on population dynamics and persistence [54, 68]. Overall, the reddening of river flow regimes downstream of large multipurpose dams might enhance the likelihood of prolonged detrimental environmental conditions, which endanger short-lived organisms and promote the settlement of long-lived fishes [54, 69].

Public supply represents an important item of freshwater consumption, particularly in developed regions, such as Europe and Oceania (where it constitutes about 20% of the overall water withdrawals). Recently it has been experiencing the most evident expansion among all water sectors, with an increase of water consumption of about 400% in 50 years at global scale [70, 71]. Despite a recent trend change, in the United States public supply withdrawals have tripled since 1950, jumping from 13.6 Bgal/d to 39 Bgal/d in 2015, two-thirds of which have been almost constantly supplied by surface water [72]. Accordingly, while the number of flood control structures remained relatively stable over time, the number of reservoirs devoted to water supply increased by 50% in the last 30 years [25, 73] (figure 4(b)). In the light of our findings, we suggest that the current increase of water demand for public supply [70–72] might impact the cumulative effect of dams at regional and global scales. Including water supply among reservoir functions, as observed in the U.S., would possibly reduce water resources downstream, but might potentially compensate (and even reverse) the impact of flood control on relative discharge fluctuations, leading to smoothed alterations of the internal variability and the regional diversity of flow regimes. On the other hand, the potential construction of new dams operated mainly for water supply (as hypothesized for developing countries [74]) would impact more severely the mean discharge of dammed rivers and might generate more heterogeneous and variable flow regimes (i.e. higher and more heterogeneous values of $CV_Q$). An increased erraticity of regulated flow regimes might exacerbate water conflicts in socially unstable regions [75], and originate distinctive trajectories of ecologic and morphological alterations downstream of water supply dams. These alterations are likely to be driven by the duration of persistent droughts induced by water abstractions and the frequency and timing of sporadic high flow events bypassing the dam. These results bring important clues for understanding the nature of anthropogenic alterations of river flow regimes, possibly helping the development of flexible and targeted strategies for a sustainable management of water resources. The awareness of the connection between flow regime alterations and anthropogenic water uses might be of particular importance in developing countries, where a dramatic increase of water use is expected to take place to sustain population growth and economic development. This is especially true in areas where signs of water scarcity have been already appeared, as well as in tropical regions, where rainfall is abundant but unevenly distributed in space and time and water infrastructures would be necessary to optimize anthropogenic exploitation of water resources.

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