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Key Points:

- Dams disrupted dominant natural periodicities in river flow regimes and introduced novel periodicities
- The magnitude of dam-induced periodicities changed over time, in response to climate variability and shifts in reservoir operation policies
- Wavelet-based methods can reveal missing and extraneous flow signals, informing restoration of natural flow variability in dammed rivers

Supporting Information:

Supporting Information may be found in the online version of this article.

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Spectral Signatures of Flow Regime Alteration by Dams Across the United States

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Abstract River scientists strive to understand how streamflow regimes vary across space and time because it is fundamental to predicting the impacts of climate change and human activities on riverine ecosystems. Here we tested whether flow periodicity differs between rivers that are regulated or unregulated by large dams, and whether dominant periodicities change over time in response to dam regulation. These questions were addressed by calculating wavelet power at different timescales, ranging from 6 hr to 10 years, across 175 pairs of dam-regulated and unregulated USGS gages with long-term discharge data, spanning the conterminous United States. We then focused on eight focal reservoirs with high-quality and high-frequency data to examine the spectral signatures of dam-induced flow alteration and their time-varying nature. We found that regulation by dams induces changes not only in flow magnitude and variability, but also in the dominant periodicities of a river's flow regime. Our analysis also revealed that dams generally alter multi-annual and annual periodicity to a higher extent than seasonal or daily periodicity. Based on the focal reservoirs, we illustrate that alteration of flow periodicity is time varying, with dam operations (e.g., daily peaking vs. baseload operation), changes in dam capacity, and environmental policies shifting the relative importance of periodicities over time. Our analysis demonstrates the pervasiveness of human signatures now characterizing the U.S. rivers' flow regimes, and may inform the restoration of environmental periodicity downstream of reservoirs via controlled flow releases—a critical need in light of new damming and dam retrofitting for hydropower globally.

Plain Language Summary Abundant research has shown that large dams impact river ecosystems via profound changes in their streamflow regimes. However, most large-scale analyses on dam impacts have been constrained by the assumption of stationary climates. Here we used time-series analysis (wavelets) on a large, long-term data set of daily and hourly discharge across rivers of the United States. We revealed that although free-flowing rivers consistently showed annual or seasonal flow cycles, dams often disrupted these natural cycles and introduced new ones. Notably, flow alteration patterns changed over time due to climatic fluctuations and shifts in dam operations.

1. Introduction

The world's free-flowing rivers support diverse, complex and dynamic ecosystems (Grill et al., 2019), which are essential for socioeconomic development and environmental sustainability (Anderson et al., 2019; Ripl, 2003). Over the past few decades, most rivers worldwide have experienced dramatic changes in their range of streamflow variability due to the widespread construction and operation of dams and other water infrastructure, increased human water use, and recent changes in hydroclimate (Döll & Zhang, 2010; Palmer et al., 2009; Singh et al., 2015). In particular, large-scale dam building has caused major impacts to river ecosystem functioning and structure, via alteration of flow and thermal regimes and the disruption of natural processes that require lateral and longitudinal connectivity (Barbarossa et al., 2020; Nilsson & Berggren, 2000; Tonkin et al., 2018). While the assumption of climate stationarity has underpinned the design and operation of water management infrastructure (Milly et al., 2008), widespread changes to mean flows and extremes challenge the study of hydrologic alteration and its ecological consequences (Poff, 2018). Similarly, operational signatures of reservoirs can change over time due to both changes in hydroclimate and in environmental flow management; and large geographic variability exists in how environmental, societal, and regulatory conditions relevant to the design and operation of U.S. reservoirs have changed over time (e.g., as observed from the U.S. Army Corps of Engineers reservoirs; Patterson & Doyle, 2019). As both climate and water management practices continue to change, there is an increasing need to understand hydrologic alteration under shifting hydro-ecological baselines (Tonkin et al., 2019).

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The natural flow regime concept (Poff et al., 1997) poses that preserving the characteristic patterns of flow variability (including the magnitude, frequency, duration, timing, and rate of changes of high and low flows) may maximize river ecosystem functioning and persistence of native biodiversity. As a consequence, this paradigm has played an important role in predicting ecological responses to hydrologic alteration (e.g., Poff & Zimmerman, 2010). Because shifting hydroclimates and ecological contexts (e.g., highly-invaded river ecosystems) challenge the notion of "reference" conditions, there have been mounting calls to prescribe environmental flows that sustain robust, socially-valued ecological outcomes in a flexible and adaptive management framework (Chen & Olden, 2017; Poff & Schmidt, 2016; Tonkin et al., 2019). Accordingly, identifying and preserving (or re-instating) key aspects of a river's flow regime has become a key goal of river restoration ecology, particularly in ecosystems affected by large dams (Palmer & Ruhi, 2019).

An estimated 2.8 million dams have been constructed worldwide for various water management goals such as flood control, hydropower, irrigation, and recreation (Lehner et al., 2011). Multiple studies have shown that different facets of flow alteration may be controlled by dam purpose, size, operation policies, and operation frequency (e.g., daily, weekly, annual) (Chalise et al., 2021; Mailhot et al., 2018). For example, hydropower dams are often assumed to be more impactful within shorter timescales (e.g., hourly to daily) due to short-term variation in hydropower demand and associated hydropeaking events, which can affect the structure and dynamics of aquatic production (Deemer et al., 2022) and invertebrate consumers (Kennedy et al., 2016; Ruhi et al., 2018). In turn, flood control dams are often assumed to be more impactful on longer timescales, via dampening of seasonal flood pulses that affect organisms and ecological processes that depend on the seasonal activation of floodplains (Junk & Wantzen, 2004; Talbot et al., 2018). Predicting responses of different ecosystem components (e.g., invertebrates, fishes, riparian trees) to flow alteration thus requires considering the different environmental frequencies (daily to multi-annual), as well as potential fluctuations in such alteration.

Hydrologic indices have long been used to characterize different aspects of flow regimes and evaluate the impacts of dam regulation (Gao et al., 2009; Olden & Poff, 2003; Wu et al., 2015). For instance, the Indicators of Hydrologic Alteration, IHA (Mathews & Richter, 2007; Richter et al., 1996) have been widely used to describe alteration across flow regime facets, often by comparing pre-dam to post-dam periods. Considerable research has demonstrated widespread consequences of dam operations for riverine hydrology. Dams have been shown to homogenize flows across large spatial scales (Poff et al., 2007), and within a given watershed, flow alteration may accumulate spatially, with downstream sites "inheriting" alteration signatures of upstream dams and tributaries (McManamay, 2014; Ruhi et al., 2022). The assessment of changes within flow classes, or streams sharing similar hydrology (and/or hydrological controls) can help identify patterns of hydrologic alteration due to dam regulation (McManamay et al., 2012). Previous findings support the growing realization that investigations at multiple time scales are needed to fully capture flow variability in natural and dam-regulated rivers. By using a variety of flow alteration metrics in the time domain, Bevelhimer et al. (2015) found that dam impacts on hydrology are also manifested at subdaily timescales. Other approaches have focused on quantifying flow alteration across a range of timescales—from subdaily to interannual (Shiau & Wu, 2013). Nevertheless, the large majority of studies to date require prescribing time windows or timescales for analysis; a challenging endeavor given river scientists and managers are often limited by data availability and system complexity (Wu et al., 2015). We contend that flow alteration by dams may often show complex signals due to the multi-purpose nature of dam management, combined with interactions between the human and climate systems (Chalise et al., 2021; Ehsani et al., 2017). Thus, approaches that do not require pre-specifying time windows or timescales for analysis, but rather "borrow" information across nearby watersheds that experience similar climatic fluctuations, may be beneficial.

Wavelets are a powerful tool in signal processing that allow for analyzing hydrologic dynamics in a more "agnostic" way by capturing fluctuations at multiple time scales, such as transient impacts of flow management for hydropower in some seasons but not others (Palmer & Ruhi, 2019; White et al., 2005; Wu et al., 2015). This is because unlike the standard Fourier transform, wavelets are localized in both time and frequency, and are free from the assumption of stationarity (Torrence & Compo, 1998). Thus, wavelets can be used to examine systems that show variability along a shifting baseline, for example, due to climate forcing or increasing water use. While wavelets have been widely used in the geophysical sciences, applications in the context of streamflow alteration assessment are still precursory (but see White et al., 2005; Wu et al., 2015). They may be particularly useful in the hydrologic sciences because different dam purposes may alter flow frequencies differently (e.g., diel cycles for hydropower, seasonal cycles for irrigation), and dam operations may change over time in response to shifting management goals.

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This study investigates how dams alter flow regime periodicity over time, leveraging large geographic and hydroclimatic gradients across rivers of the conterminous United States. In particular, we asked: (a) What time scales (i.e., dominant flow frequencies) are most altered by dams, and do they depend on reservoir (storage) size?; (b) How does management purpose of a dam affect the range of altered frequencies?; and (c) Do these frequencies change over time, as a consequence of climate variability and/or changes in policy and operations? To this end, we used wavelet analyses to identify dominant flow frequencies and fluctuations in their amplitude over time, based on observed flow from 175 paired (upstream-downstream) gages capturing dam-regulated and unregulated conditions. We first identified dominant frequencies in all pairs of gages over concurrent time periods, and assessed how dam size, purpose, and geography, influenced flow regime alteration in the frequency domain. We then chose eight focal reservoirs with long-term, high-quality and high-frequency data, spanning different geographies and climates of the United States, and compared their hydrographs to those of free-flowing counterparts across the range of flow frequencies. Finally, we assessed time-varying alteration in these focal systems, to understand how spectral signatures of climate and management operations may have changed over time. To our knowledge, this is the first study that uses spectral analysis to quantify human signatures on flow regime at a regional to continental scale.

2. Methods

2.1. Streamflow Data

We collated mean daily discharge data (1900–2018) from 406 USGS gauging stations over the continental United States (CONUS) included in the National Water Information System (NWIS; https://waterdata.usgs.gov/nwis), using the "dataRetrieval" R package on 15 October 2019 (Hirsch & De Cicco, 2015). This study used the same data set on regulated gages as (Chalise et al., 2021). This data set includes 209 gages located between 0.1 and 74 kms downstream from dams (mean = 17 km), hereafter referred to as *regulated* gages (Figure 1), 189 of which had already been selected in a previous similar study (Gao et al., 2009). We considered dam-affected gages that had at least 15 years of daily streamflow data after the dam was built. For each regulated gage, we sought upstream or nearby natural streamflow from gages in adjacent HUC8 watersheds, from the Hydro-Climatic Data Network (HCDN) database (Oh & Sankarasubramanian, 2012; Vogel & Sankarasubramanian, 2005), hereafter referred to as *unregulated* gages. Hydro-Climatic Data Network gages were primarily identified by the USGS for the purpose of understanding climate influences on streamflow. These unregulated gages are located in free-flowing rivers and streams, and in watersheds that are minimally influenced by human activities (e.g., diversions and groundwater pumping) (Lins, 2012). Many past studies used the HCDN classification to examine the effects of climate on stream hydrology (Chalise et al., 2021; Ficklin et al., 2018; Poff et al., 2007); here, we aimed to pair regulated with unregulated gages in watersheds that experience similar climate variability. This study used the same criteria as Chalise et al. (2021) to pair regulated with unregulated gages, namely: (a) Both the regulated and the unregulated gage had to be located in the same HUC4 region; and (b) Both the regulated and the unregulated gage had to have at least 15 years of the same period of record for mean daily streamflow data. We used ArcGIS 10.5.1 for the spatial join of regulated with unregulated gages (ESRI, 2017), which delivered a total of 175 pairs within 100 km proximity of each other (mean = 27 km). We than calculated average wavelet power for each regulated and unregulated gage, as described below. To examine sub-daily frequencies, we used a subset of 107 pairs for which high-quality hourly discharge data was also available (i.e., more than 5 years of record with <15 days of missing data). For this subset of gages selected to examine sub-daily frequencies, we averaged 15-min values into hourly bins, and we then imputed missing hourly values using three different approaches: (a) Via linear interpolation, if hourly data was missing for less than a day during the central hours of the day; (b) Via last observation carried forward (LOCF), if data was missing for less than a day, but at the beginning or end of the day; and (c) By using the historical average for that day and hour, if hourly data was missing continuously for one day or more (this occurred in 34 sites). Drainage area for the gages with daily data ranged from 58 to 723,902 km^2 (median 1,199 km^2) for regulated gages, and from 0.18 to 57,544 km^2 (median 166 km^2) for unregulated gages. We found no significant correlation between drainage area and coefficient of variation of streamflow across unregulated gages ($R = -0.04$, $p = 0.58$). This pattern suggests a lack of systematic influence of drainage area on the wavelet power values reported. In this study, we focused only on post-dam period for analyzing both regulated and unregulated gages.

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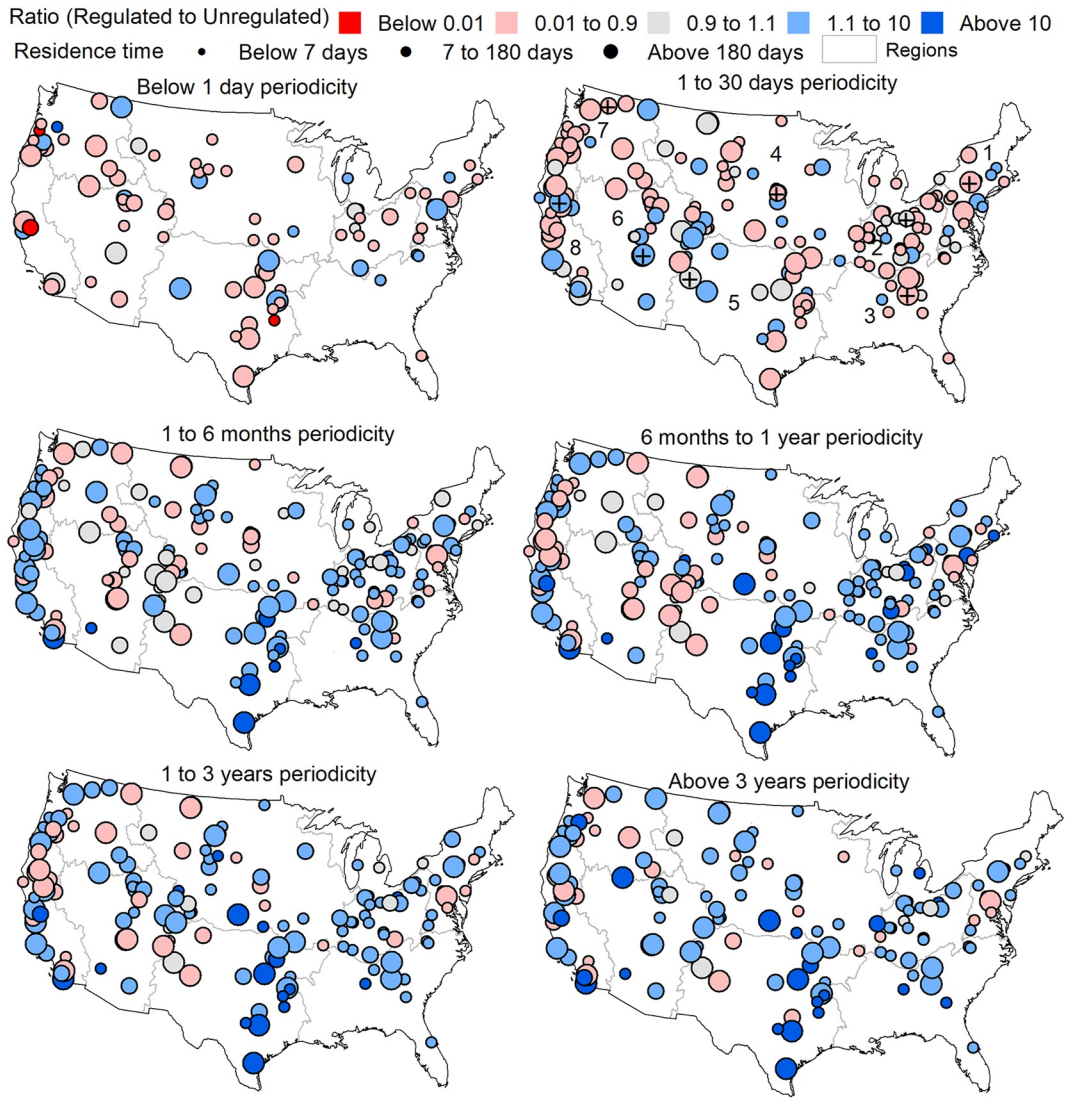

Figure 1. Ratios of normalized wavelet power between pairs of regulated-unregulated gages across the CONUS. Ratios below 1 indicate dams dampening flow variation at that periodicity, and ratios above 1 indicate dams intensifying flow variation at that periodicity. A total of 175 pairs were analyzed. Colors represent ratios, and marker sizes represent dam residence time. Markers with plus sign in the second panel denoted the selected reservoirs for case studies. U.S. is divided into 8 regions. Regions: *1 = Northeast*, *2 = Ohio*, *3 = Southeast*, *4 = Midwest*, *5 = Southcentral*, *6 = Southwest*, *7 = Northwest*, *8 = California*.

2.2. Dam Attributes

The main purpose (or management goal) of each dam, as well as its size, were obtained from the United States Army's National Inventory of Dams (NID) database (U.S. Army Corps of Engineers, 2018). Reservoir residence time, also known as degree of regulation, was then calculated as the ratio of normal storage volume of the reservoir (obtained from NID) and mean annual discharge at the regulated gage.

2.3. Continuous Wavelet Transform

Wavelets are a type of spectral method that allow time-frequency decomposition of non-stationary time series, identifying dominant frequencies, amplitudes, and phases in the environment—as well as changes in them (Torrence & Compo, 1998). Here we provide a summary of the continuous wavelet analysis transform (CWT); for a more detailed description, see Torrence and Compo (1998). We used the Morlet wavelet as a basis function

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because it provides a good balance between time and frequency resolution (Rezaei & Gurdak, 2020). This function has been used in previous wavelet-based analysis of streamflow periodicity (Ashraf et al., 2022; Hwang et al., 2021; Zolezzi et al., 2009). The Morlet function is mathematically expressed as,

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \tag{1}$$

Where $\psi_0(\eta)$ is the Morlet wavelet function, i is the imaginary unit, η is the non dimensional time parameter and ω_0 is the non dimensional frequency parameter. The continuous wavelet of a signal is computed as,

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n' - n)\, \delta t}{s} \right] \tag{2}$$

Where is $W_n(s)$ is the wavelet coefficient, s is the wavelet scale (i.e., time duration) and n' is the time step, n is the localized time index, N is the length of time series, W_n is the discrete time series ($n = 0$, …N-1), δt is the equal time interval of data sample, and ψ^* is the complex conjugate of ψ. To approximate CWT, convolutions are performed in the Fourier space using discrete Fourier transform. The wavelet function ψ is normalized with $\psi_0(\eta)$. The wavelet power spectrum (WPS) is calculated as,

$$\mathrm{WPS}_n(s) = |W_n(s)|^2 \tag{3}$$

Where $|W_n(s)|^2$ is the wavelet power at time n and scale s.

By using the hourly and daily datasets, we examined wavelet power at subdaily, daily, weekly, monthly, seasonal, annual, and interannual time scales.

2.4. Flow Alteration

To examine dam-induced flow regime alteration in the time-frequency domain over the CONUS, we first performed wavelet analysis on daily streamflow time series of each 175 paired dam-regulated (human affected) and unregulated (natural) gages. We used "analyze.wavelet" function in the "WaveletComp v.1.1" R package (Rösch & Schmidbauer, 2018) to compute and extract average wavelet power (normalized by variance) for each regulated and unregulated gage during the post-dam period. For each periodicity, we calculated the ratio of normalized power between each pair of regulated-unregulated gage. A ratio close to one at a given periodicity would indicate a similar importance of that periodicity in both gages—suggesting no flow alteration is "added" by the dam at that periodicity. In turn, a ratio below one would indicate that the dam is likely dampening flow variation at that periodicity, and a ratio above one would indicate that the dam is likely intensifying flow variation at that periodicity. An example of a wavelet analysis on a set of synthetic time series is provided in Figure S1 in Supporting Information S1.

To examine how flow alteration fluctuated over time, we chose eight focal reservoir systems that had long-term (>30 years), high-quality and high-frequency (hourly) discharge data. These reservoirs spanned different geographies and climates (Table S1 in Supporting Information S1): Cannonsville (New York), O'Shaughnessy (Ohio), Buford (Georgia), Gavin Point (Nebraska), Cochiti (New Mexico), Glen Canyon (Arizona), Grand Coulee (Washington), and Oroville (California). For each reservoir, we ran wavelets on the regulated and unregulated gage (as described in the previous section) based on the common window of record (see Figure S2 in Supporting Information S1). We then extracted wavelet power at different timescales, ranging from 6 hr to 10 years, and assessed fluctuations in wavelet power (and its statistical significance) within each gage pair.

3. Results

3.1. Dam-Induced Flow Regime Alteration

Dam-regulated gages over the CONUS showed flow alteration across all frequencies, as indicated by the comparison of wavelet power spectra in 175 pairs of dam-regulated versus unregulated gages (Figure 1). The magnitude of flow alteration was frequency dependent, with nearly 75% of regulated gages demonstrating lower flow variance at sub-daily periodicities relative to unregulated gages (ratio <1), and nearly 25% of the regulated gages exhibiting 10-fold more variance than their unregulated pairs at longer periodicities (i.e., above 3 years). While

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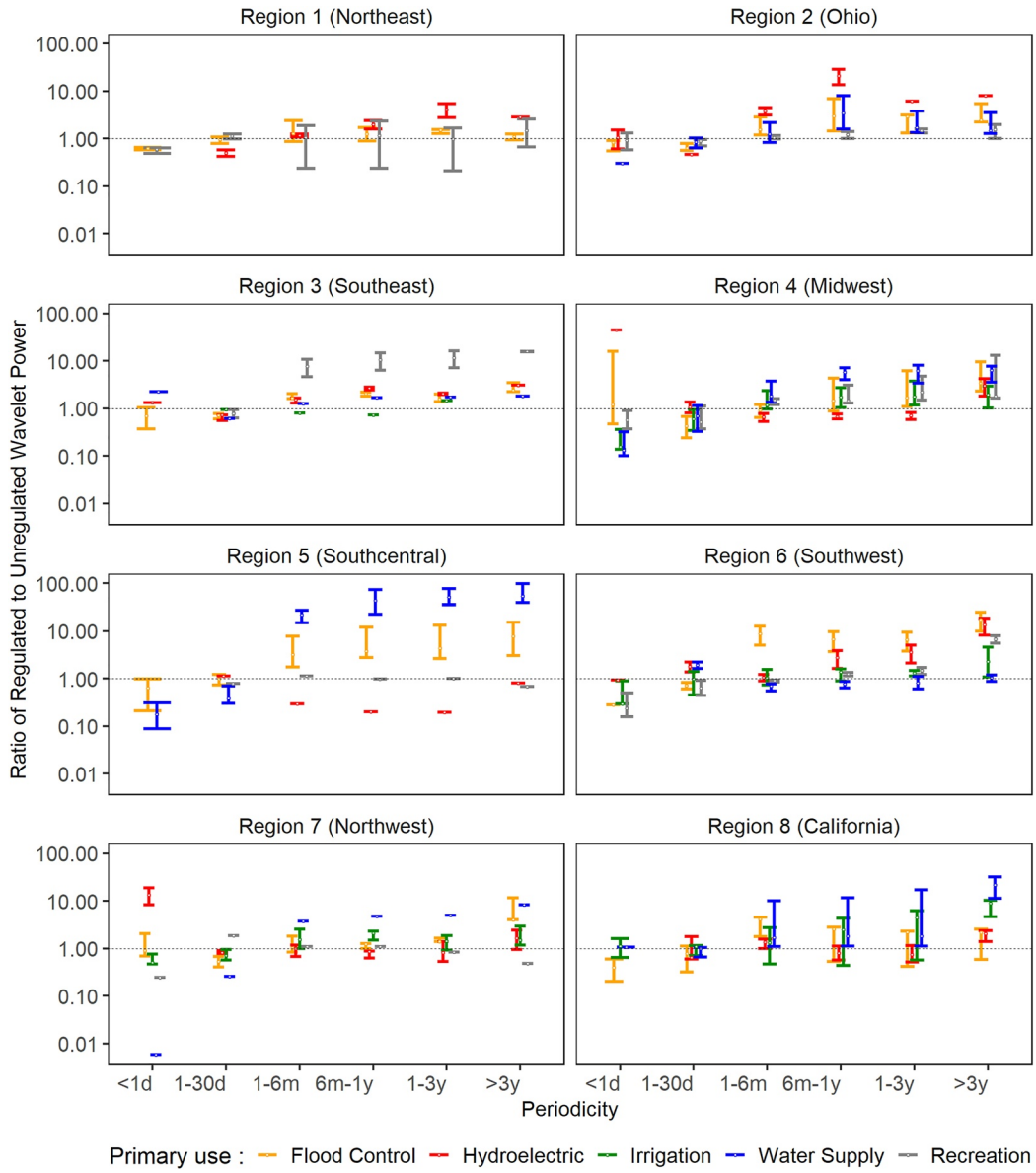

Figure 2. Comparison of the effects of dam purpose on flow alteration in the frequency domain, across 8 geographic regions. Points depict median wavelet power, and whiskers represent the spread between the 25th and 75th percentiles of wavelet power. Ratios below 1 indicate dams dampening flow variation at that periodicity, and ratios above 1 indicate dams intensifying flow variation at that periodicity.

no clear spatial pattern existed, we found that higher flow variances in regulated gages occurred at seasonal periodicities and longer, which were often associated with dams having longer residence times (see Figure S3 in Supporting Information S1).

Within a given region, the frequency of flow alteration was primarily associated with dam purpose (Figure 2), and secondarily explained by other factors such as dam size (Figure S4 in Supporting Information S1). The high variation of wavelet power across dam categories suggests that dams have a "signature" frequency that is related to their operation purpose. For example, hydropower dams in most regions showed relatively higher power at sub-daily frequencies, resulting from the short-term flow releases for hydropeaking ("load-following"). In turn, some frequency signatures were region specific. For example, irrigation dams in the southeastern U.S. (region 3) showed smaller variability in their wavelet power across different periodicities, whereas in the Southwest and West (region 5 and 8) dams showed higher variability in their wavelet power across different periodicities. These

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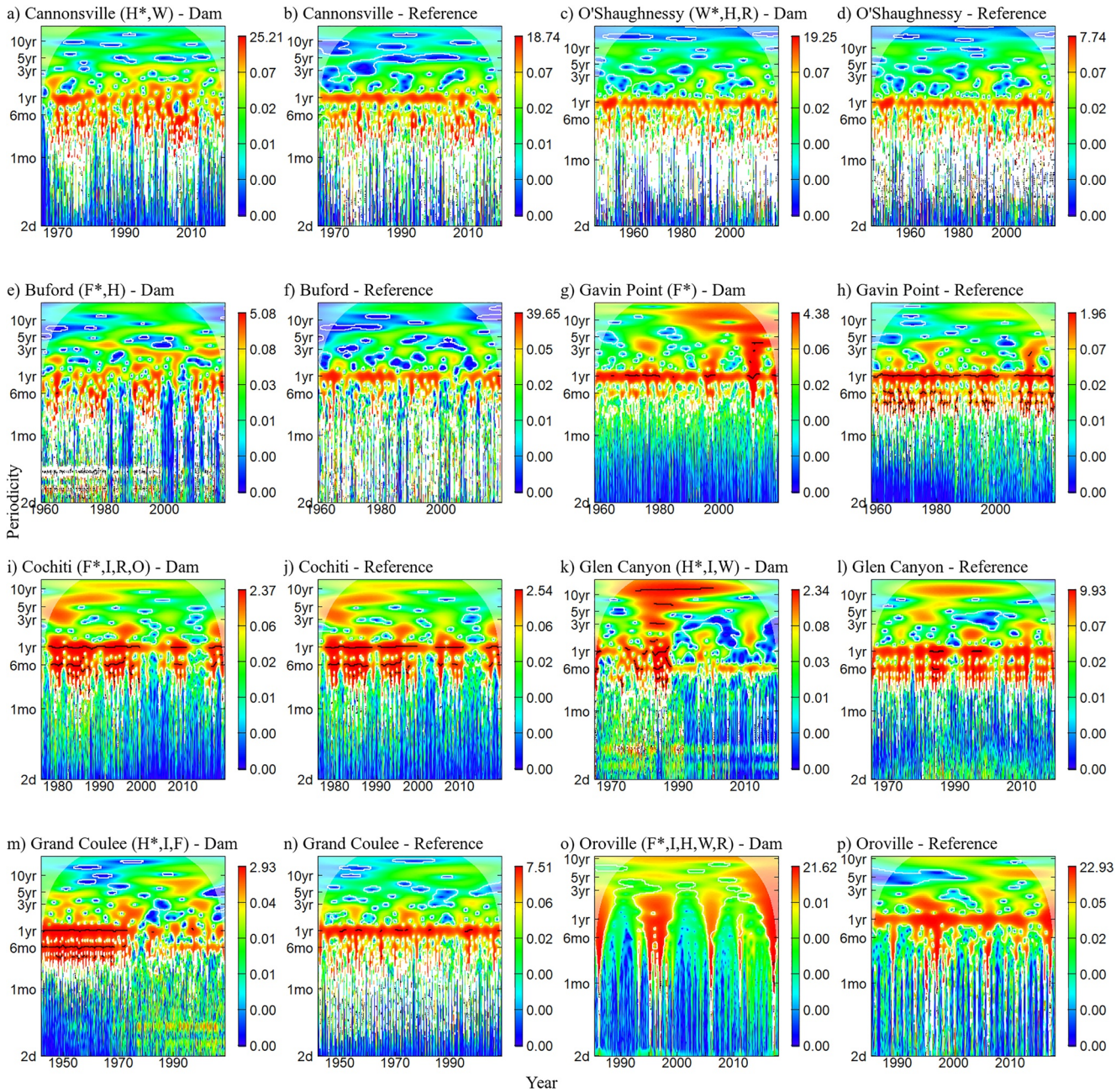

Figure 3. Wavelet Power Spectra (WPS) diagrams of natural and regulated flows for the 8 "focal" reservoirs. Colored bars show normalized wavelet power (warmer colors represent higher power; scale is plot-specific). *F*, *H*, *I*, *R*, *W* refer to *Flood control*, *Hydropower*, *Irrigation*, *Recreation*, and *Water Supply* respectively, and * indicates the primary management goal of each dam.

results show that dams profoundly alter flow regimes in the frequency domain, with both size and management purpose controlling the direction and magnitude of the alteration.

3.2. Flow Alteration in Focal Reservoirs

To examine alteration in further detail, we chose 8 focal reservoirs that have long-term, high-frequency, high-quality data spanning different geographies and climates (Figure 1). While natural flow regimes consistently showed either annual or seasonal cycles, or both, dams disrupted these frequencies and introduced new periodicities resulting from their operation (Figure 3). For example, Buford Dam (Figure 3e) introduced a new periodicity

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at the weekly scale that was absent in its unregulated pair (Figure 3f); Gavin Point Dam (Figure 3g) showed long term variance (3–10 years) after the year 2000; and Oroville Dam (Figure 3o) showed periodic switching between high and low variance at the annual scale, unlike its consistently-seasonal unregulated pair (Figure 3p). In contrast to these examples, O'Shaughnessy Dam (Figure 3c) consistently showed an annual cycle that was similar to that of its unregulated pair (Figure 3d).

Further, our results indicate that alteration of flow frequencies may depend on both primary and secondary purposes of a dam (Figure 4). For example, hydropower operation at Buford dam introduced a strong daily to a weekly cycle in flow releases (Figure 4c), which suggests that even as a secondary purpose hydropower can dominate high frequencies of a flow regime. Flood control in Cochiti dam showed similar seasonal and annual cycles to its natural pair (Figure 4e), but in Gavin Point dam it produced strong changes in seasonal and annual frequencies. In contrast to Buford and Gavin Point dams, irrigation and hydropower use in Oroville dam produced a strong change in monthly periodicity, illustrating that multi-purpose dams may in some cases create new cycles that can emerge from compounding periodicities. When dams had hydropower as their primary use, their secondary use also influenced flow periodicity alteration. For example, water supply in Cannosville, irrigation and water supply in Glen Canyon, or irrigation and flood control in Grand Coulee all exhibited strong seasonal and annual cycles (Figures 4a, 4f, and 4h). Unlike hydropeaking in Buford, O'Shaughnessy showed similar patterns relative to its upstream natural flow—a pattern consistent with being a run-of-river hydropower dam (Figure 4b).

Focusing on these eight reservoirs, natural versus dam-regulated rivers showed distinct changes in dominant flow periodicities over time (Figure 5). We found higher temporal fluctuation in wavelet power in regulated relative to unregulated pairs at daily, monthly, seasonal, and annual periods (Figure 5a, see also Figure S5 in Supporting Information S1). In contrast, temporal fluctuations in wavelet power were highly synchronized between regulated-unregulated pairs at the 3-year periodicity and longer (Figure 5b, see also Figure S5b in Supporting Information S1). Notably, these fluctuations were coherent with changes in dam operations and environmental regulation. For example, in Glen Canyon dam annual periodicity decreased after 1990, but wavelet power at the seasonal scale increased (Figures 3 and 5). Environmental flow constraints such as minimum flow, maximum flow, and maximum ramp rate were imposed in Glen Canyon Dam in 1990 (USBR, 2015), and the relative importance of altered frequencies shifted in agreement with these changes. On a similar note, Grand Coulee showed an abrupt decrease in annual periodicity relative to its unregulated pair after 1975, coinciding with an increase in reservoir capacity from 2,253 to 6,809 MW over the 1975–1980 period (USBR, 2017). Overall, we confirmed that altered flow frequencies in dam-impacted rivers may fluctuate in importance over time, mostly as a consequence of changes in policy and operations.

4. Discussions and Conclusions

Mounting evidence points to the extent of the human domination of the water cycle (Abbott et al., 2019; Cooley et al., 2021), which is profoundly impacting river ecosystems and river-dependent societies globally (Anderson et al., 2019; Palmer & Ruhi, 2019). Here we focused on understanding how dams influence fundamental rhythms in a river's flow regime (Jackson et al., 2022), using quantitative approaches in the time-frequency domain (wavelets) on long-term hydrologic data across the United States. We found that dams have unique spectral signatures on a river's flow regime, with most dams reducing natural flow variance at shorter periodicities by reducing peak-flow variations, and increasing natural flow variance at longer time scales to meet the continually increasing demand. We also found that alteration was influenced by dam purpose, size, and management objective, with changes in these characteristics (e.g., due to tightening environmental regulations or dam enlargements) being reflected in signals that emerged or disappeared over time. The implications of these findings are far-ranging, and advance the notion that hydrologic alteration is best assessed in a time-varying rather than time-averaged way (Poff, 2018). Understanding how and when flow periodicity has been altered by flow regulation and hydroclimatic fluctuations could inform reservoir re-operation actions suited to restore natural flow variability (e.g., via flow releases that restore natural seasonality, or that dampen flow cycles at novel timescales) (Tonkin et al., 2019; Wang et al., 2015), a critical need given the new wave of damming in highly-biodiverse, developing economies (Winemiller et al., 2016).

Our analysis suggest that dam operations have unique "signatures" on the frequency domain: while hydropower dams showed higher wavelet power at shorter frequencies, flood control and irrigation dams enhanced the longer (seasonal) frequencies of river flow regimes. Artificial subdaily to weekly cycles represent a novel flow regime

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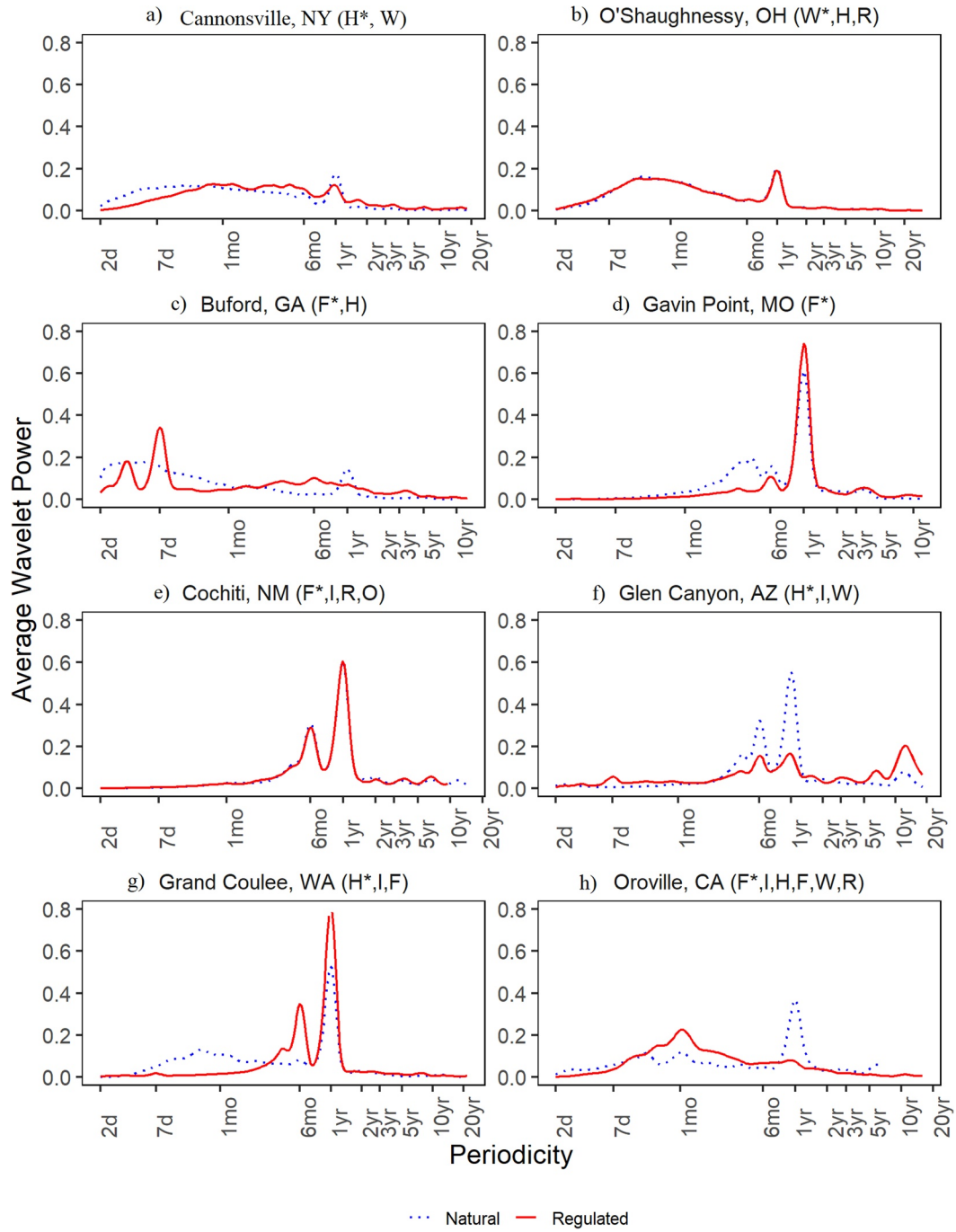

Figure 4. Average Wavelet Power Spectra for the eight focal dams (solid line) and their reference pairs (dashed line). Relevant periodicities are shown in the *x* axis. *F*, *H*, *I*, *R*, *W* refer to *Flood control*, *Hydropower*, *Irrigation*, *Recreation*, and *Water Supply* respectively, and * indicates the primary goal of each dam.

that has deep impacts on riverine ecosystem structure via organismal drift, stranding, and alteration of thermal regimes (Kennedy et al., 2016; Moreira et al., 2019; Ruhi et al., 2018). Our analysis also showed that frequency of flow alteration from "load following" fundamentally differed from a typical run of river operation (Figure S6 in Supporting Information S1). In turn, irrigation is one of the largest water uses in the U.S. Southwest, and water demand has increased due to combined population growth and decreased inflows arising from multi-year droughts (MacDonald, 2010; Milly & Dunne, 2020; Sankarasubramanian et al., 2017). The need to move water from wet to dry seasons, or to divert it from wet to dry watersheds, particularly during drought conditions, is

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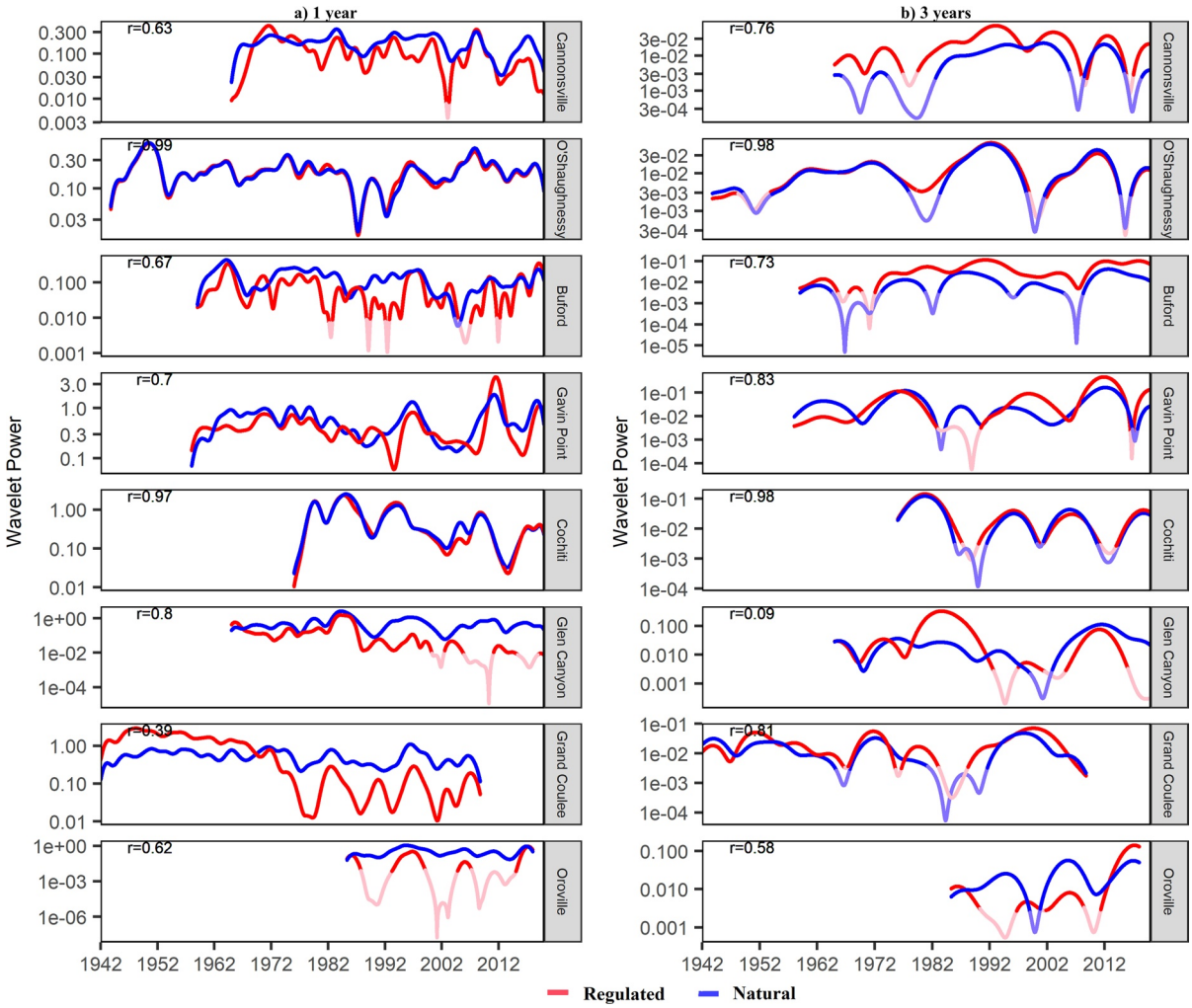

Figure 5. Wavelet power time series for eight focal dams (red lines) and their reference (blue lines), at annual and 3-year periodicity. Bright colored portions of the time series indicate statistically significant power (p-value < 0.05). The Pearson's correlation coefficient between regulated and unregulated wavelet power series for each pair is shown on the top left of each panel.

likely behind the dampening of seasonal (and longer) flow frequencies. We note here that most dams in our study areas are multipurpose in nature, which may influence their spectral signatures in region-specific ways. For example, irrigation dams in the Western U.S. show relatively higher flow alteration at a subdaily time scale, comparable to signatures from hydropower dams. We suggest this is because most irrigation dams in the Western U.S. have hydropower as an additional purpose. Rapidly growing human populations has led to the doubling of water supply withdrawal since 1980 in the U.S. (Sankarasubramanian et al., 2017), potentially explaining higher flow alteration at the seasonal scale by water supply dams across the Southwest.

By investigating 8 focal reservoir systems, we showed that flow altered frequencies may evolve over time. For example, annual flow periodicity at Glen Canyon dam (Arizona) decreased after 1990, consistent with changes in environmental flow regulations; and annual flow periodicity at Grand Coulee (Washington) decreased in the late 1970s, coinciding with a 3-fold increase in reservoir capacity. These results suggests that different management goals and dam operations control not just the frequency of flow regime alteration, but also fluctuations in such alteration. These results are consistent with recent research showing that dams alter river flow regimes across multiple frequencies over time (Hwang et al., 2021). Stronger departures in wavelet power between regulated-unregulated gage pairs occurred at shorter frequencies (e.g., subdaily), while wavelet power at longer frequencies (e.g., 3 years, 8 years) was highly synchronized within regulated-unregulated pairs. This finding is also consistent with previous studies showing that reservoirs shifted flows at the annual scale (e.g., in China,

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Zhang et al., 2018). We also found greater shifts in seasonal and annual variance over time, reflecting reservoirs that are "forced" to increasingly dampen natural flow variability to ensure downstream water requirements for humans and the environment. This result illustrates that the effects of climate change on water availability may increasingly affect both natural and regulated flow regimes (Das Bhowmik et al., 2020; Sankarasubramanian et al., 2017).

Our wavelet-based analysis complements previous research using metrics of hydrologic alteration in the time domain in three different ways. First, because wavelets do not require specifying a frequency of interest, they provide an opportunity to explore alteration across timescales, revealing signals that may not be readily evident if one focuses on pre-specified frequencies (e.g., annual and seasonal cycles) (Ashraf et al., 2022; Ruhi et al., 2018). Second, methods in the time-frequency domain such as wavelets may reveal whether flow alteration is itself time-varying, with signals emerging or disappearing with changing operations (Cheng et al., 2021; Raath & Ensor, 2020; Ruhi et al., 2018). In turn, this frees the investigator from having to specify a time window across which conditions may be summarized, which is particularly challenging (and may lead to wrong inferences) when analyzing non-stationary processes. In this vein, wavelets can parse out the effects of a continuously shifting hydrologic baseline (e.g., due to climate change; Villarini & Wasko, 2021; Yang et al., 2021) from alteration that is "added" by dam regulation. To illustrate this point, by using a comparison of pre-dam to post-dam hydrologic conditions on the same set of gages, Chalise et al. (2021) found that dams altered some flow metrics (e.g., reversals, rise and fall rates). However, that approach did not show that human signals may have intensified or ameliorated with changes in operations within the post-dam period, due to potential climate change and increased demand. Overall, while having true "reference" hydrographs (from pristine watersheds in the present, or from altered watersheds historically) is immensely valuable, a combination of methods in the time and frequency domains may best describe the timescales and persistence of flow alteration.

This study focused on dam induced flow alteration, but dams alter many other aspects of the environment, including temperature, nutrient and sediment regimes, water quality, longitudinal and lateral hydrologic connectivity, and composition of biological communities (Maavara et al., 2020; Olden & Naiman, 2010; Poff et al., 1997). Further research could build on our current approach and assess how these regimes are impacted by dams in time-frequency domain, or link ecological outcomes to such alteration. Additionally, due to constraints on the availability of daily and hourly data, and on the pairing of regulated with unregulated gages, our study necessarily captured only a small fraction of the tens of thousands of large dams in the United States (U.S. Army Corps of Engineers, 2018). This limitation constrains our ability to generalize, even if the mechanisms behind flow alteration are likely transferrable to other geographies. Finally, many multi-purpose dams are aged and face operational hurdles, particularly when managing extreme flows (e.g., Oroville spillway failure in 2017) (Ho et al., 2017). This can further challenge inferring causal drivers of "transient" alteration signatures even when data is available. More generally, our work provides a broad perspective on the alteration of flow frequencies as a function of dam purpose, residence time, and regional hydroclimate. Detailed watershed-level research is needed to reduce the hydrologic impacts of dams (Chen & Olden, 2017; Wang et al., 2015), as well as to predict the spatial propagation of flow alteration impacts (Ruhi et al., 2022).

From an applied perspective, our study goes beyond demonstrating the well-recognized effects of dam regulation on flow magnitude and variability, and shows significant impacts on the periodicity (or natural streamflow "cycles") of river flow regimes. Life-history traits of species, and emergent community properties, are strongly linked to flow periodicity at both ecological (days to years) and evolutionary (decades to millennia) time scales (Lytle & Poff, 2004). Thus, this form of flow alteration has broad implications for riverine ecology given the new wave of hydropower damming in developing economies and calls for retrofitting existing dams for hydropower production. For example, the United States Department of Energy's (USDOE's) Oak Ridge National Laboratory has quantified the hydropower resource potential from non-powered dams, showing there is a 12.1 GW of hydropower potential in 54,391 non-powered dams (Hadjerioua et al., 2012). While this potential is unlikely to be realized in full scale, and most of it could be in the form of run-of-the-river facilities, we infer from our study that retrofitting of non-powered dams for hydropower production could potentially introduce weekly, daily, and subdaily flow frequencies. Thus, any efforts to add hydropower potential to existing non-powered dams should carefully evaluate potential downstream impacts on flow alteration across a wide range of periodicities. More importantly, 3,700 new hydropower dams are expected to be commissioned in developing countries (Zarfl et al., 2015), and many are projected to affect the world's most biodiverse river basins (Flecker et al., 2022; Winemiller et al., 2016). Operational rule curves for such systems should consider environmental flow targets

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under current and future hydroclimates (Chalise et al., 2021; Chen & Olden, 2017), as well as ecological limits to the alteration of short- and long-frequency flow cycles (Kennedy et al., 2016).

Understanding dam-driven alteration of flow periodicity in a time-varying way is a valuable step towards identifying particularly impactful dams, but is equally important in helping develop reservoir management practices that seek to minimize flow alteration for existing and new systems (Wang et al., 2015). Although it may be an unrealistic target to restore rivers impacted by large dams back to pristine condition (Tonkin et al., 2019) new frameworks are showing that impacts may be partially mitigated through new decision frameworks that balance needs for society and ecosystems (Chen & Olden, 2017; Poff & Schmidt, 2016; Sabo et al., 2017). We contend that approaches to reoperate reservoirs in a more sustainable way should consider flow alteration in both the time and frequency domains using quantitative approaches that, like ours, account for climate non-stationarity.

Data Availability Statement

The daily streamflow data were retrieved from the USGS National Water Information System available at https://maps.waterdata.usgs.gov/mapper/index.html using the "dataRetrieval" R package (Hirsch and De Cicco, 2015). The dam attributes were retrieved from United States Army Corps of Engineer's National Inventory of Dams (NID) database available at https://nid.sec.usace.army.mil/#/ (U.S. Army Corps of Engineers, 2018). We used the "analyze.wavelet" function in the "WaveletComp" R package v.1.1 (Rösch & Schmidbauer, 2018) to run wavelets on the streamflow time series.

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