Reservoir regulation affects droughts and floods at local and regional scales

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Abstract
Hydrological extremes can be particularly impactful in catchments with high human presence where they are modulated by human intervention such as reservoir regulation. Still, we know little about how reservoir operation affects droughts and floods, particularly at a regional scale. Here, I present a large data set of natural and regulated catchment pairs in the United States and assess how reservoir regulation affects local and regional drought and flood characteristics. My results show that (1) reservoir regulation affects drought and flood hazard at a local scale by reducing severity (i.e. intensity/magnitude and deficit/volume) but increasing duration; (2) regulation affects regional hazard by reducing spatial flood connectedness (i.e. number of catchments a catchment co-experiences flood events with) in winter and by increasing spatial drought connectedness in summer; (3) the local alleviation effect is only weakly affected by reservoir purpose for both droughts and floods. I conclude that both local and regional flood and drought characteristics are substantially modulated by reservoir regulation, an aspect that should neither be neglected in hazard nor climate impact assessments.

1. Introduction
Droughts and floods can have particularly strong impacts if they affect large regions with high human presence where they are modulated by human intervention such as reservoir regulation. To reduce these impacts, we need estimates of event magnitude at local and regional scales which consider that hydrological extremes are modulated by reservoirs operated for different purposes such as hydropower production, recreation, or irrigation. Despite the potential impact of reservoir regulation on droughts and floods, both local and regional hydrologic extremes are often studied assuming natural flow conditions even though a substantial part of the world’s watersheds is regulated through reservoirs or water abstractions (Dynesius and Nilsson 1994, Abbott et al 2019). Such modifications have not only been shown to strongly affect flow regimes (Arheimer et al 2017) and annual flow (Yang et al 2021) but also hydrologic extremes (Verbunt et al 2005, He et al 2017, Tijdeman et al 2018, van Oel et al 2018).

Reservoirs have been shown to mostly alleviate droughts and floods in different parts of the world in both model- and observation-based studies (Verbunt et al 2005, He et al 2017, Wang et al 2017, Tijdeman et al 2018). Model-based studies simulate naturalized streamflow with a hydrological model and compare this simulated natural flow to observed regulated flow. In contrast, observation-based studies either compare regulated conditions downstream of a reservoir to natural upstream conditions or pre-dam construction conditions to post-dam construction conditions (Rangecroft et al 2019, Van Loon et al 2019). Observation-based studies are often limited to a few catchments while large-scale assessments are predominantly model-based and rely on specific assumptions regarding water demand and flow regulation (Yassin et al 2019). The drought alleviation effect of reservoirs has e.g. been demonstrated in observation-based studies for the United Kingdom (Tijdeman et al 2018) and in model-based studies for California (He et al 2017), in China (Tu et al 2018, Chai et al 2019), in the United States (Wan et al 2017),
and globally (Wanders and Wada 2015) while other studies have reported an increase in drought severity and duration for certain reservoirs in China (Zhang et al. 2015). Similarly, model- and observation-based studies have shown reductions in flood peaks, e.g. for the Rhine basin, in Italy, and the United States (Verbunt et al. 2005, Wang et al. 2017, Volpi et al. 2018), and in flood volumes e.g. in Thailand (Mateo et al. 2014).

While the potential impact of reservoir regulation on hydrologic extremes has been clearly demonstrated for individual case studies, in smaller regions, and at a local scale, it is largely unknown how human flow alterations affect extremes over larger regions. Regional flood hazard depends on the strength of spatial connections between extremes across different catchments (Brunner et al. 2020b), which has been shown to vary by season and region (Brunner et al. 2020a). To properly address the management challenges arising from regional flood and drought events in human-modified systems, we need to understand how spatial flood and drought connections are modulated by reservoir regulation.

The specific impact reservoirs have on local and regional extremes may depend on their purpose. At a local scale, a reservoir constructed with a main purpose of hydropower production might not show the same drought alleviation effect as a reservoir specifically designed for water supply. Similarly, a reservoir not specifically designed for flood control might not as efficiently or not at all alleviate flood magnitudes. At a regional scale, several reservoirs jointly operated for flood control may lead to bigger reductions in flood risk than several reservoirs operated for a variety of purposes. However, even if reservoirs are not specifically operated for flood control or water supply, they may still contribute to flood and drought alleviation, respectively. Still, it remains largely unexplored how regulation effects differ in regions with different reservoir purposes. That is, we know little about how flood and drought magnitudes are modulated by reservoirs operated for different purposes.

Here, I therefore ask how reservoir regulation affects local drought and flood characteristics and their spatial connectedness (i.e. number of catchments a catchment co-experiences extreme events with) and how this effect depends on reservoir purpose. To answer these questions, I compile a unique large-sample data set of catchment pairs in the United States consisting of a nearly natural catchment upstream of a reservoir or a set of reservoirs and a regulated catchment downstream of this reservoir or set of reservoirs. I use this data set to compare local extremes at nearly natural reference gauges with extremes at regulated gauges and assess how flow regulation affects spatial drought and flood connectedness across catchments. This large-sample data set enables studying the impact of reservoir regulation not just on local but also regional extremes, an aspect yet unexplored in human-impact assessments on hydrologic extremes. In addition, the data-driven approach proposed here allows me to assess reservoir regulation impacts on extremes for different reservoir purposes, which may be difficult using a model-based approach because hydrological models hardly differentiate between different reservoir purposes (Wada et al. 2017, Veldkamp et al. 2018, Yassin et al. 2019) and often suffer from a sub-optimal/simplistic representation of reservoir regulations—partly related to a lack of data (Brunner et al. 2021a).

2. Data and methods

2.1. Data and catchment pairs
To assess the impact of reservoir regulation on hydrologic extremes, I compile a data set of natural and regulated catchment pairs upstream and downstream of reservoirs in the United States. The catchment pairs are identified within the Dudley18 data set (Dudley et al. 2018), a data set consisting of 2683 gauges operated by the U.S. Geological Survey (USGS). The Dudley18 data set provides data for the period 1966–2015 and catchments were classified into nearly natural, regulated, urban, and other catchments by Ryberg et al. (2019). I here focus on the catchments in this Dudley18 dataset belonging to the categories nearly natural, i.e. catchments with minimal human alteration belonging to the Hydro-Climatic Data Network (HCDN) (Lins 2012), and regulated catchments, i.e. basins with high reservoir storage. To pair natural upstream with regulated downstream catchments, I check which regulated gauges lie downstream of which natural gauges along the streamflow network. To do so, I use the National Hydrography Dataset Plus (NHDplus) (Environmental Protection Agency EPA 2012), which provides geospatial data of the flow network in the United States and enables linking individual river segments with USGS gauges. For each of the natural gauges in the Dudley18 dataset (496 catchments), I go downstream the NHDplus flow network and check whether there is a gauge labeled as regulated (527 catchments). I determine all downstream flowlines of natural and regulated catchments using the ‘to’ identifier in the NHDplus data base. Then, I search for those natural gauges that share downstream flowlines with a regulated gauge. Following this procedure, I identify 114 pairs of natural and regulated catchments over the United States, which are separated by one or several reservoirs (figure 1(a)). The catchment pairs are spread in space and cover a variety of regions in the United States with diverse catchment attributes, climate characteristics, and reservoir storage capacities. Catchment areas of regulated catchments range from a first quartile of 2000 km² to a third quartile of 12 000 km² and mean elevations from 360 to 1800 m.a.s.l. Mean annual precipitation ranges from a first quartile of 570 mm to a third quartile of 1130 mm. Reservoir
storage capacities of the regulated catchments considered range from a lower quartile of 40 megaliters total storage per km² (1 Ml = 1000 000 l = 1000 cubic meters) to an upper quartile of 300 megaliters total storage per km².

For each of the 228 catchments in the data set (114 natural and 114 regulated ones), I downloaded daily streamflow data from the USGS streamflow data base (USGS 2019) using the R-package dataRetrieval (De Cicco et al 2018). Further, I derived catchment boundaries from the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) data set (Falcone et al 2010, Falcone 2011) and information on reservoir locations, capacities, and primary purposes from the National Inventory of Dams (NID) (U.S. Army Corps of Engineers (USACE) 2019). Purposes considered in the NID are flood control, hydropower production, irrigation, water supply, recreation, fish habitats, fire protection, and others. For each regulated catchment, I identify existing reservoirs and determine the primary reservoir purposes of the reservoirs with capacities exceeding 100 000 m³ (i.e. I exclude those reservoirs with very small capacities to focus on purposes of reservoirs potentially substantially affecting streamflow). Then, I determine reservoir purpose fractions for each catchment, i.e. I determine the relative importance of each reservoir purpose. I do so by weighting each purpose by the storage capacity of all reservoirs in the catchment which share that purpose as their primary purpose. That is, instead of assigning equal weight to all reservoirs independent of their storage capacity, I assign more weight to the purposes of the reservoirs with large storage capacities. Flood control is the most relevant purpose in terms of storage capacity in the eastern and central United States while hydropower production is important in the Pacific Northwest and irrigation in the Southwest (figure 1(b)).

2.2. Hydrological extremes

To assess the effect of flow regulation on local and regional hydrologic extremes, I identify local and spatial flood and drought events in both natural and regulated catchments. I identify independent flood events in the daily time series of the individual catchments using the 25th percentile of the corresponding time series of annual maxima as a threshold and by prescribing a minimum time lag of 10 d between events (Brunner et al 2020a, 2020b). Using the 25th percentile resulted in ~1.5 events chosen per year and catchment on average and a minimum time lag of 10 d was used to ensure independence between individual events (Diederen et al 2019). For each flood event, I define different characteristics including specific peak discharge (i.e. peak discharge normalized by catchment area; m³ d⁻¹), specific flood volume (i.e. volume normalized by catchment area; m³), and duration (days), some of which require defining the start and end of an event (for an illustration of the event characteristics see figure 2(a)). The start and end of an event are defined as the time when discharge first exceeds the threshold before peak occurrence and the time when it first falls below the threshold after peak occurrence, respectively. For each catchment, I then determine the mean number of events, mean peak discharge, mean flood volume, mean duration, and Kendall’s rank correlation between peak discharges and flood volumes as a measure of dependence between the two variables. Comparing variable dependence in regulated and natural catchments will allow me to assess how reservoir regulation affects the relationship between different variables.

Drought events at individual sites are extracted using a variable threshold-level approach suitable for catchments with a seasonal streamflow regime (Van Loon and Laaha 2015). The daily series are smoothed over a time window of 30 d prior to event extraction to minimize the risk of identifying dependent events and the variable threshold is computed using the 15th percentile for each day of the year determined within a moving window of ±15 d before and after the day of interest (Brunner et al 2021b). For each event, I define different characteristics similarly as for floods: specific drought intensity (absolute value of discharge-threshold at the time of minimum flow normalized by catchment area; m³ d⁻¹), specific drought deficit (deficit volume...
Figure 2. Reservoir influence on local flood and drought characteristics. (a) Relative change in mean number of flood events, peak discharge, flood volume, flood duration, and peak-volume (Q–V) dependence between regulated and natural catchments (sample size 114). (b) Relative change in mean number of drought events, drought intensity, drought deficit, duration, and deficit-duration (D–D) dependence. Positive and negative values indicate increases and decreases in the characteristics of extremes through reservoir regulation, respectively.

Figure 2(a). Reservoir influence on local flood characteristics. (a) Relative change in mean number of flood events, peak discharge, flood volume, flood duration, and peak-volume (Q–V) dependence between regulated and natural catchments (sample size 114).

over whole drought duration normalized by catchment area; m$^3$), duration (days) (for an illustration of the event characteristics see figure 2(b)). The start and end of an event are defined as the time when discharge first falls below the threshold before minimum flow occurrence and the time when it first rises above the threshold after minimum occurrence, respectively. For each catchment, I then determine the mean number of events, mean intensity, mean drought deficit, mean duration, and Kendall’s rank correlation between drought deficit and duration.

In addition to local drought and flood characteristics, I look at how floods and droughts are spatially connected across catchments using the connectedness measure introduced by Brunner et al (2020a) to study spatial flood dependencies. This connectedness measure quantifies the number of catchments a specific catchment co-experiences flood or drought events with. The spatial analysis is separately performed for droughts and for floods and for the two spatial sets of natural and regulated catchments. To compute the connectedness measure for each catchment pair, I first pool all flood or drought events identified in any of the 114 catchments. Second, I identify independent events by reducing the pooled event set to a subset of independent spatial events by only choosing one event within a 7 d window, i.e. the event where most catchments were affected. For each spatial event, I then determine the affected and unaffected catchments and summarize these results in a binary matrix where 1s indicate events a catchment was affected by and 0s indicate events a catchment was unaffected by. I use this binary matrix of flood occurrences to quantify the connectedness of hydrologic extremes for each pair of catchments within both the natural and regulated set. To do so, I count the number of catchments a certain catchment co-experiences extreme events with (pair of catchment shares >1% of total number of events). I compute connectedness not only at an annual but also at a seasonal scale to represent seasonal variations in connectedness.

Finally, I quantify the effect of reservoir regulation on hydrologic extremes by comparing local and spatial flood and drought characteristics of regulated and natural catchments. I determine the effect of flow regulation on characteristics of local extremes.
for each pair of natural and regulated catchments as the relative change in a characteristic: \( \frac{c_R - c_N}{c_N} \), where \( c_R \) and \( c_N \) represent mean characteristics in regulated and natural catchments, respectively. The effect of flow regulation on spatial extremes is quantified for each catchment as the absolute difference between its connectedness in the regulated catchment set and its connectedness in the natural set.

3. Results

3.1. Local extremes
Reservoir regulation affects both local flood and drought characteristics (figure 2). The comparison of flood characteristics in pairs of regulated and natural catchments shows that duration is the flood characteristic most strongly affected by reservoir regulation followed by peak discharge and flood volume while the dependence between peak discharge and volume are only weakly affected (figure 2(a)). Floods in regulated catchments last longer but are less severe, i.e. have smaller peak discharges and flood volumes, than floods in natural catchments. Reservoir regulation can increase flood duration by up to 200% while it can decrease peak discharge and flood volume by \( \sim 70\% \) and \( \sim 30\% \), respectively. It may also slightly increase the number of events (median change 10%) and lead to slightly later flood occurrence and lower peak-volume dependence. In addition to flood characteristics, drought characteristics are affected by reservoir regulation. Drought intensity and deficits are most strongly affected while drought duration, the number of events, and the duration-deficit dependence are less affected. Droughts in regulated catchments are less severe than droughts in natural catchments with intensities being reduced by \( \sim 45\% \) and deficits by \( \sim 30\% \).

3.2. Regional extremes
Reservoir regulation not only affects local but also regional drought and flood characteristics as shown by the comparison of flood and drought connectedness in regulated and natural catchments (figure 3). Reservoir regulation effects on spatial connectedness in hydrologic extremes differ by extreme type and season. Spatial flood connectedness is reduced by reservoir regulation in winter and fall and may increase or decrease depending on the catchment in spring and summer. Drought connectedness is also reduced in winter but increased in summer and may increase or decrease in spring and fall depending on the catchment.

3.3. Effect of reservoir purpose
Reservoir regulation effects on local flood and drought characteristics only weakly depend on reservoir purpose as shown by the impact analysis stratified by groups of catchments with the same major reservoir purpose (figure 4). Almost independent of their purpose, reservoirs lead to longer but less severe floods and to less severe droughts of similar duration than in natural catchments. This beneficial effect of severity reduction is strongest for catchments with reservoirs designed for ‘ecological’ purposes such as recreation or fish protection, for both floods and droughts. However, there are some purposes that lead to different changes than shown in the non-stratified analysis described in section 3.1. In the case of floods for example, flood duration may be reduced in catchments with reservoirs for fish and...
Figure 4. Changes in local flood and drought characteristics magnitude/intensity (red), volume/deficit (orange), and duration (green) for catchment pairs grouped by major reservoir purpose determined according to largest capacity (flood control: 56 catchments, hydropower: 22, irrigation: 13, water supply: 1, recreation: 6, fish: 6, fire protection: 1; see figure 1). (a) Median relative change in mean flood characteristics over catchments sharing the same major reservoir purpose. (b) Median relative change in mean drought characteristics over catchments sharing the same major reservoir purpose.

fire protection while it is increased in catchments with reservoirs fulfilling other purposes. Similarly, flood volumes may be increased instead of decreased in catchments with reservoirs designed for recreational purposes. In the case of droughts, drought severity is most efficiently reduced in catchments with reservoirs serving ‘ecological’ purposes and duration changes are only weakly dependent on reservoir purpose.

4. Discussion and implications

The results of this study show that regulation impacts are slightly more expressed for floods than for droughts. This might relate to the fact that a substantial part of the regulations in the data set compiled relate to flood control (figure 1(b)). Flood control seems to alleviate flood peaks and to a slightly lesser degree flood volumes by distributing discharge over longer event durations (figure 2(a)). The flood alleviation effect goes beyond local extremes as spatial flood dependencies are generally reduced, particularly in winter. Flood water is stored during this main flood season in the Eastern and Western United States (Villarini 2016), which prevents the development of joint flooding in multiple catchments. Similar to floods, reservoirs also alleviate local droughts both in terms of intensity and deficit. These findings corroborate findings from e.g. an observation-based study in the UK, where Tijdeman et al (2018) have shown a decrease in streamflow drought occurrence for some of the catchments with reservoirs and a model-based study in California, where He et al (2017) have shown that drought management reduced drought deficit during the 2014 drought by 50%. This alleviation effect can be partly achieved thanks to using the flood water stored during the winter season. While the reservoir-regulation effect is mostly positive at a local scale, spatial drought dependencies may be slightly strengthened in summer, i.e. drought synchronization across catchments intensifies in the presence of reservoirs. This synchronization increases the probability of widespread droughts and introduces new management challenges because water transfers to dry catchments from water abundant upstream or neighboring catchments may no longer be feasible. This finding contrasts findings by Wan et al (2017) who have shown that water management decreases drought spatial extent particularly in the irrigation season. My results also suggest such decreases but not for the summer season. The potential drought-alleviation effect may extend to water scarcity as shown by earlier studies that highlighted the potential of reservoirs to alleviate water scarcity (Liu et al 2018, Brunner et al 2019, Kellner and Brunner 2020). While my results show that reservoir regulation can clearly alleviate hydrological extremes not just at a local but partially also at a regional scale, we must not forget the negative side effects of reservoir regulation. Reservoirs have been shown to increase evaporation (Hogeboom et al 2018), change biotic composition and habitats, reduce flow connectivity and therefore hinder fish migration, introduce exotic species (Bunn and Arthington 2002), and reduce species richness (Andersson et al 2000). Reservoirs may therefore lead to trade-offs between flood and drought alleviation and reaching ecological goals.

My analysis is observation based, which has the advantage of avoiding model assumptions on flow regulations and enables integrating different reservoir purposes. However, using observations also has some limitations as it does not entirely prevent us from making specific analyses choices, is related to a limited sample size, and does not allow us to fully control
for confounding factors such as multiple reservoirs or reservoir purposes. Specific analysis choices made in this study include flood and drought thresholds to identify events and time lags to remove dependent flood and drought events. The limited sample size prevents a regional analysis which could reveal potential regional differences in reservoir regulation impacts on local and particularly regional extreme flows. Most regulated catchments in the dataset contain several reservoirs which means that I can not isolate the effect of one single reservoir on hydrologic extremes. Similarly, reservoirs mostly serve several purposes, which makes it difficult to isolate the effect of certain operation targets on hydrologic extremes. For example, if a second purpose of a flood reservoir is irrigation, the drought alleviation effect will still be attributed to the primary purpose, i.e. flood regulation. I assess the impact of flow regulation on extremes by comparing extremes in regulated with extremes in natural catchments. In doing so, I attribute all the differences between regulated and natural catchments to regulation even though regulated catchments also differ from their natural counterparts because of other reasons such as differences in climate, geology, different land uses, or different types of water regulations such as water abstractions. Still, the effects I detect are relatively uniform across a large sample of catchment pairs, which suggests that reservoir regulation effects are relatively robust. However, the reservoirs in the study region have to a large degree primarily been constructed for flood control and reservoirs with other primary purposes such as fish protection or water supply are underrepresented in the selection. In order to fully generalize the results to other regions of the world, the catchment pair selection would have to be expanded to regions with potentially different reservoir operation schemes. However, data on reservoir purposes is hardly available and the NID data base for the United States is one of the few exceptions providing such information.

Observation-based analyses such as this one could be complemented by model-based studies where targeted model experiments would allow us to answer specific ‘what if’ questions. For example, we could ask how flood peaks would change if flood control reservoirs were mainly operated for water supply purposes. In addition, the impact of single reservoirs and particular reservoir purposes could be studied in more detail using targeted modeling experiments. While such model-based studies would allow us to test the effect of different reservoir management scenarios on extreme flows, their results would hinge on the model assumptions behind human-regulated hydrological systems.

The findings of this study show that reservoir impacts can be substantial which suggests that they should neither be neglected in hazard nor climate impact assessments. Hazard assessments may be improved by including regulated catchments and if model-based by improving the representation of reservoir regulation in hydrological models (Masaki et al 2017, Veldkamp et al 2018). Such regulation needs to also be realistically represented at a local scale where data is difficult to obtain (Brunner et al 2021a). A realistic representation of reservoir regulation in hydrological models is also essential to improve climate impact assessments on hydrologic extremes, which are typically model based. Arheimer et al (2017) have shown that reservoir impacts on future streamflow regime changes can be stronger than those of climate change for snow-dominated river basins in Scandinavia. It remains to be investigated how the relative importance of human and climate impacts differs for hydrologic extremes and for different regions of the world with different hydro-climates and reservoir purposes. Furthermore, it needs to be determined which role reservoirs can play in climate adaptation and whether they can alleviate part of the expected drought intensification linked to increasing temperatures (Dai 2013, Diffenbaugh et al 2015). In this context, it will be important to consider trade-offs between alleviating different types of extremes and fulfilling other energy, ecological, and water provision purposes (Ehsani et al 2017).

5. Conclusions

I here present a spatial set of natural-regulated catchment pairs to study the effect of reservoir regulation on local and regional flood and drought characteristics in the United States. My comparison of flood and drought characteristics in regulated and natural catchments shows that (1) reservoir regulation reduces drought and flood severity (peak/intensity, volume/deficit) but increases event duration at a local scale; (2) this local alleviation effect is almost independent of the major reservoir purpose for both droughts and floods, i.e. reservoirs can have a beneficial effect even if their main purpose is not directly related to the type of extreme of interest, e.g. flood control reservoirs can not only alleviate floods but also droughts; and (3) reservoir regulation also affects regional hazard by reducing spatial flood connectedness particularly in winter but increasing spatial drought connectedness in summer, i.e. it can decrease the risk of widespread flooding but may increase the risk of large-scale drought. These findings highlight the need to consider human flow regulation in both hazard and climate impact assessments. Such consideration requires an increased effort in realistically representing flow regulations in hydrological models and in collecting data on reservoir regulation and other types of water abstraction. Increasing our understanding of flow regulations on hydrologic extremes will
allow society to develop suitable reservoir operation schemes also for unprecedented and future extreme conditions.

Data availability statement

The Dudley18 dataset can be downloaded from the USGS (https://www.sciencebase.gov/catalog/item/5b183960e4b092d965219d62), daily streamflow time series from the USGS (https://waterdata.usgs.gov/nwis/sw), catchment characteristics also from the USGS (https://water.usgs.gov/GIS/meta data/usgs/wrd/XML/gagesII_Sep2011.xml), and reservoir data from the NID (https://nid.se.usace.army.mil/ords/?p=1051:1:1:::). The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.4211/hs.19935a37955b49bfb1642c411f2e8753a.

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