Diversity in the observed functionality of dams and reservoirs

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Abstract

Knowledge and modeling of the observed functionality of dams and reservoirs are desirable for better water resources management. In this study, we examine the functionality of dams and reservoirs over much of the globe through a hydroclimate assessment over 990 Global Runoff Data Center stations that have at least one dam/reservoir over the corresponding drainage areas and available streamflow records of at least 25 years. To quantify the potential capacity of human disturbance/alteration, annual cumulative maximum storage (CMS) of the dams are computed and then annual potential changes in the residence time of water (PRT; CMS divided by annual mean monthly flow) are assessed. In addition, the Man–Kendall tests for annual maximum, mean, and minimum monthly streamflow, and drainage area-averaged precipitation are conducted. Results show that the size of CMS and the main purpose have an explanatory power of the designed hydrologic response (i.e., flattening of the seasonality) while 6% of dam-affected stations experienced the opposite hydrologic response (intensifying of the seasonality) due to the overwhelming impact of anthropogenic climate change. This study finds that the magnitude of PRT is a potential indicator to identify a considerable impact of dams and reservoirs for the regional hydrologic regime. The findings of this study suggest diversity in the observed functionality of dams and reservoirs, which is still a challenge in global hydrological modeling.

1. Introduction

Over the land surface, permanent water bodies have been changed due to anthropogenic climate change and local human disturbance. New permanent water bodies over land (184,000 km²) have formed due to a major contribution from filling dams and reservoirs with a minor contribution from climate change (Pekel et al 2016). Dam impoundment has a significant impact on not only the flow regime but also the local climate and environment. The construction of a dam with an artificial lake or reservoir change the water residence time in the river system (Morris and Fan 1998). In general, a dam is functioned to sustain the designed flow close to annual mean flow \( Q_{\text{mean}} \) throughout the year (Hurst 1951), by increasing annual minimum flows \( Q_{\text{min}} \) and decreasing annual maximum flows \( Q_{\text{max}} \) (e.g., flattening the seasonality of streamflow). As a result, the risk of flood and drought over dam-affected river basins is manageable if the dam is function as designed. However, a series of dams with different dam storage capacity and operations for their own purpose can amplify or weaken the hydrological and environmental impacts of the dams in the upstream catchment (Deitch et al 2013).

Over the last decade, hyper-resolution global land surface hydrologic models have been developed (Wood et al 2011). As the spatial resolution of a global hydrologic model is higher, land surface information and streamflow records at the corresponding scale are more critical for model validation and evaluation. Through an international cooperative effort to construct global observation datasets, two datasets are now available: the Global Reservoir and Dam (GRanD) version 1.1 database including the detailed information of 6862 dams over the globe (Lehrner et al 2011) and the Global Runoff Data Center (GRDC) discharge data including 9543 gauge stations over the globe (GRDC 2017a). While the GRanD database contains a considerable number of dams over the globe, the number of the dams registered in the GRanD database is largely underestimated.
comparing to existing dams around the world. For example, the United States has more than 90,000 dams from the National Inventory of Dams database (Song et al 2021) while 1902 dams are registered in the GRanD version 1.1 database.

The impact assessment of dams and reservoirs have been conducted over the globe as the global dataset of dams and streamflow records are available. Jaramillo and Destouni (2015) reported observation-based evidence of the significant impact of dams and reservoirs on global water and energy budgets over the 100 large basins across the globe. Zhou et al (2015) assessed the cumulative impacts of dams and reservoirs on variabilities of terrestrial water storage over 166 large basins over the globe. Other studies about the impact of dams and reservoirs on large river basins have conducted from other perspective such as nutrient cycle (Syvitski and Kettner 2011), biodiversity (Vörösmarty et al 2010), and fluvial geomorphology (Grill et al 2015). A previous study (Shin et al 2019) utilized the GRanD database and developed a high-resolution (5 km) hydrologic model over the United States accounting for 1889 reservoirs.

In hyper-resolution (within one-kilometer) hydrological modeling, the representation of human impacts from water management is still a grand challenge (Wood et al 2011). A global observational study of the sensitivity of flow alteration to dams and reservoirs is necessary as the first-step of modeling water management at the hyper-resolution scale and can provide an opportunity to test the hypothesis, ‘stationarity is dead’ (Milly et al 2008). The ‘stationarity is dead’ hypothesis is whether dam-affected basin has experienced anthropogenic influence that already overcame the water engineering system’s capacity. Previous studies (Klijn et al 2004, Milly et al 2008) addressed that it becomes sufficiently large to fail the stationarity assumption for water infrastructure design and water policy as anthropogenic climate change (a deterministic component of a system that is forced by gradual changes in atmospheric composition due to human activities) is accumulated over time.

Here, this study aims to investigate the sensitivity of hydrologic response to local human disturbance (mainly, dams and reservoirs) by integrating monthly streamflow records from the 990 GRDC stations with about 2800 dams registered in the GRanD v.1.1 database (figure 2). By harnessing these global datasets, this study attempts to answer the following questions: what is the observed sensitivity of hydrologic response to dam and reservoir? How well can the structure information of dams and reservoirs (e.g., the cumulative storage or the prevailing main use) explain the flow alteration (e.g., flattening of seasonality)? What are key potential factors of the observed functionality of dams and reservoirs? Have any dam-affected GRDC stations experienced an emerging signal of ‘stationarity is dead’ (e.g., intensifying of seasonality)? The findings of this study will emphasize the importance of anthropogenic influences, particularly the representation of dams and reservoirs in hyper-resolution Earth system modeling, and provide a caveat of uncertainties in the functionality of dams and reservoirs that can be changed abruptly to meet the water demand of local communities (that is, diversity in the functionality of dams and reservoirs).

2. Data and methods

2.1. Streamflow records from Global Runoff Data Center (GRDC)

GRDC provides the two main datasets including the river discharge data and geospatial data. The river discharge data include daily and/or monthly river discharge records at over 9300 gage stations around the world (GRDC 2017a). Geospatial data provide upstream catchment masks for 4902 GRDC stations (GRDC 2017b). The Shuttle Radar Topography Mission (SRTM) elevation data at 500 m (15 arc-second) spatial resolution has been used to create the corresponding the corresponding drainage area mask. In this study, we computed the annual minimum, mean, and maximum streamflows ($Q_{\text{min}}$, $Q_{\text{mean}}$, and $Q_{\text{max}}$, respectively) from the GRDC monthly streamflow data at the stations that have available streamflow records of at least 25 years. It is worth noting that the start/end year of the record or the continuity of the record is not considered to filter out a station. There are 4893 GRDC stations that satisfy this criterion out of the 6402 GRDC stations.

2.2. Global Reservoir and Dam database (GRanD)

The GRanD version 1.1 (Lehner et al 2011) includes 6862 reservoirs with dams over the globe, including the important information of dams and reservoirs such as identification number, geographical location (latitude and longitude), maximum storage capacity, upstream catchment drainage area into a reservoir, year (not further specified if it is construction, completion, or commissioning year), main use, and so on. Some dams have missing information for year, main use, or drainage area. In this study, 5285 dams and reservoirs are used from the GRanD database, which provide the main use information, upstream catchment area, and construction year. In the GRanD database, the main use of reservoirs is classified into 10 types: irrigation, hydropower, water supply, flood control, recreation, navigation, fisheries, pollution control, livestock, and other. It is worth noting that the information for construction year is not specified as year of completion, construction,
and commissioning, which might cause uncertainties in the timing of hydrologic changes due to dam construction. The detailed information for the GRanD Database is available at the Global Water System Project website.

### 2.3. Catchment-averaged annual mean precipitation

To compute upstream catchment-averaged annual mean precipitation ($P_{\text{mean}}$), we used the two global monthly precipitation data, the Climate Research Unit Time Series v4.00 (CRU) (1901–2015; Harris et al. 2014) and the Global Precipitation Climatology Centre v7 (GPCCv7) (1901–2013; Schneider et al. 2015). These two monthly catchment-averaged precipitation data are used to test the sensitivity of precipitation trends to the data source, but the results show no significant difference (not shown). The upstream catchment mask shape files are regridded at the 50 km spatial resolution. The drainage area averages of monthly precipitation are computed using the re-gridded masks of the 4893 GRDC stations.

### 2.4. Calculation of potential changes in residence time

To understand changes in the accumulative water storage capacity over time, annual time series of accumulative maximum water storage of reservoirs within the drainage area are computed (figure S1). Annual potential changes in residence time (hereafter, PRT) are computed from annual time series of the ratios of the cumulative maximum storage capacity (in km$^3$) to annual mean discharges ($Q_{\text{mean}}(t)$ in m$^3$ s$^{-1}$). The slope of a linear trend of annual time series of PRT is computed over the full period of record for each GRDC station. This liner trend can account for the timing of construction of the existing dams and reservoirs. The magnitude of the slope is a discharge-weighted indicator of how much the existing dams and reservoirs can control the streamflow regime.

### 2.5. Identification of the GRDC stations affected by dams and reservoirs

In this study, the 990 GRDC stations and the 2793 GRanD-registered dams and reservoirs are selected through the following four criteria: (1) the length of streamflow records (at least 25 years), (2) the presence of dam construction within the period of records, (3) the availability of upstream drainage area, and (4) the non-zero values of streamflow records. The latitudes and longitudes of the 5285 dams and reservoirs from the GRanD database are used to identify the GRDC stations that have been affected by dams and reservoirs from the 4893 GRDC stations. Through over 25 million iterations (4893 upstream catchments × 5285 dams), 1459 dam-affected GRDC stations are identified as dam-affected river basins. This identification processes of dam-affected river basins was done using a NCAR Common Language (NCL) function 'gc_inout.ncl' (NCL 2017). Second, the 1323 (out of 1459) stations are selected if they have longer than 25 years of the records that have all the 12 monthly discharge data in each calendar year (at least 300 (12 months × 25 years) monthly streamflow records). It is worth noting that Asia has many stations with recently constructed dams, but unfortunately they are excluded in this study because of their relatively short-term records (see figure 1). Next, 1029 (out of 1323) stations are selected due to the changes in PRT over the period of available record. Then, 1017 (out of 1029) stations are selected because they have the information of the corresponding drainage area. Lastly, 990 (out of 1017) stations are selected because they have non-zero $Q_{\text{mean}}$ over the period of record.

The histograms of the selected 990 GRDC stations for different characteristics are shown in figure 2. The magnitude of the slopes of PRT ranges from less than one day/century through 40 years/century. Most of the 990 GRDC stations are located in North America and Europe (55% and 20%, respectively). 75% of the selected stations have more than one dam within the upstream catchments, and 60% of the selected stations show that the fraction of the streamflow records after the construction year of the largest dam is equal to or greater than 0.8. It is worth noting that an ideal record fraction for dam impact assessment would be 0.5 (the equal record length before and after a major dam construction) to avoid a bias from the timing of abrupt change in the streamflow statistics due to the major dam construction.

### 2.6. Determination of the prevailing use of dams and reservoirs

The cumulative maximum storage capacity of the dams and reservoirs for each type within the corresponding drainage area is computed for the 990 GRDC stations to determine the prevailing dam and reservoir type. The prevailing use of dam and reservoir is assigned into the type that contributes mostly to the cumulative maximum storage capacity. It is worth noting that the prevailing use for some of the 990 GRDC stations is missing because the main use information of at least one reservoir in the upstream is not available from the GRanD database. In this study, the results from the four prevailing uses of dams and reservoirs (irrigation (82 GRDC stations), hydroelectricity (212), water supply (129), and flood control (112)) are reported because

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1 http://gwsp/fileadmin/downloads/GRanD_Technical_Documentation_v1_1.pdf.
the other types of dams and reservoirs have relatively small maximum storage capacity, which is negligible for the impact on streamflow statistics.

2.7. Trend analysis for annual streamflow statistics and precipitation
In this study, the Mann–Kendall (MK) trend tests of $Q_{\text{mean}}$, $Q_{\text{min}}/Q_{\text{mean}}$, $Q_{\text{max}}/Q_{\text{mean}}$, and $P_{\text{mean}}$ are conducted. The normalized time series of $Q_{\text{min}}$ and $Q_{\text{max}}$ by $Q_{\text{mean}}$ show a clear impact of dams and reservoirs on these flows, by removing the climate signals embedded in $Q_{\text{mean}}$. The trend significance is tested at the significant level, 0.05 ($\alpha = 0.05$). To test the significance of autocorrelation in streamflow statistics, the residuals are computed by subtracting the linear trends and adjusted the number of temporal degrees of freedom over the stations where the records show significant one-lagged autocorrelation ($\alpha = 0.1$) in the residuals. There is a minor decrease of the numbers of the stations with statistically significant trends (less than five stations) after the adjustment for autocorrelation in the precipitation and streamflow data (not shown).

3. Results

3.1. Spatial patterns of trends in streamflow and precipitation
The results from the MK trend analysis of $Q_{\text{mean}}$ ($P_{\text{mean}}$ from CRU) show that 114 (237) and 58 (37) GRDC stations experienced statistically significant increasing and decreasing trends, respectively (figures 3(a) and (b)). Most of the stations show the same direction in their increasing or decreasing trends in $Q_{\text{mean}}$ and $P_{\text{mean}}$, particularly over the Midwestern U.S., Uruguay, and West Africa, indicating that the trends in $Q_{\text{mean}}$ are strongly associated with the trends in $P_{\text{mean}}$. This result is expectable by the fact that dams and reservoirs are supposedly operated to maintain sustainable available water resources (close to annual mean flow) throughout the year, implying minor impacts of dams and reservoirs on $Q_{\text{mean}}$ over these regions. Other regions like the northeastern U.S. region, Scandinavian Peninsula, and east China show significant increasing trends in $P_{\text{mean}}$, but no significant trend in annual mean streamflow. This finding indicates a potential cause of growing human activities (e.g., irrigation and dam operation) to weaken associations between $Q_{\text{mean}}$ and $P_{\text{mean}}$ over these regions. It is worth noting that the GPCPv7 precipitation data show a consistent spatial pattern with the significant trends in $P_{\text{mean}}$ from the CRU precipitation data (not shown).

Overall, the trend analyses of $Q_{\text{min}}$ and $Q_{\text{max}}$ show that dams and reservoirs functioned well as designed by flattening seasonality. The 441 (314) GRDC stations show statistically significant increasing (decreasing) trends in $Q_{\text{min}}$ ($Q_{\text{max}}$) flows (figures 3(c) and (d)), expecting decreased floods and droughts since the dam construction. Interestingly, GRDC stations over arid regions, such as the southwest U.S. region or eastern Africa, show an increasing trend of $Q_{\text{min}}$, $Q_{\text{mean}}$, and $Q_{\text{max}}$ with no trend in $P_{\text{mean}}$. Over these regions, water scarcity and security issues have been reported due to increased evaporation due to warming-driven loss of reflective snow (Milly and Dunne 2020) and the rapid growth of water demand of local communities (Falkenmark 1990, Adhikari et al. 2015). Based on the global hydrologic and climate data, consistent detectable increasing
trends in annual mean precipitation and streamflow are found over some of the dam-affected watersheds in the Mid-western US, West Africa, and northern Europe (see figure S2 and table S1). Interestingly, 55 out of the 990 GRDC stations show decreasing trends in $Q_{\text{min}}$ and increasing trends in $Q_{\text{max}}$. This finding indicates intensifying of the seasonality, which is opposite to the expected and implies that dam-affected basins will face a higher risk to fail the stationarity assumption for water infrastructure design in the near future. That is, this finding is observed evidence to support ‘stationarity is dead’ (Milly et al 2008). For example, a GRDC station along Goeta Aelv River, Sweden (Vargoen KRV; GRDC ID: 6229500) shows a significant increasing and decreasing trend in $Q_{\text{max}}$ and $Q_{\text{min}}$, respectively (see figure S3). Over the corresponding drainage area, the purposes of all the five dams are hydroelectricity supply mainly for the local heavy steel industry since the industrial revolution, resulting in growing demand for industrial water use. Over Goeta Aelv River, the wet season precipitation ($P_{\text{wet}}$; June–November) and the dry season surface temperature ($T_{\text{dry}}$; December–May) both show a significant increasing trend (+1.1 mm/month/decade and +0.1 °C from both the CRU. This finding is consistent with the findings from previous studies (Göransson et al 2013, Destouni et al 2013). During the wet season, the increasing trend of precipitation have overcome the storage capacity of the existing dams, which put the downstream community at a higher risk of severe floods and landslides. During the dry seasons, the decreasing trend of temperature with the growth of water demand make the local community more vulnerable to droughts and wildfires in the future. This finding alerts water policy makers and local stakeholders about the need to revisit and upgrade water resources management and policy for climate change adaptation.

3.2. Functionality of dams and reservoirs: trend in PRT
We compared the box plots of the PRT trends for the 990 GRDC stations with the box plots for 2673 stations without dam impact are also represented as the reference (figure 4). These 2673 stations were used to test the
Figure 3. Spatial distribution of significant trends in streamflow statistics and precipitation: (a) annual mean monthly flow anomalies normalized by the long-term annual mean flows, (b) annual mean precipitation from the CRU TS v4 data, (c) annual maximum monthly flows normalized by annual mean monthly flows, and (d) annual minimum monthly flows normalized by annual mean monthly flows. Blue (red) dots depict stations with statistically significant increasing (decreasing) linear trends at the significant level, 0.05 ($\alpha = 0.05$) adjusted by the one-lagged autocorrelation. Grey dots depict the stations with insignificant trends.

Figure 4. Box plots of changes in streamflow statistics as a function of the magnitude of the trend in RT from less than one day per century through greater than four years per century: (a) annual minimum monthly flows, (b) annual mean monthly flows, and (c) annual maximum monthly flows. The first two box plots are computed from the changes in streamflow statistics over the 990 (red) and 2673 (blue) GRDC catchments with/without GRanD—registered dams and reservoirs, respectively. ‘weak’ Budyko hypothesis proposed in Milly et al. (2018). The box plots show the five statistics of each group including the 10th, 25th, 50th, 75th, and 90th percentiles of each group. Results show that the medians of $Q_{\text{min}}$ show increasing trends, regardless of the existence of dams and reservoirs. However, the medians of $Q_{\text{min}}$ for the dam-affected GRDC stations with greater than two years per century of PRT are near the maximum of the $Q_{\text{min}}$ trends among the no dam-affected GRDC stations, indicating that two years per century of PRT might be the minimum threshold value of dam size in hydrological modeling for anthropogenic influence. The medians of the trends in $Q_{\text{max}}$ over the dam-affected GRDC stations with greater than four years per century of PRT are $-10\%$ per decade, which is near the 75th percentile of those over the no dam-affected GRDC stations. This finding indicates that different threshold values of PRT for high and low flows are required in global hydrological modeling to reproduce the impact of dams and reservoirs for high and low flow conditions. Overall, the 25th–75th percentile range of the trends of $Q_{\text{min}}$, $Q_{\text{mean}}$, and $Q_{\text{max}}$ are significantly wider when the PRT magnitude is greater than 3 month per century, indicating that the PRT magnitude is possibly an indicator to identify stations with a considerable impact of the existing dams and reservoirs.

3.3. Functionality of dams and reservoirs: main use
The box plots of the trends in $Q_{\text{min}}/Q_{\text{mean}}$, $Q_{\text{mean}}$, and $Q_{\text{max}}/Q_{\text{mean}}$ for the four major uses of the dams and reservoirs are computed (figure 5). To explore the impact of the size of dams and reservoirs, the stations are classified into the two groups: stations with trends of PRT less than 3 months per century (blue colored box plots) and 3 months per century or greater (red colored box plots). Overall, the stations with the significant
changes in PRT (3 months per century or greater) show significant increasing trends in $Q_{\text{min}}$ (the first quartile is greater than zero) at the dam-affected GRDC stations for irrigation and hydroelectricity ($+2\%$ and $+3\%$ of $Q_{\text{mean}}$ per decade, respectively) with a wider 25th–75th percentile range ($+0.5–+3\%$ and $+1–+6\%$, respectively). The dams and reservoirs for water supply and flood show a minor impact on $Q_{\text{min}}$ (the medians of the trends of $Q_{\text{min}}$ are $+0.5\%$, regardless of the dam and reservoir size). Overall, the stations with the major dam for irrigation show a decreasing trend (the medians are $−5\%$ of $Q_{\text{mean}}$ per decade) with a wider range of the 25th–75th percentile range ($0–15\%$ of $Q_{\text{mean}}$ per decade) than those with other prevailing uses. It is worth noting that the stations in Africa are prevailed by the irrigation dams, implying that the storage capacity of the current reservoirs is not enough to meet the water demand for irrigation, implying that more dams and reservoirs in Africa would be built in the future to meet a high demand of water resources for agriculture. Overall, the dam affected GRDC stations with greater than 3 months per decade of PRT show a decreasing trend of $Q_{\text{max}}$, regardless of the main use of dams ($−5\%$ of $Q_{\text{mean}}$ per decade).

Results show that the stations with dams and reservoirs for irrigation show a wider 25th–75th percentile range of the trends in the flow statistics than any other prevailing dam type, indicating that the human factors (e.g., water demand) play a role in the dam operation and thus the flow regime changes over the irrigated areas. In addition, the stations classified as prevailing for big hydroelectricity dams (3 months per century or greater) have a narrower interquartile range of trends in $Q_{\text{mean}}$ and $Q_{\text{max}}$ than the range in $Q_{\text{min}}$. It indicates that big hydroelectricity dams are operated in a consistent manner under normal and wet flow conditions while they are operated differently during under dry flow conditions.

4. Conclusions

In this study, the observed functionality of dams and reservoirs on a catchment-by-catchment basis is assessed over much of the globe. This study found that existing dams and reservoirs generally function as intended by altering the seasonality of streamflows (e.g., increasing $Q_{\text{min}}$ and/or decreasing in $Q_{\text{max}}$). The hydrologic impact of dams and reservoirs varies, depending on the size and purpose of dams and reservoirs and the water demand of local communities. This study also found that the magnitude of the PRT trend is a potential indicator to determine a considerable impact of dams and reservoirs, which can be used as the threshold value to determine which the dam-affected basin areas are required to account for dam and reservoir impact in high-resolution global hydrologic and Earth system modeling. This study provides a new insight into how big datasets can be harnessed to revisit and examine the validity of the previous theories or hypotheses (herein, the ‘stationarity is dead’ hypothesis). Accordingly, this study confirmed that few stations with huge dams show the opposite functionality of dams and reservoirs to the expected due to the overwhelming impact of anthropogenic climate change. Also, the findings of this study emphasize the value of the data continuity and the ongoing international data sharing efforts in the field of global hydrological and Earth system modeling.

Understanding of a combined impact of anthropogenic climate change and local human disturbance remain a grand challenge due to missing of the information about new dams and reservoirs, particularly over Asia. The GRanD database is needed to timely update with new dams and reservoirs through the inclusiveness of the Asian hydrology research community in the global hydrology community. This observation-based study found diversity in the functionality of dams and reservoirs, which can cause large uncertainties in investigating interactions between local human disturbance and anthropogenic climate change from hyper-resolution
global hydrological and climate models. A better understanding of behaviors of not only built-in environmental systems (physical systems) but also the social response to anthropogenic climate changes and socioeconomic structure changes (social systems) will improve the predictability of hyper-resolution global hydrological and Earth system models, which can provide actionable information to local stakeholders, decision makers, and policy makers.

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Data availability statement

The data that support the findings of this study are openly available at https://doi.org/10.7910/DVN/0YKBQY.

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