

1 **Impacts of climate change and human activities on the flow regime of** 2 **the dammed Lancang River in Southwest China**

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8 **Abstract**

9 The Lancang River (LR) in China (the upper portion of the Mekong River which is
10 among the world's most important transboundary rivers) originates on the Tibetan
11 Plateau and provides important freshwater resources for living, agriculture, industry,
12 and hydropower generation for millions of people downstream. The natural flow
13 regime of the LR is critical to sustain native biodiversity and ecosystem integrity;
14 however, it has been changing due to the combined effect of climate change and
15 human activities. Accurate quantification of the impacts of climate change and human
16 activities on changes in the flow regime is a prerequisite for water resources and
17 hydropower exploitation and environmental protection. This study aims to evaluate
18 climate- and human-induced impacts on the LR during 1980–2014. A distributed
19 hydrological model CREST-snow combined with remote sensing and streamflow data
20 and the Budyko framework were jointly used to address this scientific question during

21 three time windows determined by the Mann–Kendall test and the history of dam
22 construction. Results show that compared with the baseline period (1980–1986) when
23 no dam was constructed, significant changes (~6%) in mean annual streamflow
24 occurred during 1987–2014, particularly after 2008 when the construction of the
25 largest hydropower plant (Nuozhadu) in the Mekong River basin began. Climatic
26 change contributed ~57% to streamflow changes during the transition period (1987–
27 2007), whereas human activities contributed ~95% during the post-impact period
28 (2008–2014). At the seasonal scale, climatic variation plays a more significant role
29 during the dry season (December–May), with precipitation the most important factor
30 among climate variables, whereas human activities contributed more during the wet
31 season (June–November), benefiting the downstream areas through mitigating floods.
32 Among human activities, reservoir construction is a dominant factor affecting
33 streamflow over agricultural, industrial, and domestic water uses. The findings of this
34 study enhance our understanding of hydrological changes in the LR basin that may
35 impact the Lower Mekong River, serve as a basis for water resources and hydropower
36 exploitation and environmental protection, and highlight the need for considering
37 reservoir operation strategies in streamflow projections in similar basins globally
38 under climate change scenarios.

39 **Keywords:** Streamflow change; climate change; human activities; distributed
40 hydrological model; attribution

41 **1. Introduction**

42 As the most important transboundary river in the world, the Mekong River (MR)
43 flows through six countries (i.e., China, Myanmar, Laos, Thailand, Cambodia, and
44 Vietnam) with a total length of ~4,350 km and a drainage area of ~795,000 km²
45 (MRC, 2010a). The Lancang River (LR) in China, i.e., the upper portion of the MR,
46 originates on the Tibetan Plateau (TP) and flows through Qinghai, Tibet, and Yunnan
47 Provinces. The LR provides important freshwater resources for domestic, agricultural,
48 industrial uses, and hydropower to China and downstream countries. The natural flow
49 regime of the LR is critical to native biodiversity and ecosystem integrity in rivers
50 (Poff et al., 1997). In addition, an improved understanding of the hydrology of the
51 basin is the scientific foundation on integrated water resources management (Carlisle
52 et al., 2010; Commission, 2009) and on modeling potential changes in the streamflow
53 of the LR in the future.

54 Both climate change and human activities have exerted significant pressure on the LR.
55 First, runoff from the TP tends to be sensitive to climate change as a result of
56 changing precipitation and snow and glacier melting processes due to climate
57 warming (Chen et al., 2017; Chen et al., 2018; Huang et al., 2018a; Lauri et al., 2012;
58 Long et al., 2014; Lutz et al., 2014; Tang et al., 2018). Second, growing population
59 leads to increased water resource and energy demands that may subsequently result in
60 extensive hydropower exploitation in both the mainstream and tributaries of the LR
61 (Pokhrel et al., 2018). Quantifying the impacts of climate change and human activities

62 on the streamflow of the LR is therefore fundamental to water resource management
63 and environmental protection and therefore has received considerable attention from
64 the scientific community (Immerzeel et al., 2009; Jeelani et al., 2012; Räsänen et al.,
65 2017).

66 Recent studies associated with the impact of hydropower generation mainly focused
67 on historical changes in streamflow of the lower MR (Cochrane et al., 2014; Lu et al.,
68 2014; Mohammed et al., 2018; Räsänen et al., 2012; Räsänen et al., 2017). Lu et al.
69 (2014) and Räsänen et al. (2017) examined changes in river discharge at the Chiang
70 Saen gauging station in Northern Thailand since 1960, whereas Li et al. (2017a) used
71 streamflow observations at five gauging stations along the mainstream of the MR to
72 assess the alteration of flow regimes over the period of 1960–2014. These studies
73 mostly compared the streamflow before and after dam construction based on
74 streamflow observations and confirmed the significant effect of cascade reservoirs
75 upstream.

76 However, discrepancies of the findings exist due to different study periods and
77 changes in the intra-annual streamflow distribution. Lu et al. (2014) found a 9%
78 decrease in discharge at the Chiang Saen gauging station in August but a 15%
79 increase in discharge in July over the post-dam period (1992–2010) than that over the
80 pre-dam period (1960–1991). But Räsänen et al. (2017) found an increase of 121–187%
81 in discharge during Mar–May and a decrease of 32–46% in discharge during July–
82 August in 2014 compared with the mean discharge over the period 1960–1990 at the

83 Chiang Saen gauging station. Mohammed et al. (2018) explored the variability in
84 streamflow of the Lower MR by examining changes in the Upper MR inflow using a
85 hydrological model. Moreover, several studies simulated the effects of projected
86 climate change scenarios and reservoir operation strategies on streamflow. For
87 example, Ngo et al. (2016) applied the Soil Water Assessment Tool (SWAT) and Water
88 Evaluation and Planning (WEAP) models to the tributaries of the Lower MR in
89 Vietnam and Cambodia for the future period 2010–2100 to assess the impacts of
90 different reservoir operation strategies on flow regimes. Wang et al. (2017) adopted
91 the Geomorphology-Based Hydrological Model (GBHM) to study the combined
92 effect on floods in the MR basin from 2010 to 2099, indicating that reservoir
93 operation could mitigate the effect of flood intensification caused by climate change
94 before 2060.

95 Despite recent efforts, the impacts of climate change and human activities on the
96 streamflow of the LR have remained inadequately assessed. First, few studies
97 quantified climate and human impacts on the historical streamflow of the LR. Tang et
98 al. (2014) used a Back-Propagation Artificial Neural Network (BP-ANN) model and
99 concluded that human activities exerted a larger impact on streamflow changes in the
100 LR than climatic variations (54.6% and 45.4%, respectively) during 1986–2008.
101 Second, as mentioned above, the LR has been less studied than the MR or only
102 studied over a short time period (Tang et al., 2014; Zhao et al., 2012). The LR
103 originates at elevations of over 5100 m on the TP, with its runoff sensitive to climate

104 change as a result of snow and glacier melting (Immerzeel et al., 2009; Lutz et al.,
105 2014). Assessing the hydrological impacts of climate change over the LR basin thus
106 requires more sophisticated hydrological models with a snow and glacier module and
107 adopts a multiple dataset calibration method to ensure both accurate simulation of
108 streamflow and a reasonable contribution of snow and glacier meltwater to total
109 runoff (Finger et al., 2015).

110 The overall objective of this study was therefore to quantify climate- and
111 human-induced impacts on changes in streamflow of the LR during the period
112 1980–2014. To achieve this objective, we relied on the Coupled Routing and Excess
113 SStorage (CREST) model (Wang et al., 2011) coupled with a snow and glacier melting
114 module (Chen et al., 2017) (termed CREST-snow hereafter) and streamflow
115 observations at the Yunjinghong gauging station at the outlet of the LR basin to
116 generate historical natural streamflow. We analyzed interannual, seasonal, and
117 monthly changes in streamflow and quantified the contributions from climatic and
118 anthropogenic effects. In addition, we partitioned the impacts of human activities
119 during 1980–2010 based on a global monthly gridded (0.5°) sectoral water
120 withdrawal dataset (Huang et al., 2018b). The findings advance our understanding of
121 hydrological changes in the LR basin and highlight the role of reservoir construction
122 and operation in influencing streamflow regimes. This study can serve as a basis for
123 examining climate and human impacts on streamflow for dammed rivers, and provide
124 reference for projecting future streamflow changes, particularly for snow-fed rivers

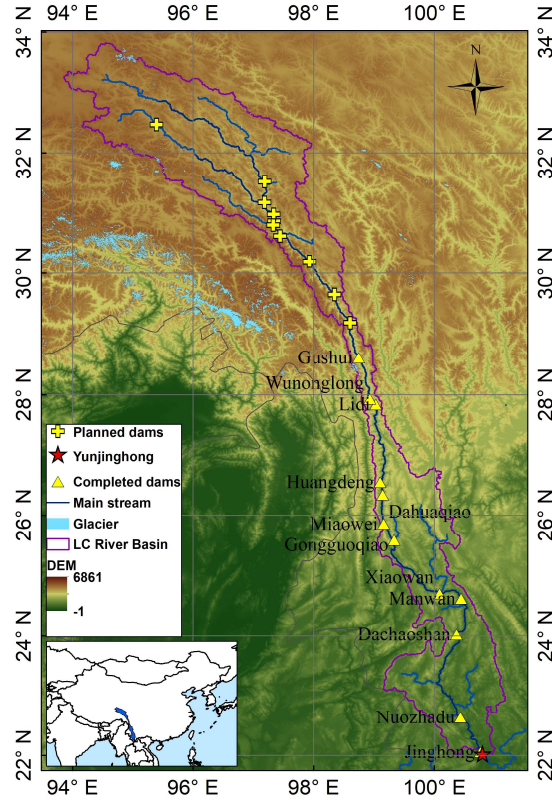
125 that are dictated by reservoir operation.

126 2. Study area

127 The LR is located within the domain 22°05'–33°40'N and 93°50'–101°30'E in
128 Southwest China (**Figure 1**), with a total length of ~2,140 km and a drainage area of
129 ~142,000 km² (Long et al., 2014). It has a complex terrain, with a mean elevation of
130 ~3,300 m and an elevation difference of ~5,500 m decreasing from the northwest to
131 the southeast (Shi et al., 2013).

132 The LR features a humid climate with a mean annual precipitation of ~735 mm based
133 on a 35-year record (1980–2014) of the China Gauge-based Daily Precipitation
134 Analysis (CGDPA) product (Shen and Xiong, 2016). The westerlies and Indian
135 monsoon bring abundant moisture and rainfall over the LR basin from June to
136 September, which accounts for nearly 70% of the annual rainfall. Correspondingly,
137 streamflow in the LR also exhibits strong seasonality, with 70% of the annual
138 discharge and the peak discharge normally occurring between August and September
139 (Jacobs, 2002).

140 The unique geographical features and the large energy demand in Yunnan Province
141 and Eastern China have contributed to the burgeoning development of hydropower
142 plants in the LR basin (Chen et al., 2010; Hennig et al., 2013). The six largest dams
143 (storage capacity > 1 hundred million m³) on the mainstream were included in our
144 analysis, with their detailed information listed in **Table 1**.



145

146 **Figure 1.** Location of the LR basin, Yunjinghong streamflow gauging station, dams including
 147 those to be built shown by yellow crosses, mainstream, and elevations (m).

148 **Table 1.** Detailed information on six largest dams along the Lancang River mainstream

Hydropower station	Manwan	Dachaoshan	Jinghong	Xiaowan	Gongguoqiao	Nuozhadu
Date of river closure	1987.12	1997.11	2005.1	2004.10	2008.12	2007.11
Date of power generation	1993.6	2003.1	2008.6	2009.9	2011.11	2012.9
Drainage area (10^4 km^2)	11.45	12.10	14.91	11.33	9.73	14.47
Mean annual discharge (m^3/s)	1230	1340	1840	1220	985	1750
Dead reservoir storage (10^8 m^3)	6.68	3.71	8.10	43.50	3.16	103.00
Total reservoir storage (10^8 m^3)	9.20	9.40	14.00	153.00	3.65	227.00
Installed capacity (10^4 kW)	150	135	150	420	90	500
Height (m)	132	115	118	300	105	255

149 **3. Data and Methods**

150 **3.1 Data**

151 Streamflow observations at the Yunjinghong gauging station for the time period
152 1980–2014 were obtained from the China Hydrology Data Project
153 (<http://depts.washington.edu/shuiwen/>) (Henck et al., 2011) and local water resources
154 administrations. Snow water equivalent (SWE) was estimated based on a snow depth
155 product from the Environmental and Ecological Science Data Center for West China
156 (<http://westdc.westgis.ac.cn/>) (Che et al., 2008; Dai et al., 2015; Dai et al., 2012) and
157 snow density calculated using in situ measured snow depth and snow pressure (Chen
158 et al., 2017). Here the discharge and SWE dataset were jointly used to calibrate
159 CREST-snow and partial discharge data were used to validate the hydrological model.
160 The CGDPA precipitation product developed by the National Meteorological
161 Information Center of the China Meteorological Administration, was generated using
162 rainfall measurements of ~2400 national gauges and the climatological optimal
163 interpolation (OI) algorithm (Shen and Xiong, 2016) (<http://cdc.nmic.cn>). Other
164 meteorological data, including daily time series of maximum, mean, and minimum air
165 temperatures, dew point temperature and pressure, were obtained from the
166 ERA-Interim product, the latest global atmospheric reanalysis produced by European
167 Centre for Medium-Range Weather Forecasts (ECMWF). Both CGDPA and ERA
168 meteorological data were converted from a resolution of 0.25° to a resolution of
169 0.0625° using the nearest neighbor method for driving the hydrological model.

170 Daily temperature, dew point temperature, and pressure estimates for the period

171 1980–2014 were used to calculate wet-bulb temperature and force CREST-snow.
172 ERA-interim temperature estimates were used to estimate potential evapotranspiration
173 according to the Hargreaves method (Hargreaves and Samani, 1985), with the
174 parameters adjusted to be applicable to Southwest China (Hu et al., 2011). The digital
175 elevation model (DEM) provided by NASA's Shuttle Radar Topography Mission
176 (SRTM) at a spatial resolution of 0.0083°, was used to delineate the LR basin
177 boundary and derive flow direction and flow accumulation for use in CREST-snow.

178 Huang et al. (2018b) generated a global monthly gridded (0.5°) sectoral water
179 withdrawal dataset for the period 1971–2010, using various sources of reported data
180 and some spatial and temporal statistical downscaling algorithms. This dataset
181 comprises six water use sectors including irrigation, living, electricity generation
182 (cooling of thermal power plants), livestock, mining, and manufacturing and was used
183 here to partition the effects of human activities on streamflow.

184 **3.2 Methodology**

185 **3.2.1 CREST-snow hydrologic model**

186 The Coupled Routing and Excess STorage (CREST) model (Wang et al., 2011) is a
187 distributed hydrological model jointly developed by the University of Oklahoma and
188 the National Aeronautics and Space Administration (NASA) SERVIR Project Team
189 (<http://www.servir.net>). The CREST model computes infiltration and runoff using the
190 variable infiltration capacity curve updated from the Xinanjiang model (Zhao, 1992)
191 and VIC model (Liang et al., 1996), and simulates sub-grid cell routing in a study
192 basin employing linear reservoirs, which results in more accurate streamflow
193 simulations than that using old routing methods (Shen et al., 2016; Wang et al., 2011).

194 CREST has been coupled with a snow and glacier melting module based on the
195 temperature-index method (Chen et al., 2017), in which wet-bulb temperature was
196 used in this study to partition total precipitation into solid and liquid phases because
197 precipitating droplets (e.g., rain, sleet, and snow) have a temperature closer to
198 wet-bulb temperature than air temperature (Ding et al., 2014). CREST-snow was set
199 up at a spatial resolution of 0.0625° (~ 7 km at the equator) to simulate daily
200 streamflow at the Yungjinghong gauging station on the LR.

201 The performance of the model was evaluated using the Nash-Sutcliffe model
202 efficiency coefficient (*NSE*) (Nash and Sutcliffe, 1970), the Nash-Sutcliffe Efficiency
203 Coefficient with logarithmic values (*LogNSE*), correlation coefficient (*R*), and relative
204 differences (*Bias*). *NSE* has been widely used to measure the overall performance of
205 the hydrological model whereas *LogNSE* could better assess the simulation of low
206 flows (De Vos and Rientjes, 2008). *Bias* is defined as the sum of the difference
207 between simulated and observed runoff, divided by the sum of observed runoff.

208 **3.2.2 Identification of streamflow break points**

209 The Mann–Kendall test (Hamed and Rao, 1998) was used to identify the break point
210 of streamflow time series at the Yunjinghong gauging station for the period
211 1980–2014. The intersection point approaches year 2008, corresponding to the year
212 when the construction of the largest reservoir, Nuozhadu, on the LR started and the
213 river was intercepted. The first reservoir on the LR, Manwan, was under construction
214 since 1987.

215 Based on the history of dam construction and trends in streamflow, we divided the
216 historical 35-year period (1980–2014) into three time windows: (1) the baseline

217 period 1980–1986 when no dam was constructed, (2) the transition period 1987–2007
218 when small dams were constructed but there was no significant change in the trend of
219 streamflow, and (3) the post-impact period 2008–2014 when large dams were
220 constructed and significant changes on streamflow were observed. Daily streamflow
221 observations during the baseline period were used to calibrate the model, whereas
222 streamflow observations during the transition period were used to validate the model,
223 because the streamflow did not significantly change during the transition period.

224 **3.2.3 Contribution of climate change and human activities**

225 Both climate change and human activities can alter the flow regime of the LR. In this
226 study, CREST-snow and a method based on the Budyko hypothesis were used to
227 evaluate these impacts. The total change in observed streamflow (ΔQ) can be
228 attributed to the combined impacts of climate change (ΔQ_{cc}) and human activities
229 (ΔQ_{ha}):

$$230 \qquad \qquad \qquad \Delta Q = \Delta Q_{cc} + \Delta Q_{ha} = O_i - O_0 \qquad (1)$$

231 where O_i and O_0 are the observed mean annual streamflow (m^3/s) for the
232 assessment period (transition or post-impact period) and the baseline period,
233 respectively.

234 Streamflow simulation using CREST-snow represents the impacts of variability in
235 precipitation and temperature that reflects a changing climate system on the flow
236 regime. CREST-snow was used to generate natural streamflow in response to climate
237 change and variability. The climate-induced change in streamflow can be calculated as

238 follows:

$$239 \quad \Delta Q_{cc} = R_i - R_0 \quad (2)$$

240 where R_i is the simulated annual streamflow for the assessment period (m^3/s) and
241 R_0 is the simulated annual streamflow for the baseline period (m^3/s). Thus, the
242 human-induced streamflow change can be calculated as the difference
243 between ΔQ and ΔQ_{cc} :

$$244 \quad \Delta Q_{ha} = \Delta Q - \Delta Q_{cc} \quad (3)$$

245 We defined I_{cc} and I_{ha} as the contributions of climate change and human activities to
246 the total streamflow change:

$$247 \quad I_{cc} = \frac{|\Delta Q_{cc}|}{|\Delta Q_{cc}| + |\Delta Q_{ha}|} \times 100\%, \quad I_{ha} = \frac{|\Delta Q_{ha}|}{|\Delta Q_{cc}| + |\Delta Q_{ha}|} \times 100\% \quad (4)$$

248 Equations (1)–(4) are also appropriate for seasonal analysis of contributions of climate
249 change and human activities during wet season (June–November) and dry season
250 (December–May) or monthly analysis.

251 The Budyko framework has been widely used to separate the effects of climate
252 change and human activities on streamflow changes (Guo et al., 2015; Li et al., 2011;
253 Li et al., 2017a). In this study, we decomposed the climate and human impacts based
254 on the Budyko hypothesis at the annual timescale to make a cross-validation with our
255 estimates from CREST-snow. We adopted the Ture-Pike equation (Pike, 1964) and
256 quantified the climate-induced change ($\Delta Q'_{cc}$) of streamflow:

$$E/P = (1 + \phi^{-2})^{-0.5} \quad (5)$$

$$\phi = E_0/P \quad (6)$$

$$\Delta Q'_{cc} = \frac{\partial Q}{\partial P} \Delta P + \frac{\partial Q}{\partial E_0} \Delta E_0 \quad (7)$$

where the climate dryness index (ϕ) is the ratio of the mean annual potential evapotranspiration (E_0) to the mean annual precipitation (P). For the long-term annual water balance, soil-water storage change is assumed to be negligible, and the actual mean annual evapotranspiration (E) can be expressed as $E = P - Q$ in equation (5).

3.2.4 Partitioning effects of water use

Five water use sectors including irrigation, living, livestock, mining, and manufacturing of the global monthly gridded (0.5°) sectoral water withdrawal dataset (Unit: mm) and dead reservoir capacity data listed in **Table 1** were used to partition the effects of human activities on the flow regime of the LR for the period 1980–2010. Annual water use was calculated by spatially averaging water use values across all grid cells within the LR basin and then summing monthly values to obtain annual average values. Streamflow variation caused by each type of water use sectors was calculated using the mean annual water use value during the period 1987–2010 minus that during the baseline period 1980–1986.

Dead reservoir storage is referred to as water in a reservoir that cannot be drained by gravity through a dam's outlet works, spillway or power plant intake. We summed the dead reservoir storages of the completed reservoirs during 1987–2010 (**Table 1**) and

converted the volumetric values into millimeters based on the drainage area of the LR basin, for the convenience of comparison. The total dead reservoir storage was used to characterize the streamflow change caused by reservoir construction.

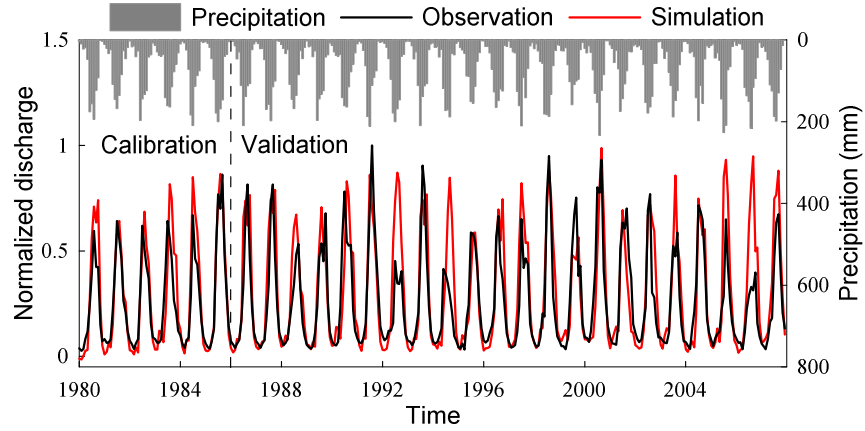
4. Results

4.1 CREST-snow model simulations

Table 2 shows monthly performance metrics of the simulation with CREST-snow. For the calibration period, the *NSE* and *Bias* values were found to be 0.73 and 0.1 respectively. For the validation period, the *NSE* and *Bias* values were 0.53 and 0.12. Some overestimates of streamflow were found particularly for the high peaks of 1992, 1994 and 2006, as seen from **Figure 2**, and we postulated that it might result from the overestimated precipitation estimates used in this study. Previous studies suggested that hydrological modeling with $NSE > 0.50$ can be considered satisfactory (Moriassi et al., 2007). Here, CREST-snow for the overall period 1980–2007 showed satisfactory performance in terms of both *NSE* (0.57) and *R* (0.85). The calibrated parameters were therefore considered suited to simulate natural streamflow.

Note that low flows were simulated better than peak flows during the overall period, with a higher *LogNSE* value (0.73) than *NSE* (0.57). This is largely due to the impact of precipitation input. We used meteorological data including precipitation, potential evapotranspiration, air temperature and wet-bulb temperature for the later decades as input to simulate the historical natural streamflow for the transition period 1987–2007

297 and the post-impact period 2008–2014. The results and analyses are presented in the
 298 following section.



299
 300 **Figure 2.** Normalized monthly simulated and observed discharge at the Yunjinghong gauging
 301 station and corresponding monthly precipitation for the LR basin for the calibration (1980–1986)
 302 and validation (1987–2007) periods, respectively. The discharge was normalized as the difference
 303 between the discharge and the minimum discharge divided by the difference between the
 304 maximum and minimum discharge at the Yunjinghong gauging station during 1980–2007.

305 **Table 2.** Performance metrics of simulated discharge at the Yunjinghong gauging station on the
 306 LR for the calibration, validation, and overall periods, respectively.

Time period	<i>NSE</i>	<i>LogNSE</i>	<i>R</i>	<i>Bias</i>
Calibration (1980–1986)	0.73	0.80	0.91	0.10
Validation (1987–2007)	0.53	0.70	0.82	0.12
Overall	0.57	0.73	0.85	0.12

307 4.2 Trend analysis of hydrological variables during 1980–2014

308 During 1980–2014, the proportional contribution of snowmelt to total basin discharge
309 was relatively low ($\sim 2\%$) in the LR basin. The impact of glacier meltwater on runoff
310 was even lower ($\sim 0.2\%$) due to the very limited glacier coverage within the study
311 basin (**Figure 1**). The simulation results therefore suggest that rainfall is the dominant
312 factor affecting runoff in the LR basin because of the relatively low contributions of
313 snow and glacier meltwater to total runoff. Time series of annual mean precipitation,
314 observed streamflow, and simulated natural streamflow from 1980 to 2014 were
315 shown in **Figure 3**. Both precipitation and simulated natural streamflow increased at a
316 rate of 0.98 mm/yr^2 (not significant) and the simulated natural streamflow increased at
317 a rate of 0.70 mm/yr^2 (not significant). Natural runoff was simulated using the
318 parameters calibrated for the baseline period and was assumed to have been
319 influenced only by climate change, which was also demonstrated by the high R value
320 (0.91) between precipitation and the simulated natural streamflow.

321 Note that during the period 1980–2014, mean annual temperature of the LR basin was
322 rising at a rate of $0.023 \text{ }^\circ\text{C/yr}$ ($p < 0.01$), and snow and glacier meltwater increased at a
323 rate of 0.064 mm/yr^2 ($p < 0.05$). However, the observed streamflow exhibited a
324 decreasing trend at a rate of 2.96 mm/yr^2 ($p < 0.1$), due to the combined effect of both
325 climate change and human activities. As seen from **Figure 3**, the discrepancies
326 between the observed streamflow and natural streamflow enlarged since 1987 due to
327 reservoir construction, demonstrating the nonnegligible impact of human activities on

the flow regime of the LR.

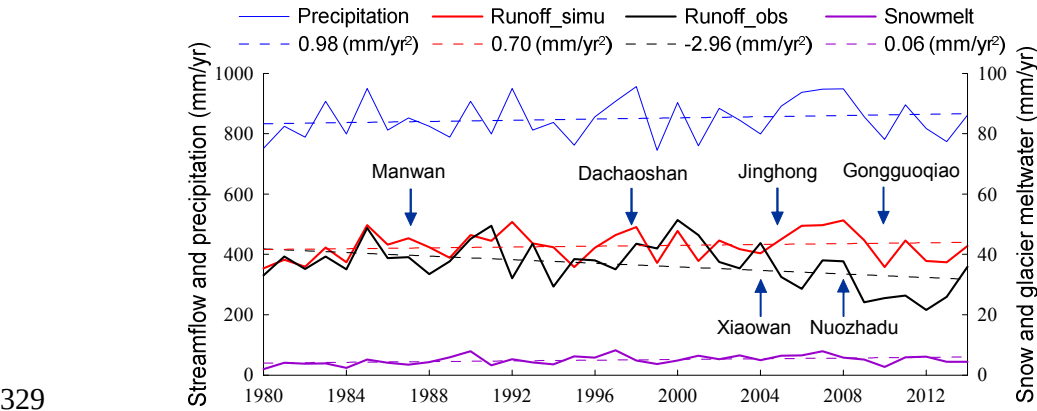
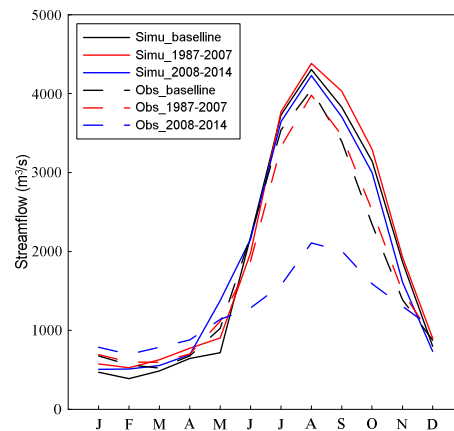


Figure 3. Time series of annual mean precipitation, observed streamflow, simulated natural streamflow, and simulated snowmelt runoff in the LR basin during 1980–2014. Dashed lines represent trend lines of the four variables and the numbers in the legend represent their change rates. Arrows denote the initial construction time of the completed dams.

At the seasonal scale, the observed and simulated streamflow also showed considerable changes during the transition and post-impact periods compared with the historical streamflow during the baseline period. Dashed lines in **Figure 4** show the observed streamflow at the Yunjinghong gauging station for all three periods. The dry season streamflow (December–May) was lowest in the baseline period. During the transition period, the dry season streamflow showed a slight increase, whereas the wet season streamflow (June–November) showed little changes. During the post-impact period, streamflow in both dry and wet seasons showed significant changes (~20% and ~40%) compared with that during the baseline period, which may be caused by reservoir construction and filling.

344 Monthly simulated natural streamflow at the Yunjinghong gauging station over the
 345 three periods is shown in **Figure 4** using solid lines. The natural streamflow changed
 346 little in the wet season during the three periods. In addition, the observed streamflow
 347 deviated considerably from the simulated natural streamflow (i.e. with large reservoir
 348 construction) during the period 2008–2014. Before year 2008, the difference between
 349 the observed and simulated natural discharge was apparently smaller. At the monthly
 350 scale, the observed streamflow showed a decrease of 40%–56% in June–September
 351 but an increase of 11%–50% in March–May on the mean discharge over the
 352 post-impact period than that over the baseline period. However, the dam construction
 353 did not affect the timing of the peak flow that was still in August. Also, the trend in
 354 low flows did not change, with the February–March low discharge period preceded by
 355 high discharge in January and followed by a sudden decline in March.



356
 357 **Figure 4.** Time series of observed streamflow (dashed lines) and simulated natural streamflow
 358 (solid lines) at the Yunjinghong gauging station for the baseline, transition and post-impact periods,
 359 respectively.

360 **Figure 5** shows time series of observed streamflow during the baseline period and
361 during the first year after each of the six hydropower plants (**Table 1**) was put into
362 operation. The reservoir operation in the wet season became increasingly significant
363 with more reservoirs built over time except 1994, because there was a severe drought
364 in the LR basin around 1994 (Xu, 2018). The inset in Figure 5 shows that the effect of
365 reservoirs on the dry season streamflow was not significant except 2013 when the dry
366 season streamflow was almost highest among all years compared due to the
367 completion of the Nuozhadu Reservoir. Räsänen et al. (2017) made a comparison of
368 observed streamflow of 2010–2014 to observed streamflow of a baseline period
369 (1960–1990) at Chiang Saen (in Thailand), Nakhon Phanom (in Vietnam) and Kratie
370 (in Cambodia) gauging stations. In 2013 when all the reservoirs in the LR basin were
371 completed, the wet season streamflow at Chiang Saen was lower than that during the
372 baseline period, which applies to Yunjinghong in our study. However, streamflow in
373 July, August, and September of 2013 at Nakhon Phanom and Kratie was even higher
374 than that during the baseline period. We could therefore infer that reservoirs
375 constructed in the LR basin has a certain impact on streamflow in Thailand, but has a
376 less impact on streamflow in Vietnam and Cambodia.

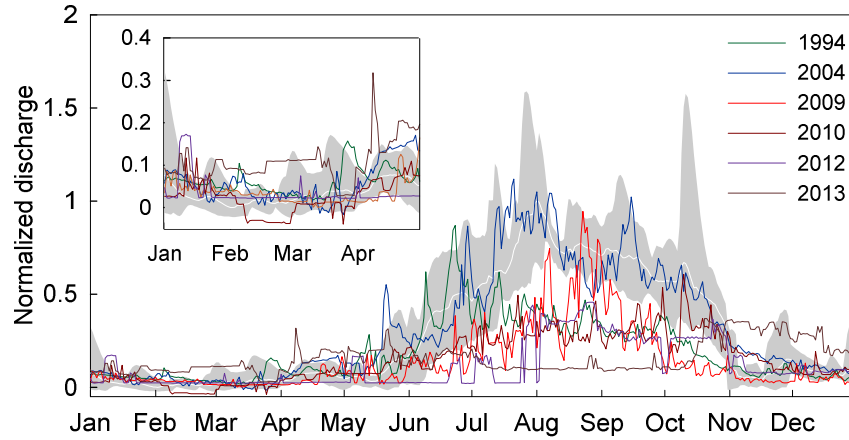


Figure 5. Comparison between the normalized observed streamflow during 1980–1986 and normalized observed streamflow of specific years related to dam construction. Shading areas represent the range of the observed streamflow during the baseline period 1980–1986 and the white line represents the mean of the observed streamflow during the same period. The normalization is the same as that shown in Figure 1. Maximum and minimum observed discharge at the Yunjinghong gauging station during the baseline period were used here.

4.3 Quantification of the impacts of climate change and human activities

Compared to the baseline period (1980–1986) when no dam was constructed, significant changes (~-6%) in mean annual streamflow occurred from 1987 to 2014, particularly after 2008 when streamflow decreased by 26.8% compared with the baseline period. The contributions of climate change and human activities to changes in streamflow accounted for ~57% and ~43 % for the transition time period (1987–2007), and ~5% and ~95 % for the post-impact period (2008–2014), respectively (Table 3), compared with the baseline period (1980–1986).

392 During the transition time period, only two large reservoirs (Manwan and Dachaoshan)
393 were built, with a total dead reservoir storage of 7.3 mm, whereas two other reservoirs
394 (Jinghong and Xiaowan) were still under construction. The impact of human activities
395 was therefore smaller than that of climate variation during this period, indicating that
396 reservoir construction and operations did not significantly impact the flow regime of
397 the LR basin during the transition period. During the post-impact period, all the six
398 reservoirs were built, including the reservoir with the largest annual regulation
399 (Nuozhadu) and the total dead storage capacity increased to 118.4 mm. The
400 construction of large reservoirs has led to a rapid increase in the impact of human
401 activities on streamflow.

402 Table 3 shows the contributions of climate change and human activities in each period
403 after the reservoir was built. During 1987–1996, Manwan was the only reservoir on
404 the LR, and then Dachaoshan was built and put into operation during 1997–2004.
405 During 2005–2007, both Xiaowan and Jinghong were under construction and
406 Nuozhadu and Gongguoqiao started to be built and put into operation during 2008–
407 2012. All the reservoirs were completed during 2013–2014.

408 It was found that first, with increasing total dead storage of reservoirs on the LR, the
409 impact of human activities on streamflow was increasingly important. Second, the
410 impact of human activities was stronger when the time-lag between the activation
411 period of two reservoirs was shorter. For example, the impact of human activities was
412 52.3% during 1997–2004 when there was only one reservoir under construction. It

became 64.6% during 2005–2007 when two reservoirs were under construction and even raised to 90.5% during 2008–2012 when four reservoirs were built together. The impact of human activities on streamflow slightly reduced during 2013–2014, when all reservoirs were put into operation and there was no need to fill dead water storage of reservoirs.

Table 3. Human- and climate-induced changes on annual streamflow for each period after the reservoir was built.

Duration	Precipitation		Runoff observation		Runoff simulation		I_{cc} (%)	I_{ha} (%)
	(mm/yr)	Relative change (%)	(m ³ /s)	Relative change (%)	(m ³ /s)	Relative change (%)		
1980–1986	833	–	1728	–	1867	–	–	–
1987–1996	839	0.7	1736	0.5	1945	4.2	52.7	47.3
1997–2004	850	2.0	1881	8.9	1940	3.9	47.7	52.3
2005–2007	925	11.0	1485	-14.1	2163	17.1	35.4	64.6
1987–2007	855	2.6	1755	1.6	1974	5.7	57.2	42.8
2008–2012	860	3.2	1215	-29.7	1927	3.2	9.5	90.5
2013–2014	818	-1.8	1387	-19.7	1806	-3.3	17.5	82.5
2008–2014	848	1.8	1264	-26.8	1893	1.4	5.0	95.0

In addition to the simulation performed by the hydrological model, the Budyko framework was also used to separate the effects of climate change and human activities at the annual scale. As shown in **Table 4**, the contributions of climate change

and human activities to the changes in streamflow accounted for ~63% and ~37 % for the transition time period 1987–2007, and ~1% and ~99% for the post-impact period 2008–2014, respectively. The difference between the two methods was approximately within 6%.

Table 4. Human- and climate-induced changes on annual streamflow calculated by the Budyko framework.

Time Period	P (mm/yr)	E_0 (mm/yr)	Q (mm/yr)	Budyko Framework	
				I_{cc} (%)	I_{ha} (%)
1980–1986	833	781	385	--	--
1987–2007	855	785	391	63.4	36.6
2008–2014	848	809	282	1.4	98.6

At the seasonal scale, during the transition period, human activities accounted for ~61% of wet season streamflow changes, whereas climatic variation accounted for ~60% of dry season streamflow changes. Similarly, during the post-impact period, human activities accounted for ~80% during the wet season, whereas climate change accounted for ~60% during the dry season. These findings indicate that human activities had a relatively larger contribution during the wet season whereas climate change was the dominant factor affecting the dry season streamflow. During the wet season, human activities contributed more in the post-impact period, providing benefits to the lower reaches with regard to flood control. For example, the flood control standard of the Jinghong Reservoir increased from 20 years to 100 years after

439 the completion of the Nuozhadu Reservoir.

440 At the monthly scale, during the transition period, the streamflow was mostly

441 influenced by climate change except July, August and October (**Figure 6**). The

442 contribution of climatic variation in March was greatest, accounting for ~67% of the

443 streamflow changes. Snow and glacier meltwater in spring (March–May) increased by

444 ~39% compared with the baseline period, and contributed to 4.5% of the spring

445 streamflow. Therefore, the change in streamflow was mainly attributed to the change

446 in precipitation. During the post-impact period, human activities contributed more to

447 the changes in streamflow for most of months except February, May and November

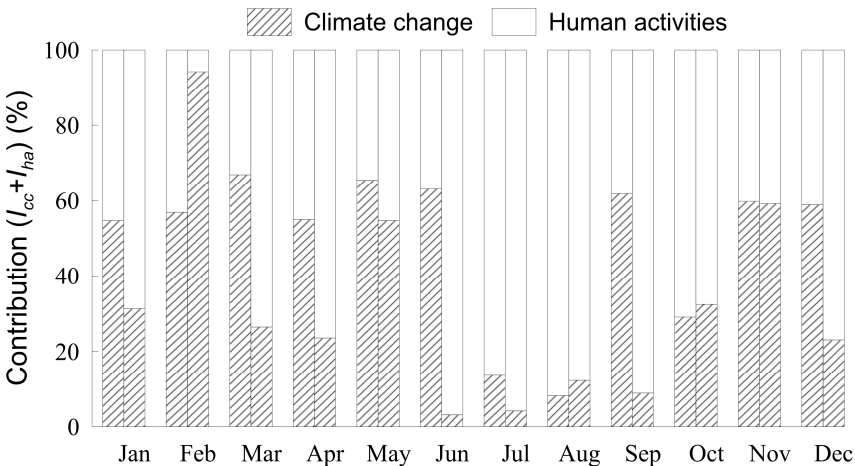
448 (**Figure 6**). The contribution of human activities in June was greatest, accounting for

449 ~97% of the streamflow changes. This is consistent with the trends illustrated above

450 that human activities were the dominant factor affecting changes in streamflow, as the

451 total reservoir dead storage capacity increased during the post-impact period and

452 human activities mainly affected the streamflow during the wet season.



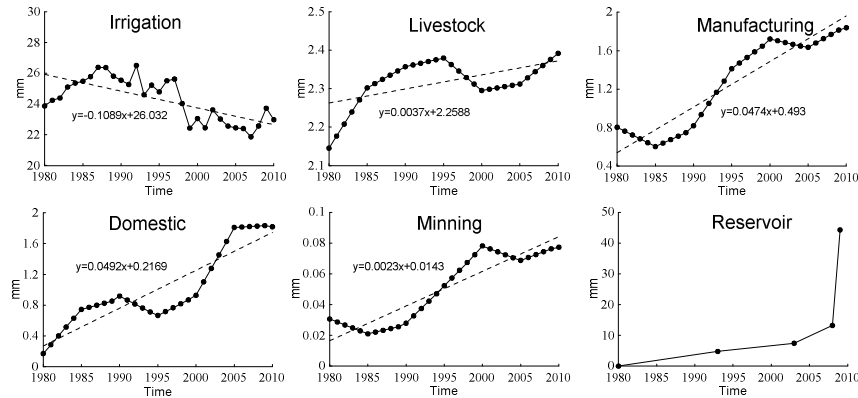
454 **Figure 6.** Contributions of climate change and human activities to monthly streamflow changes.
455 For each month, the column on the left represents the transition period whereas the column on the
456 right represents the post-impact period.

457 **4.4 Separating effects of human activities**

458 Not only reservoir construction and operation, but also other human interventions
459 such as human water withdrawal changes and land cover changes might affect the
460 flow regime of the LR. **Figure 7** shows annual mean water withdrawal time series
461 including irrigation, livestock, manufacturing, domestic and mining and dead storage
462 capacity of reservoirs in the LR basin. The proportion of irrigation, livestock,
463 manufacturing, domestic and mining water use in total streamflow during the baseline
464 period was 6%, 0.6%, 0.2%, 0.1% and 0.01%, respectively. It was found that
465 irrigation, the largest component of water withdrawal in the LR basin, exhibited a
466 decreasing trend, whereas manufacturing and domestic water withdrawal was almost
467 doubled and water withdrawal for other purposes remained almost steady.

468 Under the impacts of human activities, streamflow reduced by ~50 mm in the LR
469 basin during 1987–2010 compared with the baseline period. Water withdrawal was
470 only increased by 0.8 mm compared with the baseline period that accounts for 1.6%
471 of the streamflow change, while the dead reservoir storage increased by ~44 mm that
472 accounts for 88% of the streamflow change. The land cover in the MRB changed by
473 only 0.57% during 2000–2010, implying that the land use change was not a

474 significant factor affecting the streamflow among human activities (Li et al., 2017a).
 475 Consequently, we can draw a conclusion that reservoir construction was the primary
 476 factor among human activities that impacted the flow regime during 1987–2010.



477
 478 **Figure 7.** Annual trends (dashed lines and linear regression equations) in mean water withdrawal
 479 and the dead storage of reservoirs in the LR basin.

480 5. Discussion

481 This study evaluated annual, seasonal, and monthly changes in streamflow and
 482 attributed the changes to climate change and human activities in the LR basin over the
 483 time period 1980–2014, by applying the CREST-snow hydrological model and using
 484 long-term streamflow observations at the Yunjinghong gauging station. CREST-snow
 485 was calibrated for both streamflow and snow, allowing more reliable quantification of
 486 climate change impacts on streamflow. Runoff from the TP tends to be sensitive to
 487 climate change as a result of snow and glacier melting (Immerzeel et al., 2009; Jeelani
 488 et al., 2012). Finger et al. (2015) indicated that use of streamflow alone can lead to
 489 unrealistic glacier mass balances and snow cover evolution. The dual calibration with

490 both streamflow and snow water equivalent performed in our study was therefore
491 more appropriate to assess hydrological dynamics, though it would cause a certain
492 loss in streamflow simulation performance.

493 Impacts of reservoir operations in the LR basin can be examined by looking at
494 changes in streamflow between the baseline period (1980–1986) and the assessment
495 period (1987–2014). In our study, we found that reservoirs stored water during the
496 wet season with streamflow decreased by ~10% during the wet season of 1987–2014
497 compared with that of 1980–1986, and released water during the dry season with a
498 ~10% increase in streamflow. Our findings were consistent with the recent assessment
499 on hydrological alterations at the Chiang Saen gauging station (Li et al., 2017a;
500 Räsänen et al., 2017; Wang et al., 2017). Such reservoir operations could bring great
501 benefits to the downstream, with increasing dry season flows supplementing water
502 resources for irrigation and reducing wet season flows mitigating flood risks
503 downstream.

504 For example, influenced by the super El Nino during the dry season of 2016, all
505 countries in the LR–MR basin suffered drought of varied degrees. The Chinese
506 government implemented an emergency water supply to the MR by releasing water
507 from the Jinghong Reservoir, which effectively alleviated the drought condition in the
508 lower reaches (Li et al., 2017b). However, the building of large dams may cause
509 geological damage, affect fish migration, and cost immense manpower, material and
510 financial resources (Pokhrel et al., 2018). Evaluation of effects of dams on rivers

511 requires an integrated consideration of various factors such as hydrology, ecology, and
512 economy as well.

513 Regarding the attribution of changes in streamflow to climate change and human
514 activities, we compared our estimates with two published studies. Tang et al. (2014)
515 analyzed the contributions in the LR basin during 1956–2008, and found that climatic
516 variation contributed more during the wet season whereas human activities
517 contributed more during the dry season, in contrary to our findings. Note that their
518 study calibrated and validated streamflow at the monthly scale, as opposed to the
519 daily scale performed in our study. The BP-ANN model they used to simulate the
520 natural streamflow may not well reflect the underlying mechanisms and hydrological
521 processes. Different time periods of these analyses may also be one of the reasons for
522 the different findings. In addition, Li et al. (2017a) used the Budyko hypothesis to
523 partition the effects of climate change and human activities on the streamflow changes
524 and concluded that climate change contributed to ~82% of the total streamflow
525 change during the transition period 1992–2009, whereas human activities contributed
526 to ~62% of the total change during the post-impact period 2010–2015 in the upper
527 MRB with the basin outlet located at Chiang Saen, which was highly consistent with
528 our results.

529 Furthermore, the contribution of human activities was found to have decreased from
530 95% at Yunjinghong to 62% at Chiang Saen. The Chiang Saen gauging station in
531 Thailand is on the south of the Yunjinghong gauging station with a warmer climate

532 and much more precipitation. Some research showed that not only precipitation but
533 also interval inflow between the Yunjinghong and Chiang Saen gauging stations were
534 important components of streamflow at the Chiang Saen station (He et al., 2006). It
535 was therefore implied that precipitation is the main source of freshwater resources for
536 the lower MRB, and the impact of dam operations on the LR would become less
537 important downstream. Still, different study periods and analysis approaches may
538 have induced some discrepancies in the results.

539 There are also limitations in this study. The precipitation data that we used has some
540 uncertainties. Precipitation is the primary forcing in hydrological models. The LR
541 originating on the TP at over 5100 m elevations has sparse in situ observations, so the
542 quality of the CGDPA precipitation product used in this study may be degraded
543 relative to regions with denser observational networks in eastern and central China.
544 Although some studies (Pan et al., 2010; Wang et al., 2017) demonstrated that remote
545 sensing precipitation products can be used to effectively simulate hydrological
546 processes in basins including the MRB, the currently available remote sensing
547 products could not cover such a long time period from 1980–2014. More accurate
548 precipitation products at higher spatial resolutions are expected to improve the model
549 performance in the future. Also, CREST-snow showed some degraded reproduction of
550 the observed streamflow during the baseline period 1980–1986 (**Figure 2**). These
551 inaccuracies might be associated with uncertainties in precipitation, and calibration of
552 the model parameters, leading to uncertainties in differentiating the climate- and

553 human-induced streamflow changes.

554 This study was conducted over the time period 1980–2014 when there were only six
555 large reservoirs built on the mainstream of the LR. The total dead reservoir storage of
556 the six existing reservoirs represents ~40% of the annual streamflow at the
557 Yunjinghong gauging station. The magnitude of streamflow at Yungjinghong would
558 recover to a state prior to dam construction in the future if there is no filling of dead
559 reservoir storage and water use does not largely increase. There is a further need for
560 estimating future impacts of climate change and hydropower development in the LR
561 basin to provide a basis for water resources management, especially for transboundary
562 river management.

563 **6. Conclusion**

564 This study aims to estimate streamflow changes caused by climate change and human
565 activities in the LR basin over a historical 35-year period (1980–2014) using the
566 CREST-snow hydrological model and streamflow observations at the Yunjinghong
567 gauging station. CREST-snow was calibrated with streamflow and snow water
568 equivalent data. Based on the history of dam construction and the intercept break
569 point determined by the Mann-Kendall test, the 35-year period was partitioned into
570 three time windows for our analysis, and the contributions of climate change and
571 human activities were investigated at annual, seasonal and monthly scales. The major
572 findings of this study are summarized as follows.

573 (1) A significant change (~6%) in mean annual streamflow occurred during 1987–
574 2014 compared with that of the baseline period, especially after year 2008 when the
575 largest hydropower plant (Nuozhadu) in the MRB began to build. Increased
576 streamflow during the dry season and decreased streamflow during the wet season
577 were found.

578 (2) Compared with the baseline period 1980–1986, climatic change and human
579 activities contributed ~57% and ~43 % to the streamflow changes for the transition
580 time period 1987–2007, and ~5% and ~95% for the post-impact period 2008–2014,
581 respectively. Reservoir construction was the most significant factor affecting
582 streamflow among human activities including agricultural, industrial, and domestic
583 water uses.

584 (3) At the seasonal scale, climatic variation contributed more during the dry season,
585 and precipitation change was the dominant factor that resulted in streamflow changes.
586 Human activities were the dominant factor leading to streamflow changes during the
587 wet season mainly through reservoir filling. Streamflow released from the reservoirs
588 during the dry season could benefit irrigation and the reduced wet season discharge
589 could mitigate food risks downstream.

590 Overall, this study can serve as a basis for understanding hydrological changes in
591 dammed rivers, and provide reference for water resources management for the
592 transboundary LR-MR basin. Projections of future runoff under climate change

593 scenarios should consider reservoir construction and operation strategies, and more
594 research is needed to understand implications of the streamflow changes in the
595 dammed river on hydropower generation, ecosystems, and society.

596 **Acknowledgement**

597 This study is supported by the National Key Research and Development Program of
598 China under grant No. 2016YFE0102400 and the National Natural Science
599 Foundation of China under grant No. 91547210 and 71461010701.

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