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Research papers

Observed changes in flow regimes in the Mekong River basin

Dongnan Li[a], Di Long[a], Jianshi Zhao[a,*], Hui Lu[b], Yang Hong[a]

[a] State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, China
[b] Center for Earth System Science, Tsinghua University, Beijing, China

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ABSTRACT

Human activities, such as dam construction, significantly altered the flow regimes in the Mekong River, particularly after the completion of two large dams, namely Xiaowan and Nuozhadu in 2010 and 2014, respectively. Streamflow data from 1960 to 2014 obtained from five stations located along the Mekong mainstream are divided into three periods, i.e., the pre-impact period (1960–1991), the transition period (1992–2009), and the post-impact period (2010–2014). The flow regimes were investigated using eco-flow metrics and indicators of hydrologic alteration (IHA). The results show that the construction and initial filling of the upstream dams reduced the annual streamflow in the upstream Chiang Saen gauging station, whereas no clear effect was observed in the downstream Stung Treng station. The operation of dams reduces the streamflow in wet seasons and increases the streamflow in dry seasons, resulting in a unique seasonal variation in the streamflow based on eco-flow metrics in the Chiang Saen gauging station, observed from 2010 to 2014. In addition, the maximum flow values decreased significantly in the Chiang Saen gauging station during the year corresponding to the completion of the upstream dams. The construction and operation of dams clearly have significant impacts on low pulse duration. It is observed that climate change dictated the changes in the annual streamflow during the transition period 1992–2009 (82.28%), whereas human activities contributed more in the post-impact period 2010–2014 (61.88%). The results of this study could provide a reference for reservoir operation in the upstream regions considering both ecological and economic benefits of such operations, as well as maximize the interests of stakeholders in this region.

1. Introduction

In river ecosystems, the flow regime of runoff plays a significant role in many fundamental ecological processes (Poff and Zimmerman, 2010). Changes in flow regimes within the context of climate change and human activities are significant to the hydrological community, receiving considerable global attention. River management currently focuses not only on the total volume of runoff but also on its flow regime, which has been an important objective in environmental systems for both ecological professionals and engineering managers since the 1990s (Richter et al., 1996; Yin et al., 2011).

Climate change and human activities have been considered as the two primary factors affecting flow regimes (Li et al., 2006; Ma et al., 2014). In some basins, human activities are the main factors that alter flow regimes, particularly during the construction and operation of large reservoirs (Poff et al., 1997; Fan et al., 2015). Climate change can also be the dominant factor that alters flow regimes (Li et al., 2006), which can change the pattern of precipitation and potential evaporation (Wang and Hejazi, 2011). Human activities, such as dam construction and water withdrawal activities (i.e., irrigation, industry, and municipal demands), directly change flow regimes (Ma et al., 2014), thereby changing river ecosystems (Gippel, 2001; Poff et al., 1997; Richter et al., 2003, 2006). The impacts of the two factors are often analyzed separately. However, the effects of climate change and human activities are always combined, and their effects on some river basins are difficult to identify. For example, climate change may cause changes in precipitation, increasing the impacts caused by dams as more water would be regulated by reservoirs during the long dry seasons (Lu et al., 2014).

Many types of flow metrics and statistical methods have been proposed to analyze the impacts of changes in flow regimes. However, the characteristics of such changes are not fully understood from the perspectives of both ecological and human demands. Over 170 hydrologic metrics have been proposed to describe the variations and characteristics of flow regimes (Olden and Poff, 2003; Gao et al., 2009). Indicators of hydrologic alteration (IHA) are among the most popular metrics being widely used. The range of

* Corresponding author.
E-mail address: zhaojianshi@tsinghua.edu.cn (J. Zhao).

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Table 1
Main conclusions on streamflow alteration in recent relevant research.

Study	Mean flow	Dry season flow	Wet season flow
(Lu et al., 2008)	Post-dam period (1992–2003) had lower water levels than the pre-dam period (1962–1991).	1992 was the driest year since 1960, but water flow in dry season was not the lowest.	
(Kummu and Sarkkula, 2008)		Small rises in the dry-season lake water level would permanently inundate disproportionately large areas of floodplain in Tonle Sap.	
(Delgado et al., 2010)			During 20th century, although average magnitude floods have a negative trend, variability is increasing.
(Piman et al., 2012)		At the 3S (Sekong, Sesan and Srepok) rivers of Mekong, hydropower projects increased flows by 28% in the current period and that number will be 63% after the completed of all the dams.	Wet season flows will decreased by 4% and 22% during current period and future period at the outlet of 3S river respectively.
(Räsänen et al., 2012)		A 90% increase in December–May Flows in Chiang Saen after the construction of 6 Chinese dams.	A 20–22% decrease in June–November flows, in Chiang Saen after the construction of 6 Chinese dams.
(Cochrane et al., 2014)		Compared with pre-1991 period, mean water levels for Chiang Saen increased in excess of 30% for the dry season months of March and April	Compared with pre-1991 period, monthly increases betweenJune and December were mostly less than 5%.
(Vries et al., 2015)			Dams can only cause a small change in water levels in the flood season until 2013.
(Räsänen et al., 2017)		Discharge in March-May 2014 increased by 121–187%, 41–74% compared to average discharges in Chiang Saen and Kratie respectively.	Discharge in July-August 2014 decreased by 32–46%, 0–6% compared to average discharges in Chiang Saen and Kratie respectively.

variability approach (RVA) was proposed to measure hydrologic changes (Richter et al., 1997), suggesting that the 25th and 75th percentiles of IHA metrics should be the targets for maintaining environmental flow (Yin et al., 2011). Based on the concept of flow duration curves (FDCs), Vogel et al. (2007) proposed an eco-flow metric comprising eco-deficit and eco-surplus. The two indices are non-dimensional and directly show the deficit and surplus of streamflow at different periods. Despite their simplicity, eco-deficit and eco-surplus indices are a promising overall representation of the degree of streamflow alteration (Gao et al., 2009). Ma et al. (2014) proposed a hydrograph-based hydrologic alteration assessment containing 25 indicators, which not only describe the statistics for each year but also consider the characteristics of extreme flow events. The integrated use of these methods could measure changes in flow regimes comprehensively.

Ecological effects of streamflow alteration in some large international transboundary rivers, such as the Mekong River, are particularly significant. These effects cause significant problems affecting collaborative management among riparian countries (Ingram et al., 1994; Kirby et al., 2010). The Mekong River is the ninth largest river globally, and the Mekong River Basin (MRB) harbors one of the most productive and diverse ecosystems in South Asia (Kuenzer et al., 2013). Ecological issues in the MRB have been a major concern to stakeholders, researchers, and other professionals globally. Over 70 dams spread across six riparian countries make the management of this transboundary river quite complicated and sensitive. Several studies focused on the hydrological effects of hydropower dams on the Mekong River, particularly the dams in China. Following the literature review published by Lu et al. (2008), Table 1 shows the literature review of some important studies conducted after 2008. A common perception is that dams significantly altered the flow regimes at the basin scale (Kuenzer et al., 2013). Some researchers have argued that construction of all the 78 tributary dams would produce less energy and pose greater environmental risks as compared to having six mainstream dams upstream of the Mekong River (Ziv et al., 2012). Recently, Cochrane et al. (2014) analyzed the alteration in water levels in six streamflow gauging stations along the mainstream of the Mekong River from 1960 to 2010 and discussed the relationship between annual fluctuations and active reservoir storage. However, the two largest reservoirs built after 2010, Xiaowan and Nuozhadu, were not considered in the aforementioned study; hence, the impacts of these reservoirs remain largely unknown.

In this study, we integrate the aforementioned methods, i.e., IHA for detailed metrics and eco-flow metrics for overall evaluation, to provide a complete analysis of the changes in the streamflow regime by taking the MRB as a case study. The following are the objectives of this study: (1) conducting a comprehensive, systematic analysis to identify the alteration of the flow regimes and their spatial and temporal patterns during the period 1960–2014 in the five gauging stations located along the mainstream; and (2) analyzing the causes and effects of the alteration of the flow regimes in the MRB.

2. Study area and data

The Mekong River originates from the Tibet Plateau, flows through six countries, namely China, Laos, Myanmar, Thailand, Vietnam, and Cambodia, and then flows into the South China Sea (Fig. 1). The MRB is generally divided into two sub-basins (Xi et al., 2008). The upper Mekong Basin (UMB), which is known as the Lancang River in China, covers an area of ~195,000 km^2 (24% of the total drainage area) and flows through three provinces of China, namely Qinghai, Tibet, and Yunnan. The lower Mekong Basin (LMB), which covers an area of ~600,000 km^2 (76% of the total drainage area) and flows through five countries, is generally considered to exist in a near natural state because of less economic development compared to the UMB (Hirsch, 2010; Kummu et al., 2010; Piman et al., 2013). The Mekong River is more than 4180 km long with a drainage area of 795,000 km^2 and a mean annual streamflow of 14,500 m^3/s (MRC, 2005). The streamflow is dominated primarily by Southeast Asian monsoons, resulting in a flood season and a dry season within a hydrologic year (Cochrane et al., 2014).

Downstream of the LMB, several important ecological sites closely related to the flow regimes of the river exist; among them, Lake Tonle Sap and the Mekong Delta are the most famous. Tonle Sap, which is the largest lake in Southeast Asia (covering an area of 8800 km^2 on average) and connected with the mainstream of the Mekong River at Phnom Penh, Cambodia, is regarded as the