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Assessment of collective impact of upstream watershed development and basin-wide successive droughts on downstream flow regime: The Lesser Zab transboundary basin

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SUMMARY

Rapid population growth and socio-economic development coupled with climate change and variability have observably impaired the natural characteristics of hydrological regimes of most of large rivers worldwide. The Lesser Zab shared between Iraq and Iran was one of the few remaining rather intact transboundary river watersheds. The unregulated natural flow pattern, however, has been shifted mainly due to recent upstream anthropogenic factors incorporated with successive droughts. A new generic approach was introduced through integrating a subset of the Indicators of Hydrologic Alteration (IHA) into three generic empirical equations coupled with the application of two universally endorsed drought indices to assess the changes in hydrological patterns prior to, and after upstream watershed development twinned with consecutive drought spells. A departure of about −16% was detected in the long-term median annual runoff in the artificially impaired periods. Alterations ranged from −3.4% to −41.7% were linked to monthly medians. The 1- to 90-day minimum runoffs were dropped between −33.3% and −53.8% over the regulated period. More substantial shifts were perceived between 1999 and 2013. The rates of anomaly ranged from −55.6% to −73.1%. The extreme minimum flows were experienced low to high alterations, while low to moderate degree of anomalies were associated with 1- to 90-day maximum flows. This rate of increased water withdrawal is anticipated to develop and the vulnerability degree of the downstream riparian country is projected to increase. Findings reveal that the impact of successive basin-wide drought episodes has considerably outweighed the effect of current recent upstream damming and water withdrawals.

1. Introduction

Anthropogenic activities have been altering the characteristics of riverine flow regimes for thousands of years. The rapid growing of water demands for irrigated agriculture, fishery, and public water supply practices has noticeably altered the natural patterns of the riverine regimes worldwide (Vorosmarty and Sahagian, 2000; Al-Faraj and Scholz, 2014a,b, 2015). Climate change and variability have added additional pressure on water resources, particularly in water-stressed regions. Regardless of uncertainties in the rate and magnitude of climate change, there is a clear global mark that temperatures will be warmer over the next century, resulting in considerable changes to temperature and precipitation patterns worldwide. Most Global Climate Models predict that water-stressed areas will experience prominent reductions in precipitation, substantially altering the runoff patterns for rivers and streams.

This has emphasized the urgent need for broader and profound understanding of the combined effect of man-made interventions and climate shift on riverine systems, particularly in transboundary watersheds, where competition to access and abstract water between upstream and downstream actors is escalating. Several descriptors such as magnitude, timing, frequency, duration and rates of change of runoff have been adopted to describe the hydrologic regime of a river (Poff et al., 1997).

The critical challenge in integrated management of water resources of a transboundary basin among riparian actors is obtaining the degree to which the unaltered natural runoff pattern has been impaired. Concerning many rivers, runoff has been largely impacted by anthropogenic pressures such as damming the main river water course and tributaries, off-river storages, large-scale irrigation practices, public water supply, and fishery. Upstream

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human-induced perturbations produce a flow regime in the downstream riparian country that significantly differs from that of the pre-impact condition. Although anthropogenic-related alterations of hydrologic regimes are subject to landscape changes, channelization of streams and water withdrawal (Vorosmarty and Sahagian, 2000), damming entire river corridor and impoundment of reservoirs usually cause the greatest departure in flow regime (Magilligan et al., 2003).

A wide range of research work has been undertaken on impacts of human-induced intervention on natural flowpatterns, preserving a healthy river ecosystem and assessing hydrologic alterations (Richter et al., 1996, 1997; Poff et al., 1997; Richter and Richter, 2000; Maingi and Marsh, 2002; Kiesling, 2003; Olden and Poff, 2003; Choi et al., 2005; Gao et al., 2009; Al-Faraj and Scholz, 2014a, 2015a; Al-Faraj et al., 2014a,b, 2015). Various methods have been developed to assess effects of riverine regulations on hydrologic regime such as the range of variability approach (RVA) (Richter et al., 1997), the Suen and Eheart method (Suen and Eheart, 2006), the Histogram Matching Approach (HMA) (Shiau and Wu, 2008), and the Frequency Based Approach (FBA) (Principato and Viggiani, 2012).

The critical review of literature revealed that some work has been accomplished on hydrologic alterations regarding transboundary river basins. Some of the research focused on water engineering works (Kummu and Sarkkula, 2008; Wilk et al., 2010; Lauri et al., 2012), while some other studies were concerned with the joint impact of human-induced changes and climate shift and variability (Mango et al., 2011; Kuenzer et al., 2013). Moreover, the impact of drought episodes on various hydrological systems has been highlighted by Lorenzo-Lacruza et al. (2010) and Al-Faraj et al. (2014a,b).

The Indicators of Hydrologic Alteration (IHA) model of the Nature Conservancy developed by Richter et al. (1996) has been widely adopted in estimating the hydrologic alteration attributable to human disturbances. The method compares the hydrology of a reference "unimpaired" regime to an "impaired" paradigm. This model employs 33 hydrologic measures that are ecologically meaningful and sensitive to capture anthropogenic changes to riverine systems. These measures are structured into five major classes to statistically embody the temporal hydrologic variability in streamflow regime: (i) magnitude (twelve monthly median flows describe the normal flow condition); (ii) magnitude and duration of annual extreme conditions (ten parameters measures the magnitude of annual extremes of various durations, including 1-, 3-, 7-, 30-, and 90-day annual maxima and minima covering the daily, weekly, monthly, and seasonal cycles). The base flow index was obtained by dividing the 7-day minimum flow by the yearly average flow; (iii) timing of annual extreme conditions (julian dates for 1-day yearly maxima and minima indicate the timing of yearly extreme runoffs); (iv) frequency and duration of high and low pulses (four parameters refer to the frequency and duration of the high and low pulses). Hydrologic pulses are those periods within a water year in which the daily runoff s are either higher than the 75th percentiles (high pulse) or lower than the 25th percentile of the pre-alter flow dataset (low pulse); and (v) rate and frequency of changes in conditions (three parameters (fall rate, rise rate, and number of reversals)) measure the numbers and mean rates of both positive and negative changes in stream flow in two consecutive days) (Richter et al., 1996, 1997; Richter and Richter, 2000; Gao et al., 2009).

The RVA approach employs IHA outputs and compares the frequency of occurrence of the same parameters. This method allows users to obtain how often a specific parameter in the "post-impact" dataset falls within the same statistical quartile as the "pre-impact" time series. However, with a large number of competing hydrologic indices, two main shortcomings can be illustrious: (1) considerable effort of computation and (2) redundancy of variables. It follows that researchers are now defied with the assignment of presenting a small set of measures for assessing generic hydrologic anomalies while demonstrating major features of the hydrologic anomalies in natural flow regimes. Al-Faraj and Scholz (2014a) introduced three generic empirical formulas to estimate the collective impaired yearly average flow volume (subject to climate variability and upstream watershed development) available to a downstream country. Eqs. (1)–(3) show the empirical formulas as introduced by Al-Faraj and Scholz (2014a).

$$Q_C = C_1 \times Q_n \tag{1}$$

$$Q_{\text{artificial}} = C_2 \times Q_C \tag{2}$$

$$Q_{\text{altered}} = Q_C - Q_{\text{artificial}} \tag{3}$$

where Q_C is the yearly average runoff volume for impaired climatic conditions; C_1 denotes the ratio between the yearly average precipitation at the year under consideration and the long-term mean annual precipitation; Q_n is the yearly average runoff volume at unimpaired natural condition; $Q_{\text{artificial}}$ is the yearly average runoff volume for the artificially altered condition; C_2 signifies the ratio between the annual water abstraction to the long-term yearly average runoff volume at natural condition; Q_{altered} is the net yearly average runoff volume available to the downstream riparian country under the combined effect of upstream man-made perturbations and climate shift over the entire basin.

Richter et al. (1996) categorized the range of hydrologic anomaly factor into three groups: 0–33%, 34–67%, and 67–100% representing low, Moderate, and high degree of hydrologic anomaly, respectively. The hydrologic alteration factor (HAF) for each of the three categories was calculated using Eq. (4) as introduced by Richter et al. (1996).

$$\text{HAF} = (\text{observed frequency} - \text{expected frequency})/\text{expected frequency} \tag{4}$$

A positive value of HAF, exhibits that the frequency of values in the category has increased from the unimpaired natural to the impaired period, while a negative value suggests that the frequency of values has decreased (The Nature Conservancy, 2009a,b).

Given that zero-flow days were not observed during the examined time frame, the parameter "number of zero-flow days" was not included in the study.

Observational evidences worldwide show that many riverine systems are being affected by both human regulation arrangements (i.e. dam construction, water withdrawal for irrigation and public water supply and inter-basin water transfer) and climate change and variability. The individual or the combined influences vary substantially from one region to another and even between basins. This poses serious challenges for sound management of water resources, in particular in transboundary river basins where riparian countries compete over shared waters. The complexity of managing the transboundary river basins may mainly attributed to: (a) inconsistency and conflict of policies; (b) differences in institutional capacity, upstream unilateral-based water abstraction practices of shared water; (c) the absence of joint technical cooperation between the upper and lower riparian actors; (d) the mismanagement of water resources and the current security challenges; and (e) lack of social, economic and political stability in the lower riparian Country. Fig. 1 exhibits how riparian countries may react in different manners and have different arrangements to manage the transboundary water resources. Successive droughts at basin scale would give the upper actor a pretext to continue its unilateral action of water abstractions and build additional storage facilities and hydraulic diversion works within its