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Assessment of hydrological alterations from 1961 to 2000 in the Yarlung Zangbo River, Tibet

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Abstract

Hydrological regime that is primarily described by combinations of its magnitude, duration, frequency, timing, and rate of change, is the main driving force in river ecosystems. The Yarlung Zangbo River is the largest river in Tibet and the highest river in the world. Data from 1961 to 2000 together with Range of Variability Approach (RVA) analysis were used to calculate hydrological regime characteristics. The hydrologic regime of the Yarlung Zangbo River has been altered over the studied period and the annual flow decreased more than 10% and even 30%. The extreme low flow duration increased more than 200%. The low pulse duration and the high pulse duration increased even more than 1000%. Extreme water conditions, including extreme low or high flow pulse, may cause severe habitat alterations and should be keep in an appropriate range.

Key words: range of variability approach; hydrological regime; flow pulse; flow duration.

1. Introduction

Tibet lies in the highest plateau of Qinghai-Tibet and it is the only area in China that has not been fully developed. However, the ecological systems in Tibet are degrading with global climate changes and human activities. As the highest plateau in the world, Qinghai-Tibet plateau can influence the global environmental and climate in lots of ways (Liu, Chen 2000; Zhao *et al.* 2004). The ecological systems in Tibet are natural on the whole and their changes can reflect the change of global environmental conditions.

River flow is a driving force of ecological processes underlying the distribution, composition and diversity of lotic biota. Streamflow controls key habitat parameters such as flow depth, velocity, and habitat volume (Poff *et al.* 1997; Benda *et al.* 2004; Shiau, Wu 2007). Alteration of natural streamflow regimes modifies the distribution and availability of riverine habitat conditions, with potentially adverse consequences for native biota (Richter *et al.* 1996; 1997; 1998a; 1998b; Zhao *et al.* 2004). Riverine ecosystem is the most important element of regional and global environment. Natural streamflow variability plays an important role in maintaining healthy aquatic ecosystems (Poff *et al.* 1997; Roy *et al.* 2006). Five critical components of the flow regime regulate ecological processes in river ecosystems: magnitude, frequency, duration, timing, and rate of change of hydrologic conditions (Poff, Allan 1995; Poff 1996). There is a link between altered habitat and success of some non-native species (Poff, Allan 1995; Richter *et al.* 1996; Gurnell *et al.* 1998; Peterson *et al.* 2002; Leprieur *et al.* 2006).

Richter *et al.* (1997) developed the Range of Variability Approach (RVA) to establish flow-based river management targets that incorporate the concepts of hydrologic variability and aquatic ecosystem integrity. This method uses 33 hydrologic parameters to assess alterations in terms of flow magnitude, timing, frequency, duration and rate of change (Richter *et al.* 1996; 1998a). The RVA methodology compares hydrologic data from a pre-impact period with those from a post-impact period, where each period is ideally represented by a minimum of 20 water years. The degree of hydrological alteration is then determined by a range-of-variability analysis based on the frequency with which post-impact hydrologic parameters fall within a range of values selected from the distribution of pre-impact values (Richter *et al.* 1998a). The RVA methodology has been applied to river basins representing a variety of watershed and hydrologic regime types (Richter *et al.* 1998a; Sparks, Spink 1998; Koel, Sparks 2002; Benda *et al.* 2004; Shiau, Wu 2004; Kennen *et al.* 2008).

This study aims to evaluate the hydrological alterations of the Yarlung Zangbo River using RVA method.

2. Materials and methods

2.1. Study area and data

The Yarlung Zangbo River, located within east longitude 82ºE - 97º07´E and north latitude 28ºN - 31°26´N, 2229 km long, covering an area of 239 228 km^2, rising in the Kailas range of the Himalayas with an elevation of more than 6000 meters, southwest Tibet, China, is the largest river in Tibet and the highest river in the world, as shown in Fig. 1. For a long time it flows through dry and flat region of southern Tibet before it breaks through the Himalayas near the Namcha Barwa peak at about 7755 m.a.s.l. In southeast Tibet it turns south and flows swiftly through the Great Canyon of Yarlung Zangbo, which is the deepest valley in the world. The Yarlung Zangbo River has five reaches: Lasa, Palong Zangbo, Duoxiong Zangbo, Niyang, and Nianchu rivers. Precipitation in the Yarlung Zangbo River increases gradually from 200 mm to 6000 mm. The average annual streamflow is 5070 m^3 s^{-1}.

Most of the water resources planning in China adopt hydrological data from 1960s to 2000 because this period is a full hydrological cycle. Daily flow data from 1961 to 2000 in 3 gauging stations (Nugesha, Yangcun and Nuxia), the only three gauging stations in the main branch of the Yarlung Zangbo River, were used to evaluate the hydrological alteration. The drainage area of Nugesha, Yangcun and Nuxia are respectively 106 478 km^2, 153 191 km^2 and 189 843 km^2 (Table I). Fig. 1 identifies the 3 gauging stations and the location of the Yarlung Zangbo River.

Table I. Stream gauging stations used in this study.

Station name	Drainage area (km^2)	Location (°)	
		Longitude	Latitude
Nugesha	10 6478	89.75E	29.30N
Yangcun	15 3191	91.88E	29.28N
Nuxia	18 9843	94.57E	29.47N

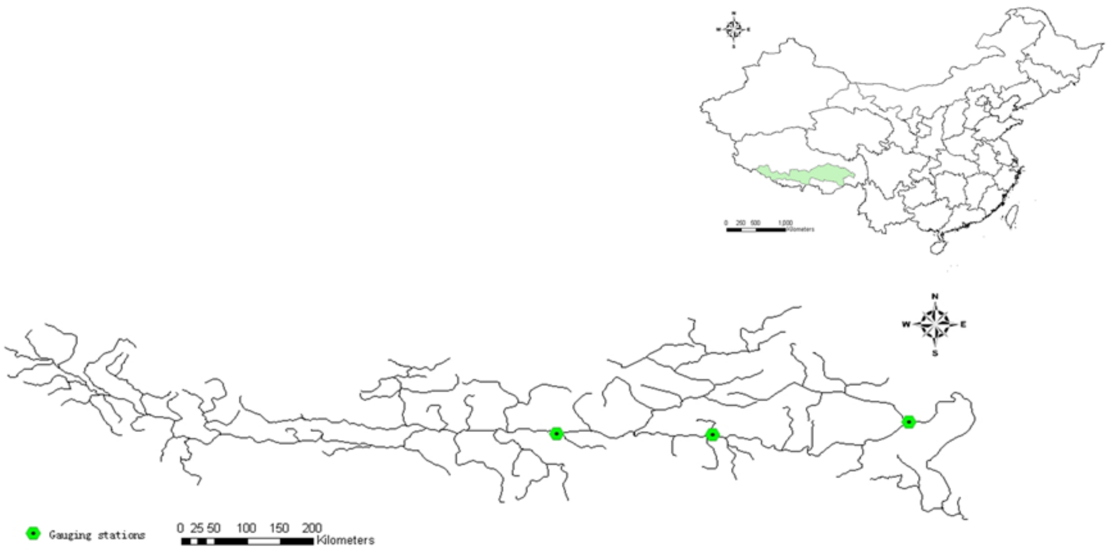


Fig. 1. Map of the Yarlung Zangbo River.

Tibet's population has grown about 140% in five decades, which is the fastest population growth rate in China (Fig. 2). Tibet had 2.51 million permanent residents in 2000 compared with 1.14 million in 1951, with a sharp increase before 1980 (Tibet Statistical Yearbook 2001).

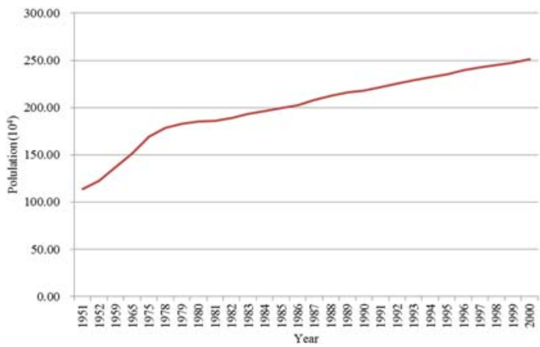


Fig. 2. Population from 1951 to 2000 in Tibet.

Agricultural water accounts for about 80% of the total water consumption. Fig. 3 shows the gross domestic product of agriculture, in which the indices are calculated at comparable prices. The domestic product of agriculture increased sharply around 1980, which could result in sharp water consumption (Tibet Statistical Yearbook 2001).

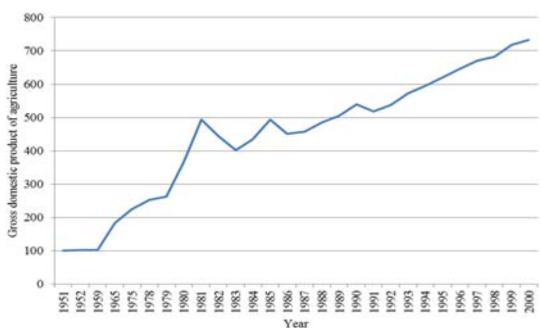


Fig. 3. Gross domestic product of agriculture from 1951 to 2000 in Tibet.

Due to population growth and agricultural development, from 1980s the environment had changed and the hydrological circle is altered because of water resources development in the Yarlung Zangbo River basin. So the period was divided into two periods of pre-1980 and post-1980.

2.2. Method

Range of Variability Approach (RVA) was used in this study to evaluate the hydrological alterations. The RVA, primarily its component the Indicators of Hydrologic Alteration (IHA) software (The Nature Conservancy 2009), has been applied most intensively since its inception, in more than 30 flow-related studies in the United States of America, Canada, Australia, and South Africa. The IHA will calculate a total of 67 statistical parameters. These parameters are subdivided into 2 groups, the IHA parameters and the Environmental Flow Component (EFC) parameters. There are 33 IHA parameters and 34 EFC parameters. The RVA aims to provide a comprehensive statistical characterization of ecologically relevant features of a flow regime, where the natural range of hydrological variation is described using different hydrological indices derived from long-term, daily flow records (Richter *et al.* 1998).

The IHA parameters are grouped into five categories based on regime characteristics with flow management targets set as ranges of variation in each index, which can be monitored and refined over time (Richter *et al.* 1996). In the majority of cases the methodology has been used in trend analysis of pre- and post-regulation scenarios, to characterize the flow-related changes experienced by regulated rivers.

Relevant flow parameters of IHA are categorized into five groups addressing the magnitude, timing, frequency, duration, and rate of change (The Nature Conservancy 2006). They are characterized as follows:

- **Group 1.** Twelve monthly mean flows describe the normal flow condition.
- **Group 2.** Ten parameters describe the magnitude and duration of annual extreme flows, including 1-, 3-, 7-, 30-, and 90-day annual maxima and minima encompassing the daily, weekly, monthly and seasonal cycles.
- **Group 3.** Julian dates for 1-day annual maximum and minimum that indicate the timing of annual extreme flows.
- **Group 4.** Four parameters, number of low pulses within each water year, mean or median duration of low pulses (days), number of high pulses within each water year, mean or median duration of high pulses (days), that refer to the frequency and duration of high and low pulses. The high pulses are periods within a year when the daily flows are above the 75th percentile daily flow of the pre-impact time period. The low pulses are periods within a year when the daily flows are below the 25th percentile daily flow of the pre-impact time period (Richter *et al.* 1996). These parameters are classified as greater than or less than a specified threshold.
- **Group 5.** Three parameters, rise rates (mean or median of all positive differences between consecutive daily values), fall rates (mean or median of all negative differences between consecutive daily values) and number of hydrologic reversal, that indicate the numbers and mean rates of both positive and negative changes of flow in two

consecutive days. Reversals are calculated by dividing the hydrologic record into "rising" and "falling" periods, which correspond to periods in which daily changes in flows are either positive or negative, respectively.

Relationship between RVA parameters and ecological systems is shown in Table II (Richter *et al.* 1996; 1997; 1998a; 1998b).

The Environment Flow Components (EFCs) parameters are further divided into five different types: i) low flows (mean or median values of low flows during each calendar month), ii) extreme low flows (frequency of extreme low flows during each water year or season), iii) high flow pulses (frequency of high flow pulses during each water year or season), iv) small floods (frequency of small floods during each water year or season), and v) large floods (frequency of large floods during each water year or season). River hydrographs can be divided into a repeating set of hydrographic patterns that are ecologically relevant and must be maintained in order to sustain riverine ecological integrity (The Nature Conservancy 2009).

All flows greater than high flow threshold, 75^{th} percentile of daily flows, are classified as high flows, and all flows less than or equal to this threshold are classified as low flows. All flows less than or equal to low flow threshold, 50^{th} percentile of daily flows, are classified as low flow events. All high flow events that have a peak flow greater than or equal to small flood minimum peak flow, 2 year return interval, and less than the peak flow value for large floods will be assigned to the small flood class. All high flow events that have a peak flow greater than or equal to large flood minimum peak flow, 10 year return interval, will be assigned to the large flood class (The Nature Conservancy 2009).

We added one hydrologic parameter, the alteration ratio, which can reflect relative alteration. Alteration ratio can be calculated as:

$$\text{Alteratio} = ((\text{Post-Pre})/\text{Pre}) * 100 \tag{1}$$

wherein "Alteratio" is the alteration ratio, "Post" is the median flow of the post-impact period after 1980, "Pre" is the median flow of the pre-impact period before 1979. The absolute value of the alteration ratio is higher when the hydrologic conditions change much and vice versa. A positive value indicates that flow is increasing; a negative value indicates that flow is decreasing.

3. Results and discussion

For each of the three gauging station, the value of each of the 33 IHA, 34 EFC, and one additional parameters were computed. Only the results of nine parameters, i.e. monthly flows for February, monthly flows for August, monthly flows alteration ratio, 1-day minimum flows, 1-day maximum flows, extreme low flows, small floods, low flow pulse duration and high flow pulse duration, are selected for analysis because these nine parameters are the most greatly affected by human induced development in the Yarlung Zangbo River. The period of 1961-2000 was divided into two periods of post-impact period after 1980 and pre-impact period before 1979. Hydrological alterations were analyzed based on two periods.

3.1. Magnitude of monthly water conditions

The magnitude of discharge at any given time interval is simply the amount of water moving past a fixed location per unit time. Magnitude can refer either to absolute or to relative discharge (Stewardson, Gippel 2003). Maximum and minimum

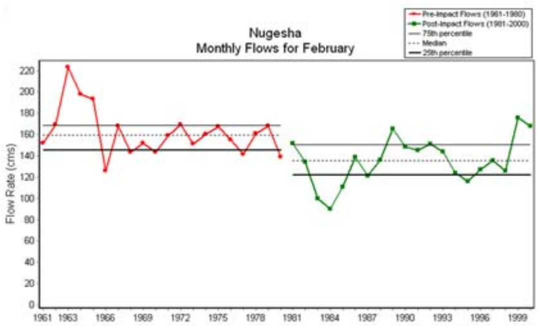
Table II. Relationship between RVA parameters and ecological systems (The Nature Conservancy 2009).

RVA parameters	Relationship between RVA parameters and ecological systems
1. Magnitude of monthly water conditions	A measure of the availability or suitability of habitat. It defines such habitat attributes as wetted area, habitat volume, or position of a water table relative to wetland or riparian plant rooting zones.
2. Magnitude and duration of annual extreme water conditions	Plays an important role in regulating the structure and function of rivers, floodplains, and estuaries.
3. Timing of annual extreme water conditions	Determines whether certain life-cycle requirements are met, or can influence the degree of stress or mortality associated with extreme water conditions such as floods or droughts.
4. Frequency and duration of high and low flow pulses	Responsible for reproduction or mortality events for various species, thereby influencing population dynamics. It says whether a particular life-cycle phase can be completed, or the degree to which stressful effects such as inundation or desiccation can accumulate.
5. Rate and frequency of water condition changes	Relates to the stranding of certain organisms along the water's edge or in ponded depressions, or the ability of plant roots to maintain contact with phreatic water supplies.

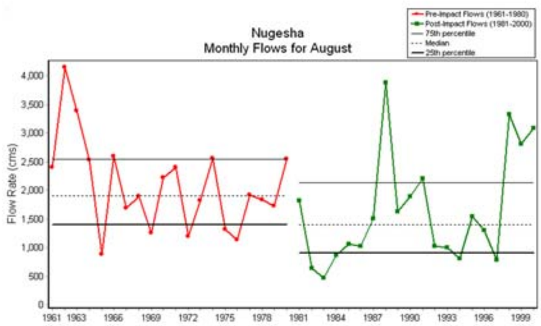
magnitudes of flow vary with climate and watershed size both within and among river systems (Gurnell *et al.* 1998).

The hydrologic regime of the Yarlung Zangbo River has been altered over the past 40 years. Annual flow decreased more than 10% at three gauging stations and even up to 30% at Nugesha gauging station. Monthly flows for February in dry season and monthly flows for August in flood season were selected to analyze monthly water condition alterations, which indicated magnitude alteration in the Yarlung Zangbo River. Median monthly flows for February, the driest month, at Nugesha, Yangcun and Nuxia respectively decreased 14.8%, 11.2% and 3.6% (Fig. 4a, c and e). Median monthly flows for August, the wettest month, account for 24% of the total annual flows and respectively decreased 26.2%, 21.7% and 26% at Nugesha, Yangcun and Nuxia (Fig. 4b, d and f). The decreasing trend of flow is obvious.

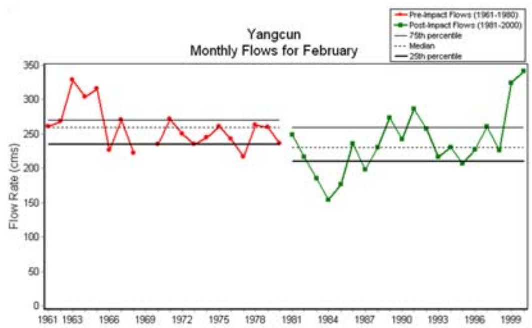
During most months flow decreased and the largest monthly alterations occurred during the mid-autumn (Fig. 5). Annual alterations are respectively -19.2%, -10.6% and -13% at Nugesha, Yangcun and



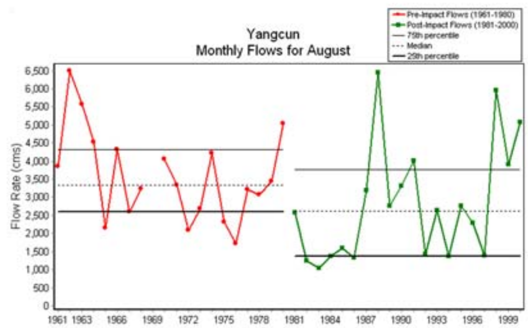
a. Monthly flows for February at Nugesha



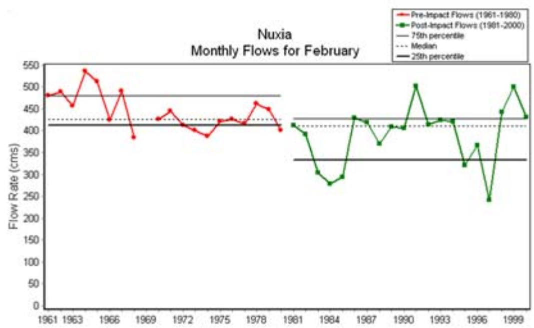
b. Monthly flows for August at Nugesha



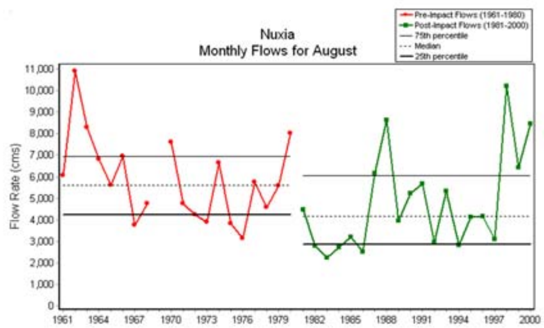
c. Monthly flows for February at Yangcun



d. Monthly flows for August at Yangcun



e. Monthly flows for February at Nuxia



f. Monthly flows for August at Nuxia

Fig. 4. Monthly flows of Yanrlung Zangbo River in February and August in the three gauging stations of for pre- and post-impact periods.

Nuxia, which indicate that flow in Yarlung Zangbo River decreased more than ten percent.

In 2000 the population of the Yarlung Zangbo River basin reaches only 1.3 million people, while its area is 239 228 km^2. Its population density thus is 5.5 ind. km^{-2} and only 1.4×10^9 m^3 water, 0.8% of total water resources, was consumed (Tibet Statistical Yearbook 2001). Therefore, human being activities were not the main drivers that altered hydrology.

3.2. Magnitude and duration of annual extreme water conditions

The extreme hydrologic events play an important role in regulating the structure and function of rivers, floodplains, and estuaries. Low frequency but high intensity events, such as severe floods or droughts, may have long-lasting effects on the structure and function of lotic ecosystems, as well as on man-made structures and human uses of rivers, floodplains, and estuaries (Sparks, Spink 1998).

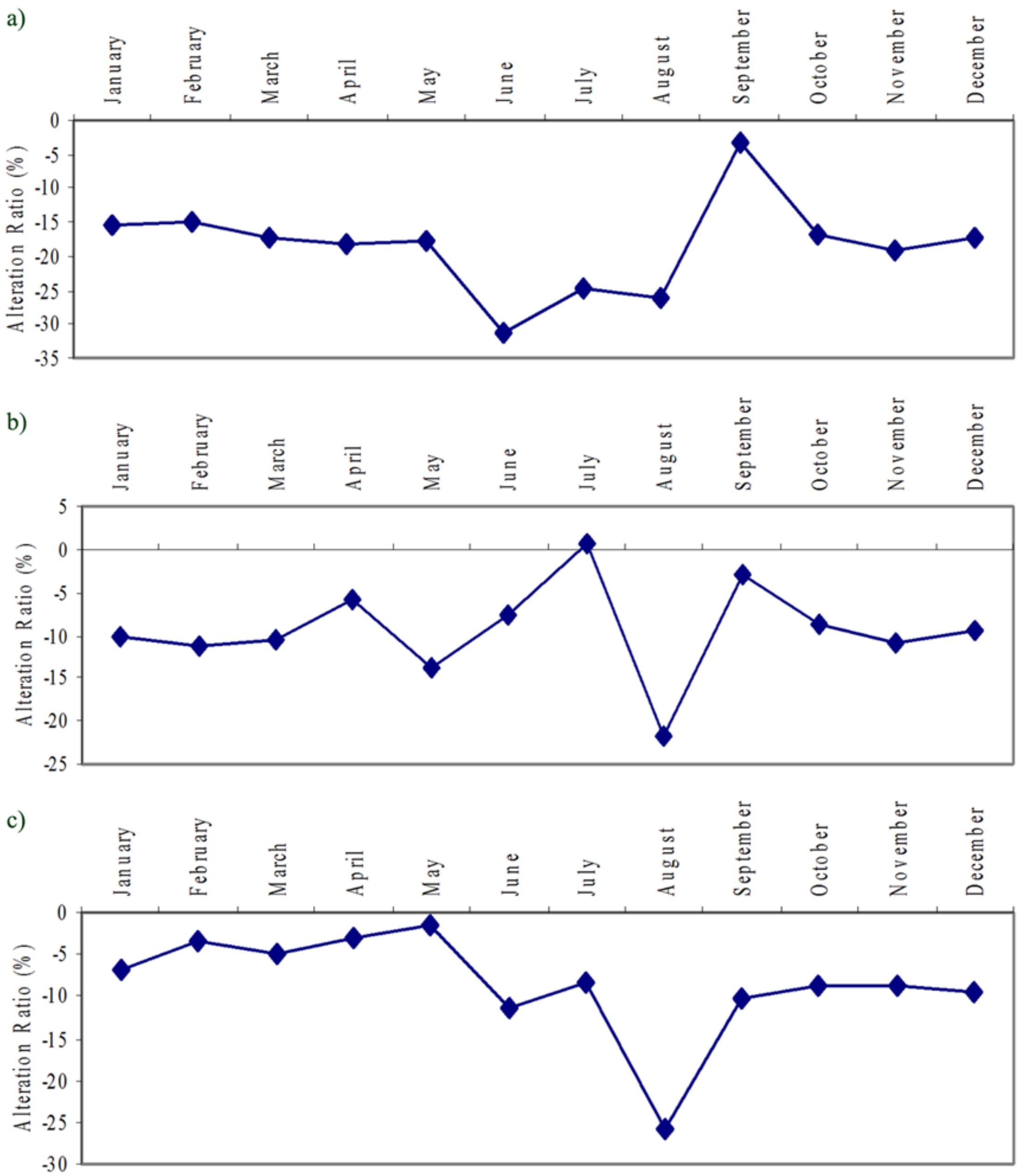
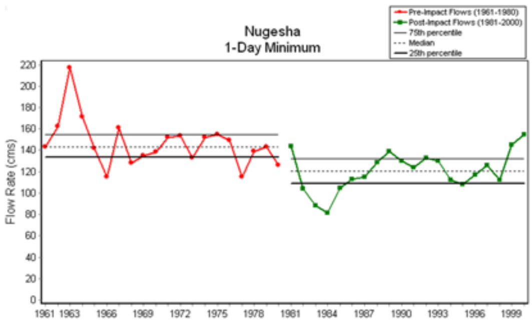


Fig. 5. Monthly flows alteration ratio (1961-2000) in Yanrlung Zangbo River at three gauging stations: a) Nugesha, b) Yangcun, c) Nuxia.

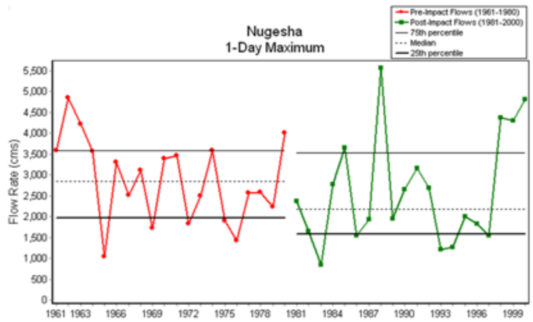
1-day minimum and maximum flow are minimum and maximum flow in a year. The 1-day minimum flows and 1-day maximum flows at these three stations all show decreases. The 1-day minimum flows at these three stations decreased 15.7%, 12.4% and 9.3% (Fig. 6a, c and e). The 1-day maximum flows at these three stations decreased 23.3%, 23.3% and 10.8% (Fig. 6b, d and f).

The extreme low flow duration during 1981--2000 was more than twice the average number during 1961-1980, and increased 333.3%, 405.9% and 225.7% at the three stations (Fig. 7a, c and e). Low flows are necessary for many processes in riverine ecosystem functioning. If the low flow situation reaches extremely low levels, however, ecological communities are impaired. Extreme low flows may be necessary to dry out floodplain areas and enable certain species of plants to regenerate. On the other hand, water chemistry and dissolved oxygen availability can become highly stressful to many organisms during extreme low flow (Chícharo *et al.* 2009).

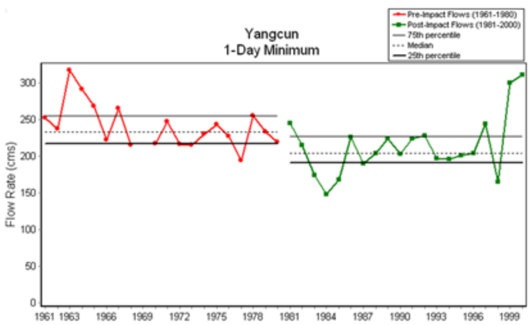
The small flood duration at Nugesha increased 9.0%, whereas decreased 36.5% at Yangcun and 56.5% at Nuxia (Fig. 7b, d and f). Small floods cause considerable addition of organic and inorganic matter to the water. Small floods include all river rises that overtop the main channel except for more



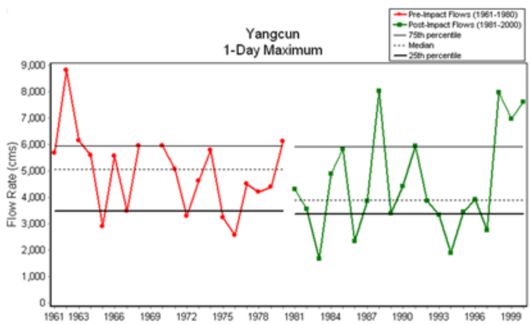
a. 1-day minimum flows at Nugesha



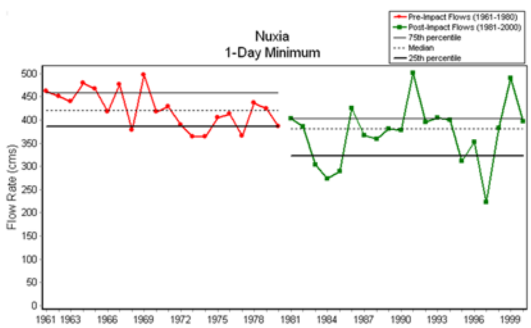
b. 1-day maximum flows at Nugesha



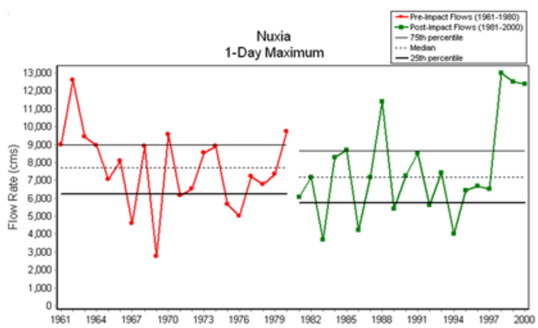
c. 1-day minimum flows at Yangcun



d. 1-day maximum flows at Yangcun



e. 1-day minimum flows at Nuxia



f. 1-day maximum flows at Nuxia

Fig. 6. 1-day minimum flows and 1-day maximum flows in Yanrlung Zangbo River at three gauging stations.

extreme floods, which provide chance for fish and other mobile organisms to move through rivers and up to floodplains to access additional habitats.

3.3. Frequency and duration of high and low flow pulses

The frequency refers to how often a flow above a given magnitude recurs over some specified time interval. The duration is the period of time associated with a specific flow condition. Duration can be defined relative to a particular flow event or a composite expressed over a specified time period (Richter *et al.* 1996).

During the periods of 1961-2000, the low flow pulse duration showed significant upward trends, increased 1030% at Nugesha and 506.1% at Yangcun (Fig. 8a and c). An exception is Nuxia (Fig. 8e), which showed a slight change. Low flow pulses are sustained by groundwater discharge into the river, which impose a fundamental constraint on a river's aquatic communities and a strong influence on the diversity and number of organisms that can live in the river.

The high flow pulse duration decreased 8.3%, 18.3% and 54.8% in those three stations (Fig. 8b, d and f). High flow pulses include any water rises that do not overtop the channel banks, which provide important and necessary disruptions in low flows. High flow pulses are vital for reducing levels of various elements in rivers by providing relief from

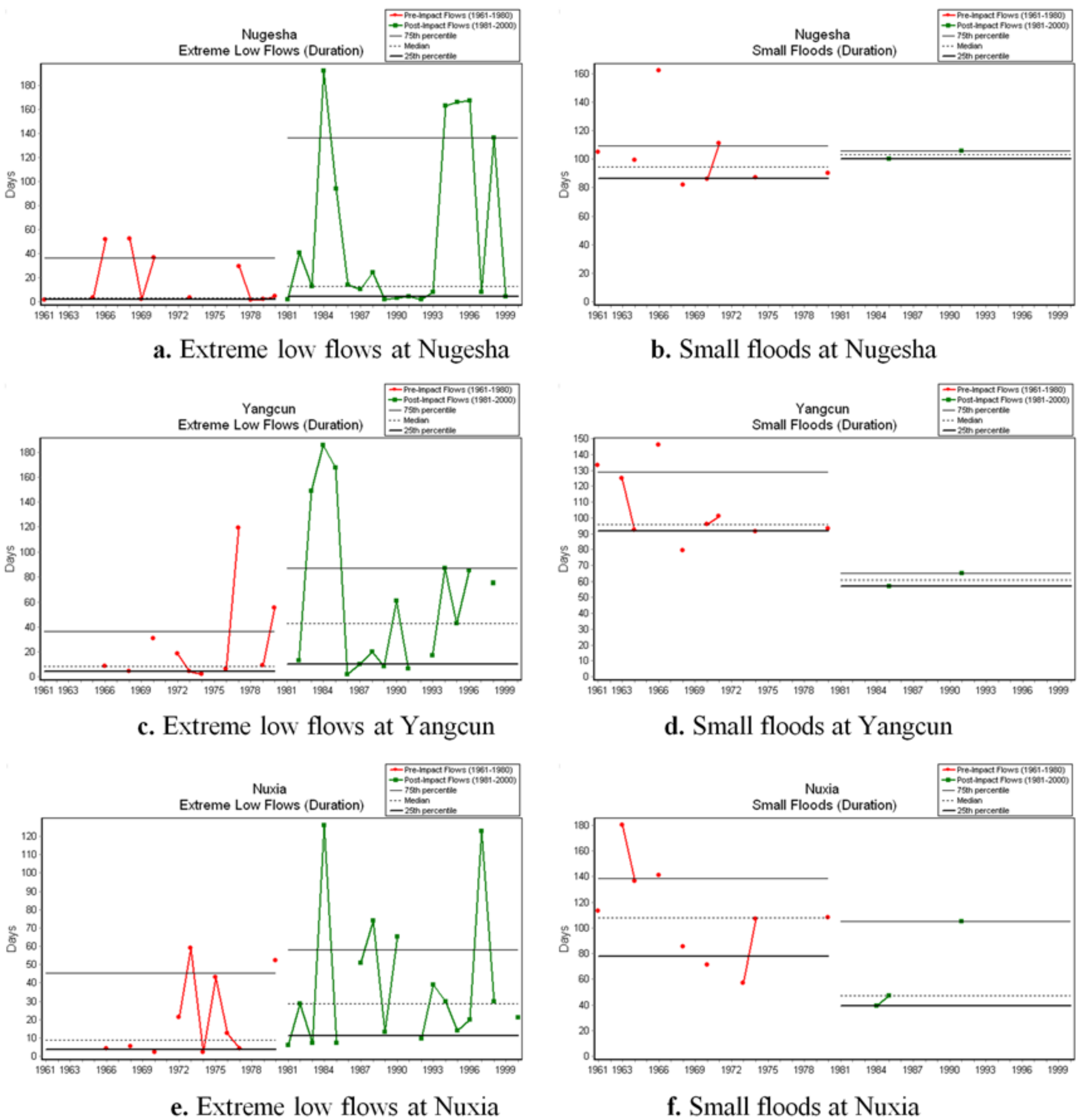


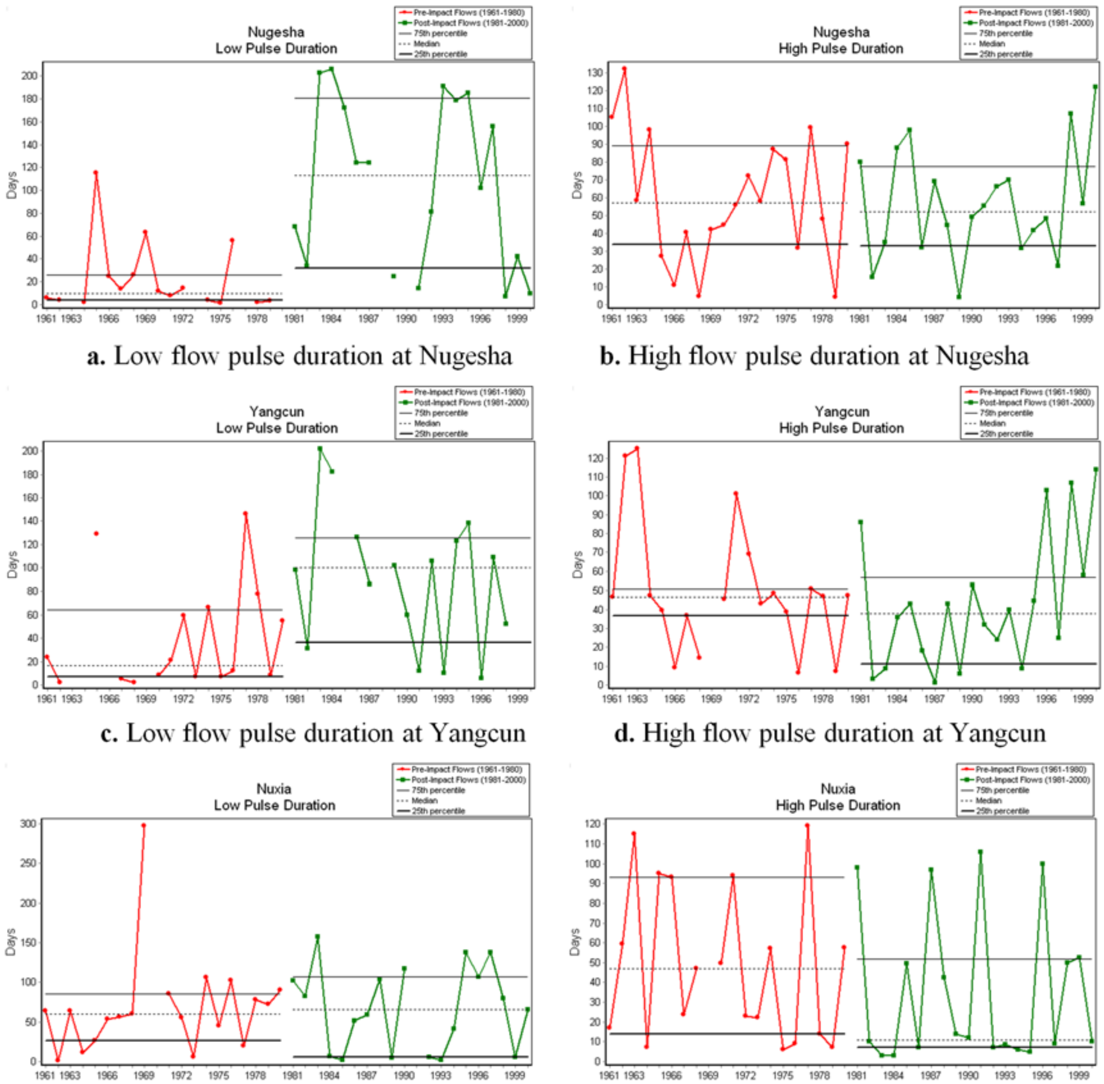
Fig. 7. Extreme low flows and small floods.

higher water temperatures or low oxygen conditions caused by low flows, and delivering a nourishing subsidy. High flows imply increased hazards for water quality because various pollutants can be washed into the river. Flooding alterations can disturb anoxia in riparian soils, which may lead to plant death.

Extreme water conditions became more serious and the ecosystems in the Yarlung Zangbo River are degrading. Important hydrologic parameters, such as low pulse duration and high pulse duration that are closely related to ecosystems, changed even more than 10 times.

Hydrologic regimes, which are strongly correlated with many critical physicochemical characteristics of rivers, such as water temperature, channel geomorphology, and habitat diversity, can be considered a "master variable" that limits the distribution and abundance of riverine species (Poff *et al.* 1997). Aquatic ecosystems rely on hydrologic regimes (flooding and drying cycles) that are critical to sustaining a variety of plant and animal communities (Chen, Zhao 2011). Modifications of hydrologic regimes can indirectly alter the composition, structure, or function of aquatic, riparian, and wetland ecosystems through their effects on physical habitat characteristics, including water temperature, oxygen content, water chemistry, and substrate particle sizes (Richter *et al.* 1996).

The importance of hydrology for living communities was also mentioned by Zalewski (2002) in the light of ecohydrology concept. The pattern



a. Low flow pulse duration at Nugesha **b.** High flow pulse duration at Nugesha

c. Low flow pulse duration at Yangcun **d.** High flow pulse duration at Yangcun

e. Low flow pulse duration at Nuxia **f.** High flow pulse duration at Nuxia

Fig. 8. Low pulse duration and high pulse duration.

and intensity of hydrological variability significantly moderate biotic structure and activity, which in turn regulate abiotic components of the environment (Zalewski 2002).

It should be also mentioned that climat change may alter the hydrological cycle and cause glacial retreat. In this region, glacial retreat is impacting the hydrological processes since the 1960s, and has caused an increase of more than 5.5% in river runoff (Yao *et al.* 2007). As also mentioned by Cao *et al.* (2006) climatic change had a significant effect on the seasonal variation of river discharge.

Conclusions

This paper outlines the role of Range of Variability Approach (RVA) as a tool for hydrological alteration analysis based on daily flow data. The results indicate that hydrological alterations in the Yarlung Zangbo River, the largest river in Qinghai-Tibet plateau, are consequences of global climate and environmental changes. The hydrological alterations were assessed on the basis of following parameters: magnitude, frequency, duration, timing, and rate of change of hydrologic conditions.

The method proposed can be used for coupling hydrologic and environmental approaches based on the assumption that hydrological alterations reflect changes of climate and environment. For example, in this research extreme hydrologic parameters including extreme low flow duration, low pulse duration and high pulse duration changed sharply. As the important drivers of ecosystems they may indicate present or expected alterations in the existing biota, and thus should be monitored, controlled and maintained in an appropriate range.

Future research should investigate the role of climate change and anthropogenic activities in hydrological alterations. The trends of population density and agricultural activities in this area are growing and can further imply hydrological alterations. Ecosystem investigation, such as fish sampling, would provide stronger insight into the relationship between hydrological alterations and ecosystem degradation. Flow regimes should be further investigated using hydrological model to improve our understanding of hydrological cycle. The management agency should maintain flow regime in water resources management plan and protect the Yarlung Zangbo River to avoid possible ecosystem degradation.

Acknowledgments

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