Analysis on the adaptive countermeasures to ecological management under changing environment in the Tarim River Basin, China

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Abstract. This article aims to explore the adaptive utilization strategies of flow regime versus traditional practices in the context of climate change and human activities in the arid area. The study presents quantitative analysis of climatic and anthropogenic factors to streamflow alteration in the Tarim River Basin (TRB) using the Budyko method and adaptive utilization strategies to eco-hydrological regime by comparing the applicability between autoregressive moving average model (ARMA) model and combined regression model. Our results suggest that human activities played a dominant role in streamflow deduction in the mainstream with contribution of 120.7%~190.1%. While in the headstreams, climatic variables were the primary determinant of streamflow by 56.5~152.6% of the increase. The comparison revealed that combined regression model performed better than ARMA model with the qualified rate of 80.49~90.24%. Based on the forecasts of streamflow for different purposes, the adaptive utilization scheme of water flow is established from the perspective of time and space. Our study presents an effective water resources scheduling scheme for the ecological environment and provides references for ecological protection and water allocation in the arid area.

1. Introduction

The flow regime is a primary determinant of the structure and function of aquatic and riparian ecosystems for streams and rivers, especially in the arid area [1]. In recent years, owing to the competing water demands for human and environment, the flow available for environmental purposes is generally insufficient to meet all ecological flow requirements [2]. To address this problem, optimization approaches have been adopted to obtain the minimum ecological water requirement in the earliest stages, the standard streamflow to maintain the step change of flow in different seasons (low-flow period, pre-high-flow period, high-flow period) or different months, and currently a dynamic hydrological process with seasonal fluctuation [3][4]. However, all of the methods depend on an assumed known volume of available streamflow or the historical natural flow hydrograph. Moreover, changes in climate conditions and anthropogenic activities have been contributing to significant alterations in the eco-hydrological patterns in the TRB, the approaches are not suitable for use in this basin due to the varying flows available for environmental purposes from year to year [5].
Consequently, there is a need to develop an adaptive optimization framework for scheduling environmental flow management alternatives under varied environmental water availability conditions. The objectives of this paper are to: (1) detect potential impacts of climate change and anthropogenic activities on streamflow alterations based on the Budyko equations; and (2) explore an adaptive utilization scheme of water flow from the perspective of time and space based on the prediction equations of streamflow for different purposes in the TRB.

2. Materials and Methods

2.1. Study area and Data sources
The TRB is the longest inland river in China, once fed by 144 branch rivers belonging to 9 major river systems. Owning to natural environmental changes and the development of dam construction and agricultural irrigation, many rivers gradually lost their hydraulic connections with the Tarim River [6]. In recent years, only three headstreams (Aksu, Yarkant and Hotan River) have natural connection with it. The TRB has a continental extreme arid climate with rare precipitation and strong evaporation. The meteorological data over the period of 1960 to 2015 were obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn). Annual streamflow and water consumption data during 1960~2015 were collected from the Tarim River Basin Administration. Land use and vegetation data in 1980, 1990, 2000, 2010 and 2015 were obtained from Resources and environment science data center in Chinese academy of sciences (http://www.resdc.cn).

2.2. Methods
The Pettitt test in trend analysis is used for determining the abrupt change point to reducing errors or leakage test from a single method [7]. While the response of streamflow variability to climate change and human activities are quantified by Choudhury-Yang equation based on the Budyko framework [8]. Furthermore, the adaptive utilization strategies to eco-hydrological regime are analysed by comparison of the applicability between ARMA model and combined regression model [9].

3. Results

3.1 Hydrological Regimes
The Pettitt test was used to examine the trends in the annual runoff, precipitation and potential evapotranspiration series of 1960~2015 and determine change points of time series of precipitation, potential evapotranspiration and streamflow. Streamflow in headstreams show significant upward trends consistently. However, streamflow in the Tarim River shows a slight decreasing trend with a slope of -0.018×10^8 m^3/year (p<0.05). The change points occurred in 1986 (p<0.05) firstly for precipitation and potential evapotranspiration at thirteen Meteorological stations within the basin. Unlike precipitation and potential evapotranspiration, the Pettitt test of streamflow illustrated the turning point for streamflow is 1972 in the Tarim river during the period of 1960~2015, while the turning points for streamflow are 1993, 1993 and 2000 in headstreams within the basin (Figure 1). Therefore, the streamflow alterations in the Tarim River were divided into three periods: the prior impacted period (1960~1972), the post impacted period I (1973~1986) and the post impacted period II (1987~2015). While the streamflow alterations in headstreams were separated: the prior impacted period (1960~1985), the post impacted period I (1986~1992) and the post impacted period II (1993~2015).

Figure 1. The trend of streamflow in headstreams and mainstream in the Tarim River Basin during 1960~2015 (Note: p value is the significance level of Pettitt-test)
3.2 Assessment of the causes of streamflow variation

Quantitative assessment for contribution of climatic change and human activity to streamflow alterations is given in Figure 2. Note that a positive percentage value represents a beneficial impact that increase streamflow while a negative percentage value is for negative impact which decreases streamflow. The results of Choudhury-Yang equation showed that climate change played a leading role in increase of streamflow in headstreams while human activity was the dominant factor to streamflow deduction in mainstream in the TRB. In the headstreams, climate change accounted for 56.5~150.6% during the post-impacted period I. During the post impacted period II, contribution of climate change to streamflow alteration increased to 148.4~152.6%. However, contribution of human activities in mainstream accounted for 120.7% of the total deduction in the streamflow during the post impacted period I and for 190.1% during the post impacted period II. In fact, climate change contributed a positive impact on streamflow in the TRB likely because increase in temperature caused more snow melting which were accumulated at the mountainous areas. Apparently the inconsistency of contributions between headstreams and mainstream revealed that human activity played a major role in streamflow deduction in mainstream within the basin.

Cultivated area expansion and agricultural irrigation, dam construction are the respective factors of human activity in the TRB. Seen from Figure 3, cultivated area increased from 24502km² in 1980 to 37203km² in 2015. The dramatic change indicated that the demand of agricultural irrigation from oasis extension was obviously deleterious to water high-efficiency and reasonable utilization of water resources. Moreover, water consumption in headstreams have been persistently increasing from 1960 to 2015, while mainstream shows a slight downward trend for the reduction of inflow. Figure 3 shows that water consumption taken from the three great plain reservoirs during 1981 to 2015 were significantly increased. It indicates that more and more ecological water is consumed for the excessive expansion of irrigated area and a large amount of evaporation and seepage losses from reservoirs. Considering the slow and partly uncontrollable influence of climatic factors, adaptive utilization measures should be taken to restrain impacts of human activities on streamflow alterations in order to restore ecological integrity in the TRB.

![Figure 2](image2.png)  
**Figure 2.** Comparison of the relative contributions of climate change and human activities to streamflow alterations in headstreams (Aksu, Yarkant and Hotan River) and mainstream in the TRB in the post impacted period I and II.

![Figure 3](image3.png)  
**Figure 3.** Plots of water consumption in headstreams (including Aksu, Yarkant, and Hotan River) and mainstream in the TRB in different ages, water consumption of three plain reservoirs (WCPR) and cultivated area in 1980, 1990, 2000, 2010, and 2015.

### 3.3 The adaptive utilization strategies to eco-hydrological regime

Table 1 lists the equations and significance of the trend, periodic and random component of eco-hydrological series using the combined regression model. The trend component of streamflow in headstreams showed significant upward trends, while the trend component of streamflow in mainstream showed a slight decreasing trend. While climate change contributed a positive impact on...
streamflow in the TRB, the inconsistency between headstreams and mainstream revealed that human activities have severely disturbed water distribution over time and space. The irrigation discharge procedure in time and space according to the trend of streamflow process can be effectively implemented and is conducive to the healthy development of the ecological environment. The equations of periodic component implied that the periods are 2, 3, 7, 17 years in the Aksu River, 3, 8, 9, 17 years in the Yarkant River, 7, 13, 17 years in the Hotan River and 3, 9, 17 years in the Tarim River. According to the periods of eco-hydrological series, we can develop the scheme of regular water allocation in different areas in the TRB.

Figure 4 shows the relationship between the observed runoff and forecast runoff using combined regression model and ARMA model. The time series (1960~2014) are divided into two periods: the calibration period (1960~1999) and the verification period (2000~2014). The results indicate that combined regression model performs better than ARMA model with the qualified rate of 80.49~90.24% in the TRB (Table 2). Compared with mainstream, simulations in headstreams have higher precision, especially in the Aksu River. Based on forecasts of available streamflow over the time period, the flow can be scheduled at various times and volumes and for various durations in order to maintain the ecological integrity of species with different flow requirements. Secondly, it can be managed at different spatial scales or different landscape scales according to the equations. Thirdly, a rational allocation of water resources is established in consideration of dry periods that species required over multiple year and irrigation water cycle for human.

| Eco-hydrological series | River | Equation | correlation coefficients | statistics | significance |
|-------------------------|-------|----------|-------------------------|------------|--------------|
| The trend component     | Aksu  | \( \hat{T}(t) = -82287.5 - 7903.9t + 5.4t^3 - 0.1t^4 + 155341.8t^{-1} - 36673.5t^{-2} + 76590\ln t \) | 0.777 | 9.581 | 0.000 |
|                        | Yarkant | \( \hat{T}(t) = -518694.5 - 17596.7t + 6.9t^3 - 0.1t^4 + 1189403.9t^{-1} - 575698.1t^{-2} + 282662.6t^{-3} + 76590\ln t \) | 0.381 | 1.065 | 0.402 |
|                        | Hotan  | \( \hat{T}(t) = -310594 - 9692.4t + 3.6t^3 + 695332.2t^{-1} - 346012.6t^{-2} + 158345.8t^{-3} + 76590\ln t \) | 0.497 | 2.063 | 0.068 |
|                        | Tarim  | \( \hat{T}(t) = -346583.4 - 14305.2t + 6.7t^3 - 0.1t^4 + 815811t^{-1} - 397146.2t^{-2} + 201885.5t^{-3} - 76590\ln t \) | 0.422 | 1.358 | 0.247 |
| The periodic component  | Aksu  | \( \hat{P}(t) = -2483.42 + 0.16x_{t-3} - 0.015x_{t-1} + 1.16x_{t-1} - 4.34x_{t-1} \) | 0.596 | 17.321 | 0.000 |
|                        | Yarkant | \( \hat{P}(t) = -88.25 - 0.004x_{t-3} + 0.344x_{t-3} - 0.21x_{t-3} - 1.21x_{t-3} \) | 0.392 | 32.285 | 0.071 |
|                        | Hotan  | \( \hat{P}(t) = -38.2 + 2.03x_{t-3} - 12.49x_{t-3} + 2.01x_{t-3} \) | 0.315 | 25.817 | 0.033 |
|                        | Tarim  | \( \hat{P}(t) = -2210.2 - 0.10x_{t-3} - 1.15x_{t-3} - 0.165x_{t-3} \) | 0.452 | 20.247 | 0.000 |
| The random component    | Aksu  | \( \hat{R}(t) = -91.59 - 0.52y_{t-1} + e_i - 0.98e_{i-1} \) | 0.256 | 18.789 | 0.002 |
|                        | Yarkant | \( \hat{R}(t) = 284.45 - 1.11y_{t-1} + e_i - 0.70e_{i-1} + 0.86e_{i-2} \) | 0.414 | 79.091 | 0.029 |
|                        | Hotan  | \( \hat{R}(t) = -62.93 - 0.41y_{t-1} + e_i + 0.99e_{i-1} \) | 0.302 | 68.193 | 0.015 |
|                        | Tarim  | \( \hat{R}(t) = -483.56 - 0.60y_{t-1} - 0.51y_{t-2} - 0.65y_{t-3} - 0.59y_{t-4} + 0.64e_{i-1} - 0.40e_{i-2} - 0.61e_{i-3} - 0.93e_{i-4} \) | 0.329 | 42.267 | 0.027 |
Figure 4. General trend of observed and simulated streamflow at a)Aksu River, b)Yarkant River, c)Hotan River and d)Tarim River during 1960–2014.

Table 2. Comparison of the qualified rate and average relative error simulated by ARMA and combined regression model for 1960–2014.

| River  | Aksu                  | Yarkant               | Hotan                  | Tarim                  |
|--------|-----------------------|-----------------------|------------------------|------------------------|
| Prediction model | ARM A(1,1) Combined regression model | ARM A(1,1) Combined regression model | ARM A(1,1) Combined regression model | ARM A(1,1) Combined regression model |
| Qualified Rate(%) | Calibration period 80.49 90.24 75.61 | 63.64 81.82 54.55 | 72.73 45.45 | 72.73 36.36 63.64 |
| Average relative error (%) | Calibration 11.65 9.29 14.95 | 11.34 16.1 | 13.02 19.46 | 19.46 13.38 |

4. Conclusion
This study presents a quantitative assessment of contributions of climatic and anthropogenic factors to streamflow alteration and adaptive utilization strategies to eco-hydrological regime in the TRB. The results indicated that climate change played a dominated role in increase of streamflow in headstreams,
while human activity was a leading factor to streamflow deduction in mainstream with the basin. According to the forecasts of ecological flows, an effective water resources scheduling scheme for the ecological environment was established from the perspective of time and space. The results in this study can provide a reference for environmental flow planning and management in the arid areas.

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