Assessing the impacts of changing climate and human activities on streamflow in the Hotan River, China
Xiaohua Fu, Bing Shen, Zengchuan Dong and Xiao Zhang

ABSTRACT

Climate change and intensified human activities are regarded as the two driving factors for most river systems having lost their connection with the Tarim River. The Hotan River is the second largest headstream of the Tarim River; therefore, it is important to determine the causes of its reduction in streamflow supply. Based on an analysis of changes in hydro-meteorological regime and the effects of direct human activities on streamflow, their contributions to the decrease in streamflow in different periods (natural period, 1964–1988; transition period, 1989–2002; post-transition period, 2003–2012) from the Hotan River to the Tarim River were quantified based on a double-mass curve of inflow and outflow in the Hotan River Basin. The results indicate that climatic changes reduced streamflow during the transition period yet increased streamflow during the post-transition period. Human activities reduced output by 73% in the transition period and by 127% in the post-transition period, which was significantly stronger than the contribution from the climate. Thus, human activities appear to be the main driving factor for the drop in streamflow from the Hotan River into the Tarim River. These results can be used as a reference for water resource planning and management.

Key words | double-mass curve, human activity, land use change, reservoir construction, streamflow evolution, Tarim River

INTRODUCTION

Hydrological cycles and water resource systems have been altered extensively by changing climate (mainly the change of air temperature and precipitation) and human activities (hydraulic projects, water withdrawal from river, land use/ covers change, etc.) (Bao et al. 2012; Patterson et al. 2015; Zhao et al. 2014; Chang et al. 2016; Pan et al. 2018). In recent years, a number of studies have used long-term historical data to perform qualitative and quantitative analyses of the impacts of changing climate and human activities on streamflow at different spatiotemporal scales (Dey & Mishra 2017). For example, Ren et al. (2002) analyzed the impacts of human activities on river runoff in northern China, including the Yellow River, Haihe River, Liaohe River, and Songhuajiang River Basin, and noted that, besides climatic change, an increase in the amount of water diverted from rivers was the direct reason for observed streamflow decreases. Wang & Hejazi (2011) proposed a conceptual model based on the Budyko hypothesis to quantify the climatic and direct human impact on mean annual streamflow for 413 watersheds in the contiguous United States, and concluded that climate- and human-induced changes were more severe in arid regions, while human impacts were likely to be more significant in watersheds with urban areas and extensive agricultural irrigation. Ye et al. (2013) empirically distinguished the relative effect of climatic variations and human activities using a coupled water and energy budgets analysis, and then confirmed their results with a quantitative
assessment. They found that the relative effects of the climate and human activities varied between sub-catchments and in the whole catchment in different decades.

The Tarim River, the longest inland river in China, is located in the arid region of northwest China. The main stream of the river is a typical pure dissipation inland river that does not yield water resources by itself, and is only supplied by runoff from headstreams (Fan et al. 2011; Bai et al. 2014). From the 18th century to the early 20th century, there were nine rivers with 144 tributaries flowing into the main stream of the Tarim River (Hartmann et al. 2016). However, most of these river systems have successively lost their connection with the Tarim River due to changing climatic conditions and intensified human activity. Currently, only three drainage systems, the Aksu, Hotan, and Yarkand Rivers, are connected to the main stream. Fewer headstreams flowing into the Tarim River and excessive water consumption in the upper and middle reaches have caused a series of environmental problems, including a reduction in flow volume, cessation of flow, deterioration in water quality, and an increase in areas of saline land (Ye et al. 2014a, 2014b). Furthermore, large tracts of the ecologically significant Euphrates poplar forest have died due to a lack of water, and the ‘green corridor,’ a vegetated corridor between the Taklimakan and Kumtag Deserts in northwest China, is rapidly shrinking. This vegetated strip helps to block the incursion of windblown sand into the surrounding oasis and protects the main road that traverses the desert region. Desertification is expected to accelerate if the corridor disappears, threatening the health of the Tarim River Basin and sustainable socioeconomic development, and degrading the ecological environment.

A statistically significant decreasing trend in streamflow has been detected in the Tarim River, and several hydrologists have tried to assess the contributions of changing climate and human activities to this decrease (Chen et al. 2006; Ling et al. 2014). Previous studies have revealed that the generation of surface runoff in glacial and snow-covered areas of arid and semi-arid regions is sensitive to changes in climate, while human activities have greatly restricted runoff in the plains surrounding oasis areas and main stream regions (Xu et al. 2013). However, the major driving factors that are reducing streamflow from the Hotan River into the Tarim River are not fully understood. Since these drivers vary between regions, it is crucial to evaluate the impact of climate change and human activities on streamflow at different spatial and temporal scales.

The Hotan River is one of the three remaining headstreams of the Tarim River. Although the Hotan River presently only discharges into the Tarim River during periods of high flow in summer, it affects the downstream water quantity and has an important role in the economic development and ecological conservation of the Tarim River Basin (Chen et al. 2008). Recent studies have demonstrated that climate change has affected the arid regions of northwestern China (Ma et al. 2008; Chen et al. 2009, 2015; Zhang et al. 2010). Increased air temperatures in the region have generated increased runoff from snow and glacial melting (Xu et al. 2010, 2011). However, the construction of the Wuluvati Reservoir and the expansion of irrigated agriculture have threatened natural ecosystems and led to water shortages in the Hotan River Basin (Hartmann et al. 2016). Furthermore, rapid population changes and unsustainable water use have greatly restricted economic growth and ecological conservation in the region. Accordingly, investigating the impact of recent climate variations and human activities on streamflow from the Hotan River into the Tarim River is critical for informing future water resource planning, ensuring sustainable water resource use, and maintaining the health of the river system. Therefore, the objectives of this study are to: (1) statistically detect variations of climatic factors and changes in the streamflow regime in the Hotan River; (2) analyze the effects of direct human activities on streamflow; and (3) further quantify the impacts of a changing climate and human activities on streamflow in the Hotan River. Addressing these objectives will provide a better understanding of the contributions of climatic variations and human activities to the streamflow of the Hotan River, which can be used to support local and global river management guidelines.

METHODS

Study area

The Hotan River Basin is located in northwest China (77° 25′ E–81° 43′ E, 54° 28′ N–40° 28′ N), covering an area of
48,870 km². It is the second largest headstream of the Tarim River, and accounts for 23.2% of the total supply (Figure 1). The climate in the area is characterized by a precipitation deficit and strong evaporation. The mean annual air temperature is 11.9 °C and the mean annual precipitation is 48.7 mm (1964–2012). Two tributaries of the Hotan River, the Karakax River and Yurunkax River, originate from the Karakorum and Kunlun Mountains, respectively. They converge in the Hotan River at Kuoshilashi. The Hotan Oasis is the largest oasis on the northern slope of the Kunlun Mountains, and includes Moyu, Hotan, Lop County, and Hotan City. It is the focal point of social and economic activities in the Hotan River Basin, and its survival and development are dependent on water from the Hotan River. Accordingly, the sustainable use of water resources in the Hotan River Basin is instrumental for ensuring sustainable socioeconomic development in the Hotan Oasis.

Uruwati and Tongguzlok are mountain-pass stations that monitor streamflow and control the volume of water flowing into the Karakax and Yurunkax Rivers, respectively. Tuzhiluke and Aigeliya, hydrological stations close to Kuoshilashi, control the volume of water flowing out of the Hotan Oasis via the Karakax and Yurunkax Rivers, respectively. The main stream of the Hotan River travels from Kuoshilashi to Xiaojiake for 319 km before merging with the Tarim River. Xiaota station, a hydrological station representative of the main stream of the Hotan River, controls its outflow into the Tarim River.

The Wuluwati Reservoir, built for irrigation, power generation, ecological, and flood control purposes, has a capacity of $3.47 \times 10^8$ m³ and is located on the Karakax River. The reservoir began storing water in 1998, and commenced operation in 2002. Since opening, the reservoir has ameliorated the impact of prolonged spring droughts and provides a water resource for land development in the Hotan River Basin. The Wuluwati Reservoir reduces the peak flow in the Karakax River to 500 m³ s⁻¹, and has moderated the 50-year return period peak flow of 1,510 m³ s⁻¹ to a safe discharge of 890 m³ s⁻¹, providing comprehensive flood control measures for the Karakax River.
Data

We used monthly streamflow data from three hydrological stations (Uruwati on the Karakax River, Tongguzlok on the Yurunkax River, and Xiaota on the Hotan River) from 1964 to 2012, and two additional stations (Tuzhiluke on the Karakax River and Aigeliya on the Yurunkax River) for 2007 to 2012. Streamflow data were obtained from the Xinjiang Uygur Autonomous Region Hydrology Statistics, the Hydrologic Data Yearbook, and the Administration of the Tarim River Basin. There are four standard meteorological stations that record daily precipitation and mean temperature around the Hotan River Basin (i.e. Pishan, Hotan, Yutian, and Alar station), which are maintained according to the standard methodology of the China Meteorological Administration (http://data.cma.cn); data from these stations were also used in our study. Land use data were obtained from time series of the land ecosystem classification dataset of China in five yearly steps (Xu et al. 2015). Population data for the Hotan Oasis between 1988 and 2012 were obtained from the China City Statistical Yearbook.

Three techniques were applied to determine time-varying trends in the data:

1. The Mann–Kendall trend test, recommended by the World Meteorological Organization, is one of the most widely used non-parametric tests for detecting trends in time series data. Recently, many researchers have applied this test to detect the significance of monotonic trends in recorded hydrologic time series, including streamflow, air temperature, precipitation, and water quality (such as Yue et al. 2002; Partal & Kahya 2006; Bouza-Deano et al. 2008; Dinpashoh et al. 2011).

2. The residual mass curve method plots the difference between annual and mean annual streamflow, which accumulates over time (Yu & Chen 2009). The cumulative anomaly method (as it is also known) is used to determine the periodicity of a time series and we use it here to determine long-term trends in streamflow.

3. The double-mass curve method is a simple, intuitive, and widely used approach to analyze the consistency, or long-term trends, of hydrological and meteorological elements (Jiang et al. 2011). The double-mass curve is a cumulative graph showing one quantity compared to the accumulation of another quantity during the same period. Breaks in the double-mass curve are caused by changes in the relationship between the variables, which can result from changes in the method of data collection or physical changes that affect the relationship (Searcy & Hardison 1960). Natural variation is not influenced by other factors; hence, it can be used as a reference variable. Conversely, test variables change according to natural variation plus other factors.

RESULTS AND DISCUSSION

Variations of climatic factors

Basin-scale averaged time-series of annual precipitation and mean air temperature for 1964–2012 are shown in Figure 2.

**Figure 2** | Time series of annual precipitation and mean air temperature in the Hotan River Basin. The dot-dashed lines are the linear trends for this period.
It can be seen that precipitation and air temperature show an increasing trend, which indicate that the climate of the Hotan River Basin has become warmer and wetter during the last five decades. The conclusion is consistent with previous annual scale studies (Xu et al. 2010).

In order to further investigate the variation of climatic factors during different periods and in different regions in the Hotan River Basin, the Z-scores of the Mann–Kendall test of monthly precipitation and mean air temperature for each station in the Hotan River Basin were calculated; results are shown in Figure 3. Most months displayed a non-significant increasing trend for monthly precipitation except for August at Alar station, which showed a statistically significant increase at $\alpha = 0.1$ level. Mean air temperature at most of the stations shows an increasing trend. Alar is the only station showing a decreasing trend in air temperature for the Hotan River Basin.

**Changes in streamflow regime**

**Trend analysis of streamflow time series**

The Z-scores of the Mann–Kendall test of annual streamflow at Uruwati and Tongguzlok stations for 1964–2012 were 0.66 and 1.01, respectively. The results of the Mann–Kendall test were below 1.64 for each station, indicating that the increase in intra-annual streamflow was not significant at the 90% confidence level. The Z-score of the Mann–Kendall test for annual streamflow at Xiaota station did not change significantly between 1964 and 2012 ($|Z| = 0.89 < 1.64$), suggesting that there was a small but non-significant decrease in annual streamflow in the main stream of the Hotan River.

The trends in monthly streamflow were variable (Figure 4). For example, flow of the Karakax River, as measured at Uruwati station, displayed increasing and decreasing trends in June and July, respectively, but with no statistical significance ($\alpha = 0.1$). August showed a significant decreasing trend ($\alpha = 0.01$), and the remaining nine months showed a significant increasing trend (September $\alpha = 0.05$, all other months $\alpha = 0.01$). At Tongguzlok station on the Yurunkax River, the monthly streamflow generally showed a consistent increasing trend: April $\alpha = 0.1$, May and September $\alpha = 0.05$, all other months $\alpha = 0.01$, although...
June, July, and August showed non-significant trends ($\alpha = 0.1$). Given that the water source and climate conditions in the Karakax and Yurunkax rivers are similar, the decrease in streamflow in the Karakax River during July and August, especially in August, is abnormal, and can be attributed to the impoundment of the Wuluwati Reservoir during the flood season. Xiaota station on the Hotan River showed a decreasing trend in July, August, and September; however, this trend was not significant ($\alpha = 0.1$). From these results, it was apparent that the decrease in summer streamflow in the Karakax River, specifically in August, was primarily responsible for the decrease in streamflow at Xiaota station.

Periodic analysis of streamflow time series

Considering that the lower reaches of the Hotan River run dry between October and May, the Hotan River presently discharges into the Tarim River only during periods of high flow (June–September). In this study, the periodic changes in streamflow were detected only by the residual mass curves of streamflow during the high-flow periods recorded at Uruwati, Tongguzlok, and Xiaota stations (Figure 5). The high-flow streamflow at Uruwati and Xiaota stations exhibited similar periodicities, and the difference product of the two hydrological stations abruptly changed at the start of the transition period from an increasing streamflow volume to a decreasing streamflow volume in 1988. However, the high-flow streamflow of the Yurunkax River (Tongguzlok station) showed a different periodicity, where the difference product of the Tongguzlok station remained stable until 1988, after which it began to decrease, and then began to increase again in 2000.

These results indicate that the headstream areas, the Karakax River, and main stream areas of the Hotan River experienced increased streamflow during 1964–1988 and drought conditions after 1989. However, the headstream area of the Yurunkax River showed more streamflow during 2001–2012, which contrasted with the drought conditions evident in the main stream and the other headstream, the Karakax River.

Analysis of abrupt changes in streamflow time series

Abrupt changes in streamflow were detected with accumulation curves of streamflow during high-flow periods in the Hotan River Basin (Figure 6).

The high-flow streamflow mass curve for Tongguzlok and Uruwati stations showed a consistent linear trend from 1964 to 2012, although there were some fluctuations. The consistency of this trend indicates that the streamflow of the Hotan River at the mountain pass was influenced by natural factors, and the impact of human activities was negligible. However, the accumulative curve of streamflow at Xiaota station only showed a consistent linear trend before 1988. Thereafter, the curve deviated downward from the original linear trend, indicating that the streamflow in the Hotan River was influenced by natural factors plus human activities after 1988.
Effects of direct human activities on streamflow

Influence of the construction of the Wuluwati Reservoir on the Hotan River streamflow

Glacier melt water and snowmelt are the main sources of mountain runoff; therefore, seasonal fluctuations can result in large differences in the partitioning of intra-annual streamflow in the Hotan River. Consequently, understanding the heterogeneity of intra-annual streamflow is important to ensure the appropriate allocation of water resources and improve flood regulation. Based on the change point of streamflow, and considering that the Wuluwati Reservoir commenced operation in 2002, the streamflow record was divided into three periods: the natural period (1964–1988), the transition period (1989–2002), and the post-transition period (2003–2012).

Table 1 shows the contributions of mean seasonal streamflow to the mean annual streamflow for the natural, transition, and post-transition periods. It is apparent that the distribution of streamflow is heterogeneous in the Hotan River. For example, the total percentage of streamflow occurring in the summer at Uruwati station during the natural period was 73.52%, with a corresponding value of 80.02% at Tongguzlok station. This reflects the characteristics of a river fed by glacial melt water and indicates that flooding control in the two tributaries of the Hotan River is a major problem. The percentage of total streamflow was smaller in spring, accounting for just 9.97 and 6.11% of total streamflow at Uruwati and Tongguzlok stations, respectively. Because of this high seasonality, natural streamflow cannot meet the demands of irrigation water in the region, limiting agricultural economic development. During the transition period, the mean annual contributions of summer streamflow at Uruwati and Tongguzlok stations were 69.09 and 78.59%, respectively, and those of spring streamflow were 11.64 and 6.14%, respectively. During the post-transition period, the mean annual contributions of summer streamflow at Uruwati and Tongguzlok stations were 58.76 and 75.46%, respectively, and those of spring streamflow was 17.70 and 7.09%, respectively. Compared with the natural period, there was no obvious change in the distribution of intra-annual streamflow in the Yurunkax River (Tongguzlok station). However, the proportion of summer streamflow at Uruwati station decreased significantly from 73.52 to 58.76% between the natural and post-transition periods, and the proportion of spring streamflow increased from 9.97 to 17.70%. This demonstrates that the construction of the Wuluwati Reservoir in 2002 has impacted the seasonal streamflow distribution at Uruwati station.

The Uruwati and Tongguzlok stations control streamflow from the Karakax and Yurunkax Rivers, respectively, while the Tuzhiluke and Aigeliya stations control outflow from the Hotan Oasis in the Karakax and Yurunkax Rivers, respectively. Based on the high-flow streamflow data (2007–2012) for these hydrologic stations, we analyzed the influence of the Wuluwati Reservoir, in terms of water loss (water consumption, evaporation and seepage loss, etc.), on the volume of water outflowing from the Hotan Oasis (Table 2).

Table 1 | Mean seasonal streamflow in different periods (natural period, 1964–1988; transition period, 1989–2002; post-transition period, 2003–2012) and the proportion of annual streamflow

<table>
<thead>
<tr>
<th>Stations</th>
<th>Period</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$10^3$ m$^3$</td>
<td>%</td>
<td>$10^3$ m$^3$</td>
<td>%</td>
</tr>
<tr>
<td>Uruwati</td>
<td>Natural</td>
<td>2.20</td>
<td>9.97</td>
<td>16.21</td>
<td>73.52</td>
</tr>
<tr>
<td></td>
<td>Transition</td>
<td>2.35</td>
<td>11.64</td>
<td>13.98</td>
<td>69.09</td>
</tr>
<tr>
<td></td>
<td>Post-transition</td>
<td>4.32</td>
<td>17.70</td>
<td>14.34</td>
<td>58.76</td>
</tr>
<tr>
<td>Tongguzlok</td>
<td>Natural</td>
<td>1.34</td>
<td>6.11</td>
<td>17.56</td>
<td>80.02</td>
</tr>
<tr>
<td></td>
<td>Transition</td>
<td>1.32</td>
<td>6.14</td>
<td>16.91</td>
<td>78.59</td>
</tr>
<tr>
<td></td>
<td>Post-transition</td>
<td>1.75</td>
<td>7.09</td>
<td>18.66</td>
<td>75.46</td>
</tr>
<tr>
<td>Xiaota</td>
<td>Natural</td>
<td>0.00</td>
<td>0.00</td>
<td>10.17</td>
<td>89.21</td>
</tr>
<tr>
<td></td>
<td>Transition</td>
<td>0.00</td>
<td>0.00</td>
<td>7.84</td>
<td>92.61</td>
</tr>
<tr>
<td></td>
<td>Post-transition</td>
<td>0.00</td>
<td>0.00</td>
<td>8.74</td>
<td>88.77</td>
</tr>
</tbody>
</table>
The amount of water lost in the Karakax River ($13.86 \times 10^8$ m$^3$) was significantly higher than that of the Yurunkax River ($8.92 \times 10^8$ m$^3$), despite the fact that the volume of water flowing into the Hotan Oasis from the Karakax River ($16.45 \times 10^8$ m$^3$) was less than that of the Yurunkax River ($20.89 \times 10^8$ m$^3$) (Table 2). The water loss rate in the middle reaches of the Hotan River was very high, and the water loss rate in the Karakax River (86.77%) was roughly double that of the Yurunkax River (46.18%). This suggests that the reduction of inflow into the Tarim River can be attributed to the reduction of water volume flowing out from the Hotan Oasis via the Karakax River. There are several possible reasons why the outflows of the Karakax River are smaller than those of Yurunkax River, for example, excessive water consumption in the oasis or reduction in the peak flow of the Wuluwati Reservoir during the flood season. Based on these findings, it is apparent that water diversion in the Karakax River requires investigation and possibly stricter controls. Because the Hotan River only discharges into the Tarim River during the flood season, marked reductions in the peak flow will cause substantial losses along the river, further reducing the volume of water joining the Tarim River because, when channel flow is considered, a greater flow volume results in less water loss.

Figure 7 presents an analysis of the monthly streamflow distribution at Uruwati, Tongguzlok, and Xiaota stations. The monthly distribution of streamflow at Uruwati and Tongguzlok stations did not vary markedly between natural and transition periods (Figure 7(a) and 7(b)). The streamflow for the two tributaries was greatest in July, followed by August. However, during the period 2003–2012, due to the commissioning of the Wuluwati Reservoir, the streamflow of the Karakax River decreased significantly in August,

### Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Karakax River</th>
<th>Yurunkax River</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uruwati</td>
<td>Tuzhiluke</td>
</tr>
<tr>
<td>2007</td>
<td>12.99</td>
<td>0.56</td>
</tr>
<tr>
<td>2008</td>
<td>14.45</td>
<td>1.51</td>
</tr>
<tr>
<td>2009</td>
<td>11.94</td>
<td>0.38</td>
</tr>
<tr>
<td>2010</td>
<td>23.52</td>
<td>7.10</td>
</tr>
<tr>
<td>2011</td>
<td>16.18</td>
<td>0.80</td>
</tr>
<tr>
<td>2012</td>
<td>19.61</td>
<td>5.16</td>
</tr>
<tr>
<td>Average</td>
<td>16.45</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Note: Loss is the difference between inflow and outflow from the Hotan Oasis; Loss rate is the ratio of loss to inflow.

**Figure 7** Impact of the Wuluwati Reservoir on the monthly distribution of streamflow for the (a) natural period; (b) transition period; and (c) post-transition period.
while that of the Yurunkax River increased (Figure 7(c)), causing flow processes in the two tributaries to lose synchronization and further increasing the losses in the main stream caused by reduced channel flow.

**Impact of population increase on the streamflow of the Hotan River**

The total population of the Hotan Oasis increased between 1988 and 2012 (Figure 8). Of the four counties in the oasis, Moyu County had the largest population, and showed an annually increasing trend. Population growth in Hotan City showed a marked increase during 2005, while the populations of Hotan and Lop Counties decreased. These trends might partly explain the reason why the water loss in the Karakax River was larger than that of the Yurunkax River.

Population is the main driver of the development and use of water resources. Thus, population increases will inevitably lead to an increase in domestic water demand. Due to the shortage of water resources in the Hotan River Basin combined with the pressures of population growth and changing climate, the available water in the region is being exploited, damaging the fragile ecological balance and further intensifying water resource supply issues.

**Impact of changes in land-use on Hotan River streamflow**

Population growth promotes economic growth, human activities directly affect the land use types in the Hotan Oasis, which inevitably lead to land use changes. Figure 9 shows the results of land-use classification for 1990, 2000, and 2010. We observed that forest, settlement, and wetland
areas had a non-significant fluctuation, while the unused land area decreased steadily, and the farmland area showed an ongoing increase in the Hotan Oasis from 1990 to 2010. The area of cultivated land increased from $1.60 \times 10^3$ km$^2$ in 1990 to approximately $1.87 \times 10^3$ km$^2$ in 2000, and to $2.15 \times 10^3$ km$^2$ in 2010. The unused land was converted to cultivated land, which led to increased consumption of surface water resources with irrigation depending both on direct diversion of river water and on water stored in reservoirs. Moreover, oasis with large proportions of irrigated land are likely to have enhanced evapotranspiration, thus leading to a reduction in the flow of the main stream in the Hotan River.

Based on our analysis, the streamflow of the two branches of the Hotan River exhibited no significant increases; however, a decreasing trend was detected in the main stream of the Hotan River. Following the findings of Zhang et al. (2012), we postulate that the decreasing trend of main stream flow in the Hotan River is linked to the increase in cultivated land surrounding the Hotan Oasis.

### Quantifying the impacts of changing climate and human activities on streamflow in the Hotan River

The Uruwati and Tongguzlok hydrometric stations are located near the source areas of the Karakax and Yurunkax rivers, respectively. Consequently, the amount of water used by humans within each tributary basin is negligible compared to the total discharge. Therefore, we assumed that the observed hydrological records from these stations reflected natural conditions, and the sum of the streamflow of these two stations was used as the river inflow from the headwater catchment region, which is mainly affected by changing climate. Streamflow from the Xiaota hydrological station downstream of the Hotan River was used as a surrogate for outflow volume, which is mainly affected by the river inflow from the headwater catchment region and human activities that consume water in the region.

The double-mass curve of inflow and outflow in the Hotan River is shown in Figure 10. To assess the relative reduction in the high-flow streamflow for the period after the abrupt change (1988 onwards), inflow and outflow information prior to 1988 was used to establish regression equations. We assumed that the environmental conditions for the period after the abrupt change were consistent with those before. Cumulative outflow until 2012 was calculated to be $548.40 \times 10^8$ m$^3$; whereas, the observed cumulative outflow ($501.75 \times 10^8$ m$^3$) was reduced by 8.51% in the Hotan River Basin.

Subsequently, the outflow in the high-flow period was calculated using the regression equation established from the double-mass curve of inflow and outflow before the abrupt change. We propose that differences between calculated values in different periods are due to the impact of changing climate, whereas differences between calculated values and observed values in the same period indicate the impact of human activities (Table 3).

### Table 3 | Impacts of changing climate and human activities on outflow in different periods (natural period, 1964–1988; transition period, 1989–2002; post-transition period, 2003–2012) in the Hotan River Basin (10^8 m$^3$)

<table>
<thead>
<tr>
<th>Period</th>
<th>Observed</th>
<th>Calculated</th>
<th>$\Delta R$</th>
<th>Impact of changing climate</th>
<th>Impact of human activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Amount</td>
<td>Percentage</td>
<td>Amount</td>
</tr>
<tr>
<td>Natural</td>
<td>11.40</td>
<td>11.28</td>
<td></td>
<td></td>
<td>-0.80</td>
</tr>
<tr>
<td>Transition</td>
<td>8.46</td>
<td>10.59</td>
<td>-2.93</td>
<td>-26</td>
<td>-2.13</td>
</tr>
<tr>
<td>Post-transition</td>
<td>9.84</td>
<td>11.82</td>
<td>-1.55</td>
<td>-14</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Changing climate led to a decrease in streamflow during the transition period, yet contributed to an increase in streamflow in the post-transition period (Table 3). Human activities reduced outflow by 73% in the transition period and by 127% in the post-transition period, which was significantly stronger than the contribution rate of the changing climate. These results indicate that human activity is the main driving factor for the streamflow decrease from the Hotan River into the Tarim River.

CONCLUSIONS

During the last five decades, both precipitation and air temperature experienced an increasing trend for the Hotan River Basin, that is, the climate has become warmer and wetter. In contrast, the annual streamflow from the two tributaries of the Hotan River did not exhibit a significant increasing trend; moreover, a decreasing trend was detected in the main stream flow due to the decrease in summer streamflow in the Karakax River. The streamflow of the Hotan River at the mountain pass was influenced by natural factors, while the impact of human activities was negligible. However, after 1988, the outflow in the Hotan River was influenced by natural factors plus human activities.

The construction of the Wuluwati Reservoir in 2002 was the driver of changes to seasonal streamflow distribution at Uruwati station, which had a major role in relieving droughts in spring and flooding in summer. However, excessive peak flow reductions caused by the Wuluwati Reservoir flood discharge operations increased water loss in the tributary. Furthermore, flood discharge operations altered the monthly distribution of streamflow, further increasing water loss in the main stream channel due to discontinuities between the flows of the tributaries, causing a reduction in the inflow into the Tarim River. Finally, due to rapid population growth, the expansion of irrigated areas in the Hotan Oasis has not been effectively controlled. Excessive river water is being diverted for irrigation of cultivated land upstream, reducing water outflow from the oasis to unsustainable levels.

Using a double-mass curve analysis, the impacts of changing climate and human activities on streamflow in the Hotan River were quantified. The contribution of human activities to the decrease in streamflow from the Hotan River into the Tarim River was 73% during the transition period (1989–2002) and 127% during the post-transition period (2003–2012). The anthropogenic effects were significantly greater than the contributions of the changing climate during the same time: 27% of the reduction during the transition period and an increase of 27% during the post-transition period.

To mitigate the misuse of water resource in the Hotan River Basin, we recommend establishing a comprehensive water resource management system that: considers the water resource carrying capacity, controls the growth of irrigated areas, prevents illegal diversion; improves the management of the Wuluwati Reservoir to maintain synchronous flood discharge between the Karakax and Yurunkax Rivers; and accelerates river regulation in the Hotan River main stream to meet the ecological targets of water flow from the Hotan River into the Tarim River.

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