Impact of reservoir on downstream runoff and baseflow recession characteristics: a case study of Chaersen Reservoir in Northeast China

Weifei Yang[1], Changlai Xiao[1], and Xiujuan Liang[1]

[1]Jilin University

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Abstract

The number of reservoirs in the world is increasing year by year, which will inevitably affect the downstream runoff and baseflow recession characteristics. In this paper, the impact of Chaersen Reservoir (Northeast China) on downstream runoff and baseflow recession characteristics is studied using a pre post comparison method, and the influence of climate change is excluded using two upstream sub-watersheds as control basins. In addition, the impact mechanism of the reservoir is further explored. The results show that the increased direct and indirect water consumption after the construction of the reservoir results in a 14% reduction in the average streamflow of the downstream Zhenxi Station. At the same time, the construction of the reservoir causes the baseflow at the recession stage to increase by a relatively constant value (about $1m^3/s$), which leads the log(|dQ/dt|) vs. log(Q) points at the low flow stage to shift to the right. This eventually results in a decrease in the recession coefficient a by about 60% and an increase of b by about 24%. The log(|dQ/dt|) vs. log(Q) scatter of the recession process after adding a constant flow is no longer in a strict linear relationship. And the master recession curve obtained by the traditional linear parameterization method is only an average approximation, which will overestimate the streamflow in the middle recession stage and underestimate the streamflow in the late stage.

1 Introduction

There are about 16.7 million reservoirs larger than 0.01 ha in the world, and this number will continue to increase (Lehner et al., 2011). Currently, about half of the stream and river flow is regulated by reservoirs and dams, and by 2030 this number will climb up to 90% (Grill et al., 2015). Reservoir's interception and regulation of river flow will obviously weaken peak flow and increase low flow (Vorosmarty et al., 1997). This will have a significant effect on the hydrological process many hundred kilometers downstream of the dam (Grill et al., 2015), as well as on the matter and energy cycle with streamflow as the medium (Pringle, 2003). Qualitative or quantitative research on the impact of reservoir construction on global or regional hydrological process and ecological environment is of profound significance.

There are many researches about the impact of reservoir on the hydrologic alteration and matter cycle: Grill et al. (2015) assessed the patterns and trends in river fragmentation and flow regulation by global dams at multiple scales; Hecht, Lacombe, Arias, Dang, and Piman (2019) reviewed the hydrological impacts of the hydropower dams of Mekong River basin; Taylor Maavara, Dürr, and Van Cappellen (2014) studied the worldwide retention of nutrient silicon by river damming; T. Maavara et al. (2015) studied the global phosphorus retention by river damming; Van Cappellen and Maavara (2016) studied the global scale modifications of riverine nutrient fluxes by damming; Meanwhile, many researchers have also studied the impact of reservoirs on downstream hydrological drought (Rangecroft, Van Loon, Maureira, Verbist, & Hannah, 2019;

Tijdeman, Hannaford, & Stahl, 2018; Anne F. Van Loon et al., 2019; Wanders & Wada, 2015). In addition, reservoir's regulation of streamflow can also influence the downstream baseflow recession characteristics. However, we have not found some quantitative global or case studies, this study may be the first attempt.

The shape of baseflow recession curve is an important feature of a basin. Baseflow recession analysis can be understood as a statistical analysis and description of the recession curve for a specific basin (Stoelzle, Stahl, & Weiler, 2013; Thomas, Vogel, & Famiglietti, 2015). The detailed baseflow recession analysis method will be described in Section 3. Baseflow recession analysis is widely used in hydrological research, water resources planning and management, and watershed hydrogeological research (Sujono, Shikasho, & Hiramatsu, 2004; Zhang, Chen, Hickel, & Shao, 2008). The main application objectives include: estimating long-term groundwater storage trends (Brutsaert, 2008), estimating watershed groundwater balance (H. Wittenberg & Sivapalan, 1999), baseflow separation (Huyck, Pauwels, & Verhoest, 2005; Hartmut Wittenberg, 1999), baseflow regionalization (Beck et al., 2013), and determining basin-wide hydrogeological parameters (Mendoza, Steenhuis, Walter, & Parlange, 2003; Oyarzún et al., 2014). The influence of reservoir on the baseflow recession characteristics will obviously affect the above application results, so we should first make clear the influence mechanism of reservoir on the baseflow recession characteristics.

At present, the main methods used to study the effects of human activities on hydrological processes include scenario modelling method (Veldkamp et al., 2015; Wada et al., 2017), paired catchments method (Best, Zhang, McMahon, Western, & Vertessy, 2003; Brown, Zhang, McMahon, Western, & Vertessy, 2005), pre-post comparison method (Liu et al., 2016), upstream-downstream comparison method (Rangecroft et al., 2019), and observation-modelling comparison method (A. F. Van Loon & Van Lanen, 2013). Anne F. Van Loon et al. (2019) has made a more detailed summary. Among them, the simpler and more widely used method is the pre-post comparison method, which selects two series before and after human activities to compare. Penas, Barquin, and Alvarez (2016) pointed out that this method is hard to separate human activities from climate change, and it is usually necessary to select a control basin to eliminate the impact of climate change. However, we must also be wary of the spatial differences in climatic characteristics between the control basin and the impact basin. These spatial differences may lead to incorrect estimates of the impact of climate change.

The main purpose of this paper is to study the impact of Chaersen reservoir (Northeast China) on the downstream runoff and baseflow recession characteristics using the pre-post comparison method with two upstream sub-watersheds as control basins. The main contents include: 1) Before and after the construction of the reservoir, two streamflow series with similar rainfall-runoff characteristics are selected to compare the differences of runoff and baseflow recession characteristics. 2) The impacts of climate change are estimated based on two sub-basins in the upper reaches of the reservoir. 3) The influence mechanism of the reservoir is further explored.

2 Study area and data

The Tao'er River basin is located in northeastern China, with elevations ranking from 100 m a.s.l. to 1600 m a.s.l. (Fig. 1). The drainage area is 41,200 km^2, of which the bed rock mountain area accounts for about 65% and mainly distributed above the Zhenxi station (Chen, Li, Li, & Liu, 2016; Kou, 2016). The forest and grassland coverage in the basin are about 25% and 36%, respectively, and the rest is mostly cultivated with corn. This basin belongs to the temperate continental monsoon climate zone, with an average annual rainfall of 463.6 mm (from 1953 to 2015).

The daily average precipitation, streamflow and water level of the four hydrological stations in Tao'er River basin (Suolun, Dashizhai, Chaersen and Zhenxi) have been monitored since 1964. The Zhenxi station is 63 km away from the downstream of Chaersen reservoir, the Chaersen station is located at the outlet of the reservoir, and the Suolun and Dashizhai stations are located in the upstream watersheds (Fig. 1). The main purpose of the paper is to analysis the influence of Chaersen reservoir on the streamflow and baseflow recession characteristics of Zhenxi station.

Figure 1. Location and topography of the Tao'er River basin.

The Chaersen Reservoir is a large-scale reservoir mainly used for flood prevention, irrigation, combined power generation, and fish farming. This reservoir started construction in 1987 and was completed in September 1989. The drainage area it controls is 7872 km^2, the total design storage capacity is 11.48 x $10^8 m^3$, the design peak discharge is 420 m^3/s, and the design irrigation area is 590 km^2. The dam of the reservoir is a loam core wall dam with a maximum height of 40 m, a crest width of 6 m and a length of 1712 m (Li, 2018). The streamflow regulation of Chaersen reservoir is usually carried out from May to October every year. From 2009 to 2013, the average daily discharge of the reservoir is between 20 to 110 m^3/s, with an average of 45 m^3/s (Fig. S1). After the construction of the reservoir, the streamflow process of Chaersen station is obviously flattened, and the flood peak originally concentrated in July and August is evenly distributed to May to October.

After excluding the construction period (1987-1989) and the initial impoundment stage (1989-1995), based on the similarity of rainfall-runoff characteristics, 1982-1986 was determined as the pre-disturbance period, and 2009-2013 was the post-disturbance period. These two periods are the same length and the annual precipitation is basically the same. Precipitation and runoff in both periods are all increasing year by year (Fig. S2, Fig. S3). The unpublished streamflow data was provided by Songliao Water Resources Commission, Ministry of Water Resources, China.

3 Baseflow recession analysis method

The process of baseflow recession analysis can be divided into three stages: 1) extracting the baseflow recession segment; 2) Selecting an appropriate theoretical model; 3) Determining the optimal model parameters (Tallaksen, 1995). Each stage has different methods. Stoelzle et al. (2013) points out that different combinations of methods will get different recession characteristics, and the parameter optimization method has the most obvious effect on the results. Therefore, based on the power function relationship of -dQ/dt and Q (Sect. 3.2), this study adopts 12 combinations of four recession segment extraction methods (Sect. 3.1) and three parameter optimization methods (Sect. 3.3) to carry out the baseflow recession analysis. Finally, the difference of mean value of recession coefficient under different parameter optimization methods is analyzed. The Matlab toolbox developed by Arciniega-Esparza, Brena-Naranjo, Pedrozo-Acuna, and Appendini (2017) facilitates the automated analysis and comparative analysis of recession analysis.

3.1 Baseflow recession segment extraction methods

There are four commonly used methods for extracting recession segments: Kir method (Kirchner, 2009), Vog method (Vogel & Kroll, 1992), Bru method (Brutsaert & Nieber, 1977) and Aks method (Aksoy & Wittenberg, 2011). See Table 1 for a summary. The Vog method selects recession segments from the decreasing parts of 3-day moving averages of streamflow. Kir, Bru and Aks methods all select the recession segment in the parts of $dQ/dt < 0$. Kir method includes all the parts of $dQ/dt < 0$, while Bru and Aks methods exclude the segments affected by rainfall or surface runoff based on different criteria. Stoelzle et al. (2013) and Arciniega-Esparza et al. (2017) has discussed these methods in detail, and this paper will not repeat them.

Table 1. Recession segment extraction methods.

3.2 Theoretical model

Hydrologists have provided a variety of theoretical models for baseflow recession analysis based on different assumptions, see Tallaksen (1995), Smakhtin (2001), and Thomas et al. (2015) for details. The current widely used theoretical models are: linear reservoir model, $S = kQ$ (Maillet, 1905), nonlinear reservoir model, $S = kQ^{\beta}$ (Hartmut Wittenberg, 1999) and power law relationship between $-dQ/dt$ and Q,$-\frac{\mathrm{dQ}}{\mathrm{dt}} = aQ^b$ (Brutsaert & Nieber, 1977). These three models are essentially based on the power law relationship between storage and discharge (also named nonlinear reservoir). The linear reservoir model presents a particular feature as it has a power exponent of 1. The power function relationship of $-dQ/dt$ and Q can be obtained by substituting the power law relationship between storage and discharge into the basin continuity equation(Wang & Cai, 2009),k and β are constants and the corresponding relationships with a and b are $k = \frac{1}{(2a-ab)}$and $\beta = 2 - b$ (Thomas et al., 2015). Therefore, this study uses the power function model of $-dQ/dt$ and Q to analyze the recession. It should be pointed out that the water storage (S) here refers to the active water storage in the basin that can be discharged to the river.

3.3 Parameter optimization methods

There are three widely used parameter optimization methods: linear regression, lower envelope, and binning (Stoelzle et al., 2013). According to the scatter plot of $\log(|\mathrm{d}Q\ /\mathrm{d}t\ |)$ vs. $\log(Q\ )$, the three parameter optimization methods determine the fitting line with different forms. The slope of the line is b , and the intercept is $\log(a\ )$,$\log\left(-\frac{\mathrm{dQ}}{\mathrm{dt}}\right) = \log(a) + b * \log(Q)$. The linear regression method is to fit the line with the least square of all scattered points. The lower envelope method uses the lower boundary (or lower 5% critical line) of the scatter points to determine the fitting line. The binning method is to segment the scattered points according to the streamflow, then calculate the average value of each segment, and finally make the least square fitting line of these average values. Stoelzle et al. (2013) and Thomas et al. (2015) have discussed these methods in detail.

4 Results

4.1 Impact of reservoir on runoff

Before the baseflow recession analysis, we first analyze the impact of the construction of the Chaersen Reservoir on the runoff of the downstream Zhenxi station. The streamflow duration curves of the two comparison periods before and after the construction of the reservoir are plotted, respectively, as shown in Fig. 2. After the construction of the reservoir, the peak flow of Zhenxi station decreases significantly, while the low-flow increases significantly (Fig. 2c). The streamflow of the two upstream hydrological stations (Suolun and Dashizhai) are not significantly different in the comparison periods (Fig. 2a, Fig. 2b), and the deviations in some stages may be mainly caused by the differences in climate characteristics. In order to quantitatively analyze the impact of reservoir construction on runoff, we have calculated some characteristic values of streamflow (maximum: Q_{max}, minimum: Q_{min}, average: Q_{mean}, seven-days minimum: $7Q_{\mathrm{min}}$) in the comparison periods, and the percentage bias between them, as shown in Table 2. The streamflow characteristic values of Suolun station in the post-comparison period is generally smaller, with a bias of -16% to -24%. However, these values of Dashizhai station in the post-comparison period are generally larger, with a bias of 11% to 60%. This opposite deviation may be caused by the spatial difference of climate characteristics, which will cancel each other when converging to downstream Zhenxi station. Considering the large difference between the streamflow magnitude of the two upstream hydrological stations, this study estimates the impact of climate change on the downstream Zhenxi station by weighted average of the two opposite deviations, with the proportion of average streamflow as the weight (Table 2). After excluding the impact of climate change, the construction of Chaersen Reservoir resulted in a 14% decrease in Q_{mean} of the downstream Zhenxi station, a 35% decrease in Q_{max}, a 380% increase in Q_{min}, and a 235% increase in $7Q_{\mathrm{min}}$.

Figure 2. Streamflow duration curves before and after the construction of reservoir. (a) Suolun station, (b) Dashizhai station, (c) Zhenxi station.

Table 2. Characteristic values of streamflow before and after the construction of reservoir, m^3/s.

4.2 Impact of reservoir on baseflow recession characteristics

According to the method in section 3, the recession coefficients of the two comparison periods are calculated, and the results are shown in Fig. 3. In general, after the construction of the reservoir, the recession coefficient a of the downstream Zhenxi station is obviously reduced, while the coefficient b is obviously increased. No significant differences are found in the recession coefficients of the comparison periods at the upstream Suolun and Dashizhai stations (Fig. 3). There are inherent differences in the coefficients calculated by different methods, Stoelzle et al. (2013) has discussed it in detail. The recession coefficients obtained by linear regression and binning methods are not significantly different, but these obtained by the lower envelope method are significantly lower. Different baseflow recession segments extraction methods always cause certain fluctuations in the coefficients. Therefore, we use the same recession analysis method combination to avoid misjudgment due to the systematic error between different recession analysis methods (e.g. using the average result of different recession extraction methods under the same parameter optimization method, Table 3).

In order to quantitatively analyze the impact of the reservoir, we calculate the percentage bias between the average results of the two comparison periods, as shown in Table 3. Under different parameter optimization methods, the average recession coefficients a in the post-comparison period of Suolun station are smaller, with a bias of -3% to -10%, and the average values of b are larger, with a bias of 0% to 3%. The average a of Dashizhai station are also smaller, with a bias of -12% to -15%, and the average b are slightly larger, with a bias of -2% to 6%. The deviation directions of the two upstream hydrological stations are the same, so this study uses the average of the two hydrological stations to estimate the bias caused by the climate change between the comparison periods of the downstream Zhenxi station (Table 3). After excluding the influence of climate change, the recession coefficient a of different parameter optimization methods decreased by 57% ˜ 63% (the average is 60%), and the b increased by 21% ˜ 27% (the average is 24%). Although different parameter optimization methods will get different results, the impact degree of reservoir construction on the analysis results of different methods is basically the same.

In order to more intuitively observe the influence of reservoir construction on the baseflow recession characteristics, we have drawn the master recession curves of the comparison periods before and after the construction of the reservoir, the equation is $Q_{(t+t)} = \left[a\,(b-1)\,t + Q_t^{1-b}\right]^{\frac{1}{1-b}}$, as shown in Fig. 4, Fig. S4 and Fig. S5. When the recession starts with average streamflow (Fig. 4a), the master recession curves of Zhenxi station before and after the construction of the reservoir intersects. And the master recession curve after the construction of the reservoir is significantly higher in the later stage of the recession, and the recession rate becomes significantly smaller. However, the master recession curves of Suolun and Dashizhai stations do not change significantly before and after the construction of the reservoir. When the recession starts with same streamflow (Fig. 4b), the master recession curves of Zhenxi, Suolun and Dashizhai stations before the construction of the reservoir are basically the same. However, after the construction of the reservoir, the master recession curve of Zhenxi station is significantly higher. In other words, the construction of the reservoir slows the baseflow recession rate and increases the drainage time, causing the master recession curve to shift upward.

Changes in the recession coefficients and the master recession curve also mean changes in the basin-scale storage-discharge (S-Q) relationship. Based on the nonlinear reservoir theoretical model (Sect. 3.2), the S-Q relationship curves before and after the construction of the reservoir are drawn, as shown in Fig. 5, Fig. S6, and Fig. S7. Before the construction of the reservoir, the S-Q relationships of the three hydrological stations are approximately linear, but the nonlinearity of the S-Q relationship of Zhenxi station increases significantly after the construction of the reservoir. In addition, after the construction of the reservoir, the storage capacity of Zhenxi station increases significantly. When the baseflow is $5m^3/s$ (60^{th} percentile), the storage capacity is 3.1 times before the reservoir construction; When the baseflow is $20m^3/s$ (32^{th}percentile), the storage capacity becomes 2.1 times as before; When the baseflow is $40m^3/s$ (22^{th}percentile), the storage capacity becomes 1.7 times as before. That is, with the increase of baseflow, the increase rate of basin-scale storage becomes slower and slower.

Figure 3. Recession coefficients analysis results of different methods. LR: linear regression, BIN: binning, LE: lower envelope.

Table 3. The average recession coefficients of different parameter optimization methods. The bias is calculated with 1982~1986 as reference.

Figure 4. Master recession curves, with the recession coefficients calculated by linear regression (LR) method. (a) Recession starts with average streamflow, (b) recession starts with same streamflow.

Figure 5. Storage-discharge (S-Q) relationship curves, with the recession coefficients calculated by linear regression (LR) method.

5 Discussion

5.1 Impact mechanism of reservoir

One of the main functions of the reservoir is to regulate runoff to reduce the influence of floods. Usually, a part of the reservoir capacity is discharged before the wet season arrives, and some of the peak flow is intercepted during the wet season. This regulation will obviously reduce flood peaks and increase baseflow during dry season, but will not directly affect the total runoff. In this study, the average streamflow of the downstream Zhenxi station decreased by about 14% after the construction of the reservoir, which may be mainly due to the increased direct consumption of water surface evaporation and indirect consumption of drinking water, farmland irrigation, etc. (T. Maavara, Lauerwald, Regnier, & Van Cappellen, 2017; Vorosmarty et al., 1997). In other words, the regulation of runoff by the reservoir directly leads to the reduction of peak flow and the increase of baseflow, and the increased direct and indirect consumption of reservoir storage leads to the reduction of average or total streamflow. Some studies have well illustrated the above point of view: Piman, Lennaerts, and Southalack (2013) showed that hydropower dams in the tributaries of the Mekong River will lead to a 25% decrease in the streamflow during the wet-season and an increase of 95% during the dry-season; In addition, Piman, Cochrane, and Arias (2016) also pointed out that the impact of hydropower dams on the downstream daily average streamflow is greater, with the maximum daily streamflow decreasing by 36% and the minimum increasing by 168%. Vorosmarty et al. (1997) pointed out that the loss of Lake Nasser on the Nile River caused by evaporation and leakage accounts for about 13% of its inflow every year, Lake Kariba on the Zambezi River loses about 20% of its inflow, while the smaller Tiga Reservoir loses about 26% of its upstream inflow. Shiklomanov (2000) pointed out that the reservoir-based evaporation would increase the consumption of the global river runoff by about 5%, which would be larger if the domestic, industrial and agricultural water consumption were taken into account.

As mentioned in Section 4.2, after the construction of the reservoir, the recession coefficient a of downstream Zhenxi station is significantly reduced, while b is significantly increased, which leads to the change of the master recession curve and S-Q relationship. Why is there such a change? We try to find the answer from the scatter plot of log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$). By comparing the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) points distribution characteristics before and after the construction of the reservoir at Zhenxi station, we find that the scatter points at the low flow stage after the construction of the reservoir are significantly shifted to the right (Fig. 6a). This also results in a counterclockwise rotation of the linear regression line, which eventually increases the slope (b) and decreases the intercept (a). This shift indicates that after the construction of the reservoir, the downstream baseflow (Q) increased during the dry-season, but the recession rate (dQ/dt) did not change significantly, which can be understood as the addition of a constant flow (Q_{con}) in the original recession process. To verify this assumption, we add a constant value (1m^3/s) to the master recession curve (MRC) of Zhenxi station before the construction of the reservoir, and then draw the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) scatter plots (Fig. 6b). It is found that the scatter points in the low flow stage are also shifted to the right after increasing the constant value of $1\mathrm{m}^3/\mathrm{s}$ to the MRC. The recession coefficient a calculated by the linear regression method is reduced to 0.01, and b is increased to 1.22, which are basically the same as the calculated values after the construction of the reservoir. In addition, it can be seen from Table 2 that after the construction of the reservoir, the Q_{min} of Zhenxi station increased from $0.29\mathrm{m}^3/\mathrm{s}$ to $1.38\mathrm{m}^3/\mathrm{s}$, increased by $1.09\mathrm{m}^3/\mathrm{s}$, and the $7\mathrm{Q}_{\mathrm{min}}$ increased by $7.03\mathrm{m}^3/\mathrm{s}$, which should not be a coincidence. That is to say, after the construction of the reservoir, the variable water storage of the basin is increased, and a relatively constant flow (about $1\mathrm{m}^3/\mathrm{s}$) is added to the baseflow recession process of downstream Zhenxi station, which causes the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) scatter points to shift to the right in the late recession stage, and finally causes the recession coefficient a to decrease and b to increase. This relatively constant flow may come from the continuous and stable drainage of the reservoir, the continuous leakage, and the continuous return flow of domestic, agricultural and industrial used reservoir water. Specific sources still require detailed field investigations.

Figure 6. -dQ/dt vs. Q scatter plots in double logarithmic coordinate system, with the Vog extraction method. The lines in the figure are linear regression lines. (a) Observed values before and after the construction of the reservoir, (b) calculated values before and after adding a constant flow.

5.2 Master recession analysis considering constant addition flow

It can be seen from Fig. 6b that after adding a constant flow, the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) scatter points no longer satisfies the linear relationship, and the slope gradually becomes larger in the late stage of the recession. The recession coefficients calculated by the traditional linear parameterization method reflect the average linear approximation of this nonlinear relationship. Therefore, a new master recession analysis method should be adopted to analyze the baseflow recession process with a constant addition flow. For example, we can deduct the constant flow (Q_{con}) before drawing the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) scatter plot for parameterization (i.e. all measured recession streamflow minus Q_{con}), and then add Q_{con} to the master recession curve (MRC). At this time, the equation of the MRC becomes $Q_{(t+t)} = Q_{\mathrm{con}} + \left[a\left(b-1\right)t + \left(Q_t - Q_{\mathrm{con}}\right)^{1-b}\right]^{\frac{1}{1-b}}$, where a and b in the formula are obtained by linear regression of the scattered points after subtracting Q_{con} . After subtracting $Q_{con} = 1\mathrm{m}^3/\mathrm{s}$ from the recession streamflow of Zhenxi station from 2009 to 2013, the recession coefficients a and b are 0.022 and 1.10 respectively, which are close to the analysis results of 1982 to 1986. Finally, the MRC considering constant addition flow is drawn (Fig. 7). After comparison, it can be found that the MRC obtained by the average linear approximation will overestimate the streamflow in the middle recession and underestimate the streamflow in the later recession, but the deviation is not obvious as a whole. That is to say, in Sect. 4.2, the recession analysis results obtained by linear approximation can reflect the overall change of the recession characteristics before and after the construction of the reservoir, but there will be some deviations in some specific stages. The master recession analysis method proposed in this paper can also be used in basins with inter-basin water transfer behavior. When there is stable inflow, Q_{con} is positive, and when there is stable outflow, Q_{con} is negative.

Figure 7. Master recession curves with and without constant addition flow, semi logarithmic coordinate.

6 Conclusions

In this paper, the impact of Chaersen Reservoir (Northeast China) on downstream runoff and baseflow recession characteristics is studied using a pre-post comparison method, and the influence of climate change is excluded using two upstream sub-watersheds as control basins. In addition, the impact mechanism of the reservoir is further explored. The main conclusions are as follows:

1) After the construction of Chaersen Reservoir, the regulation of runoff directly leads to the reduction of peak flow (Q_{max} decreased by 35%) and the increase of baseflow ($7Q_{min}$ increased by 235%) of downstream

Zhenxi station, and the increased direct and indirect consumption of reservoir storage leads to the reduction of average or total streamflow by about 14%.

2) After the construction of the reservoir, a relatively constant flow (about $1\mathrm{m}^3/\mathrm{s}$) is added to the baseflow recession process of downstream Zhenxi station, which causes the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) scatter points to shift to the right in the late recession stage, and finally causes the recession coefficient a to decrease by about 60% and b to increase by about 24%. This change also means the upward shift of the MRC, the slowing down of the recession rate, and the increase of the active water storage in the basin.

3) After adding a constant flow, the log ($|\mathrm{d}Q\ /\mathrm{d}t\ |$) vs. log ($Q$) scatter points no longer satisfies a strict linear relationship. The MRC obtained by the traditional linear parameterization method is only an average approximation, which will overestimate the streamflow in the middle recession stage and underestimate the streamflow in the later stage, but the deviation is not obvious as a whole.

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Tables

Table 1. Recession segment extraction methods.

Extraction methods	Criterion	Minimum recession length (days)	Excluding exterior p
Kir	$dQ/dt < 0$	1	–
Vog	Decreasing 3-d moving average	10	First 30%
Bru	$dQ/dt < 0$	6–7	First 3—4, last 2
Aks	$dQ/dt < 0$	5	First 2

Table 2. Characteristic values of streamflow before and after the construction of reservoir, m^3/s.

Hydrological station	Record period	Q_{max}	Q_{min}	Q_{mean}	$7Q_{min}$
Suolun	1982~1986	524.00	0.29	24.69	2.03
	2009~2013	396.00	0.24	19.54	1.71
	Bias	-24%	-18%	-21%	-16%
Dashiazhai	1982~1986	152.00	0.06	9.45	0.36
	2009~2013	170.00	0.08	10.47	0.58
	Bias	12%	31%	11%	60%
Zhenxi	1982~1986	847.00	0.29	40.07	2.92
	2009~2013	430.00	1.38	29.73	9.94
	Bias	-49%	376%	-26%	240%
	Bias (climate change) [a]	-14%	-4%	-12%	5%
	Bias (ex-climate change)	-35%	380%	-14%	235%

[a] The weighted average calculation formula is: Bias (climate change) = Bias (Suolun)*0.72 + Bias (Dashizhai)*0.28.

Table 3. The average recession coefficients of different parameter optimization methods. The bias is calculated with 1982~1986 as reference.

Hydrological station	Record period	a	a	a	b	b	b
		LR	**BIN**	**LE**	**LR**	**BIN**	**LE**
Suolun	1982~1986	0.0317	0.0317	0.0095	1.11	1.11	1.04
	2009~2013	0.0303	0.0307	0.0086	1.14	1.14	1.04
	Bias	-5%	-3%	-10%	3%	2%	0%
Dashizhai	1982~1986	0.0446	0.0473	0.0119	1.07	1.00	0.95
	2009~2013	0.0394	0.0400	0.0102	1.05	1.04	1.01
	Bias	-12%	-15%	-14%	-2%	4%	6%
Zhenxi	1982~1986	0.0363	0.0352	0.0084	1.02	1.03	0.94
	2009~2013	0.0104	0.0104	0.0026	1.31	1.31	1.18
	Bias	-71%	-71%	-69%	28%	27%	25%
	Bias (climate change) [a]	-8%	-9%	-12%	1%	3%	3%
	Bias (ex-climate change)	-63%	-61%	-57%	27%	23%	21%

[a] Estimated based on the average bias of the Suolun and Dashizhai stations.

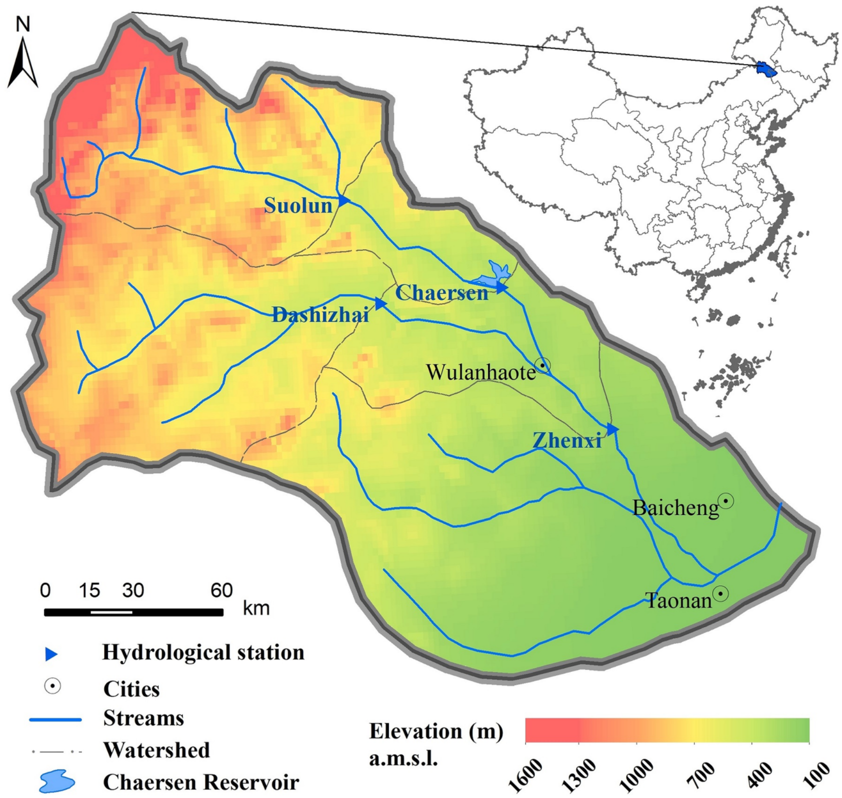

Figure 1: **Figure 1.** Location and topography of the Tao'er River basin.

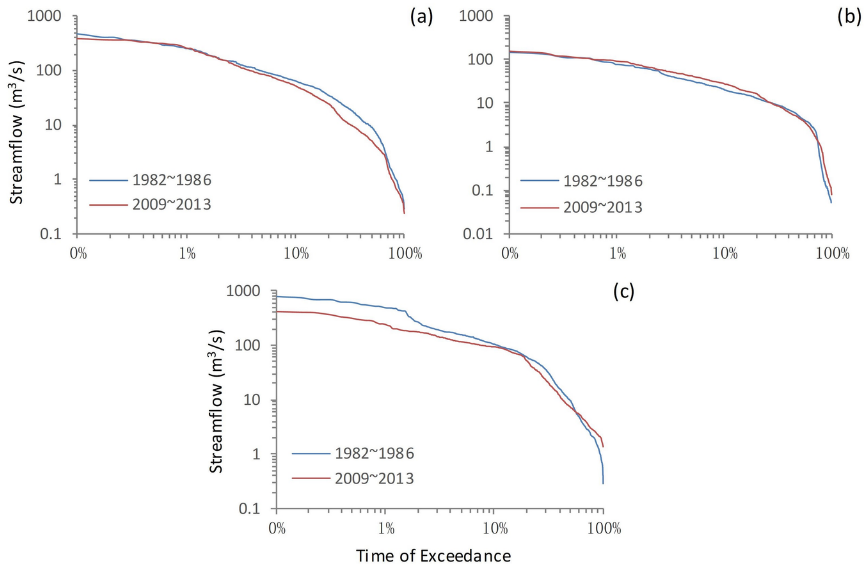

Figure 2: **Figure 2.** Streamflow duration curves before and after the construction of reservoir. (a) Suolun station, (b) Dashizhai station, (c) Zhenxi station.

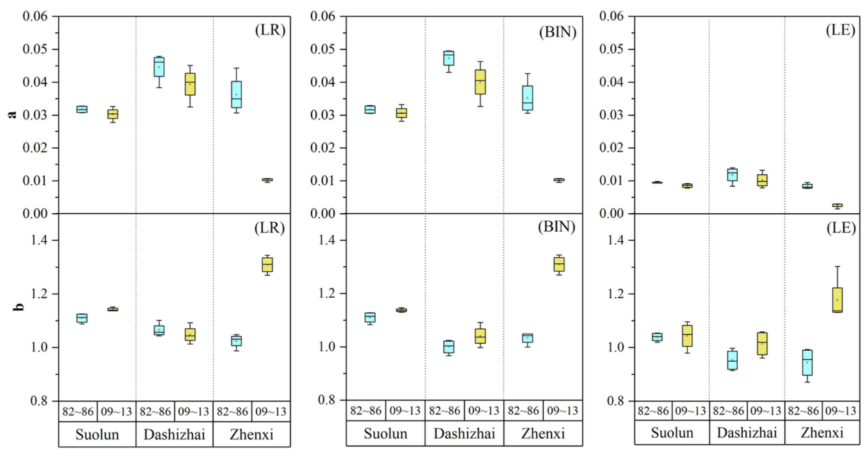

Figure 3: **Figure 3.** Recession coefficients analysis results of different methods. LR: linear regression, BIN: binning, LE: lower envelope.

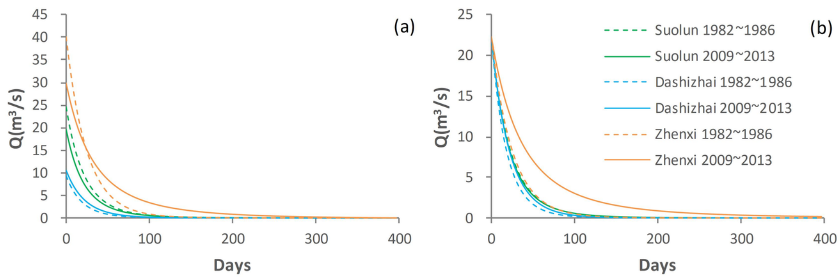

Figure 4: **Figure 4.** Master recession curves, with the recession coefficients calculated by linear regression (LR) method. (a) Recession starts with average streamflow, (b) recession starts with same streamflow.

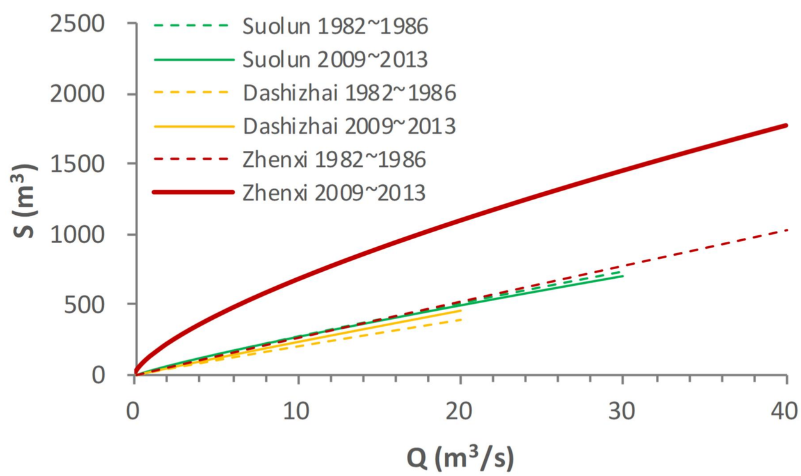

Figure 5: **Figure 5.** Storage-discharge (S-Q) relationship curves, with the recession coefficients calculated by linear regression (LR) method.

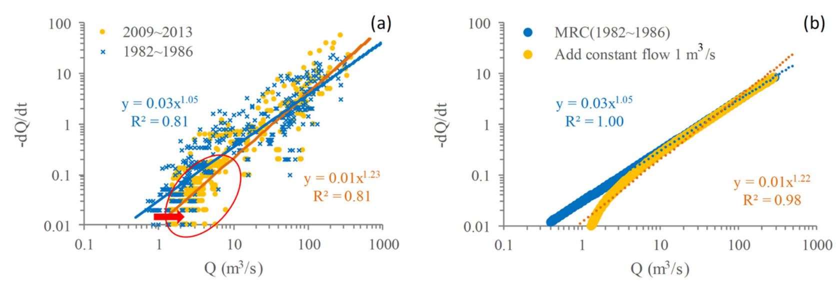

Figure 6: **Figure 6.** -dQ/dt vs. Q scatter plots in double logarithmic coordinate system, with the Vog extraction method. The lines in the figure are linear regression lines. (a) Observed values before and after the construction of the reservoir, (b) calculated values before and after adding a constant flow.

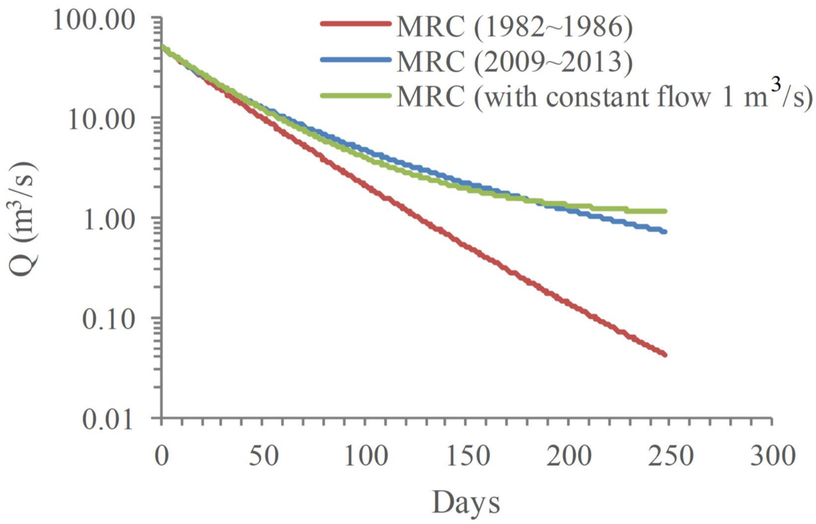

Figure 7: **Figure 7.** Master recession curves with and without constant addition flow, semi logarithmic coordinate.