Risk assessment of drought-induced water scarcity in upper and middle reaches of Xiu River

L N Liu and W L Liu

Jiangxi Provincial Key Laboratory of Hydrology-Water Resources and Water Environment, Nanchang Institute of Technology, Nanchang 330099, China

Abstract. In this paper, an index-based approach was presented to assess water scarcity risk induced by drought based on relationship between water use and water supply. Firstly, the index system of water scarcity risk was established from the viewpoint of hazard, exposure and vulnerability, which included drought hazard index (frequency, duration, and severity of droughts), exposure index (water use) and vulnerability index (relative water shortage). Then, an integrated risk index, namely water scarcity risk index (WSRI), was proposed using a multiplicative formula of drought hazard index, exposure index and vulnerability index to quantitatively assess drought-induced water scarcity risk. Finally, the WSRI-based approach was applied to a case study of assessing water scarcity risk in the upper and middle reaches of Xiu River, China. The results show that the drought-induced water scarcity risk of upper and middle reaches of Xiu River was at a low level, which was in line with the situation about the level of water resources exploitation and utilization in the study area. This study can serve as a reference for further water resources planning in the Xiu River Basin, and other relevant studies.

1. Introduction

Water resources are important strategic resources and play a critical role in human society and healthy ecosystems. However, with the rapid socio-economic development, water resources are facing a more and more serious situation of shortage, and water scarcity has already been the outstanding problem restricting the socio-economic sustainable development. Therefore, how to resolve the problem has attracted extensive attention from scholars at home and abroad [1-3].

China is one of the countries most threatened by water scarcity. Especially in recent years, along with high-speed economic development, population growth, rapid urbanization and industrialization, water scarcity is becoming more and more severe [4, 5]. Many researches have been done to evaluate and cope with water scarcity in Northern China. For example, Ruan et al. [3] assessed the water scarcity risk of capital area in China including Beijing and Tianjin with the traditional fuzzy comprehensive assessment method. Wang et al. [6] analyzed the water scarcity risk of Beijing from 1979 to 2005 based on fuzzy probability. Zhang et al. [7] studied water balance in the Haihe River Basin and evaluated water scarcity risk during 1994-2007. However, there is not enough attention paid to temporary water scarcities in Southern China. In such areas, the water scarcity occurs in drought conditions due to prolonged absence of precipitation and soil moisture deficits. Although not all water resources systems suffer water scarcity under a given drought situation, drought conditions can impose additional stress on water supply systems, which have to face the risk of water scarcity induced by drought. Therefore, it is still a necessary consideration for sustainable development of water resources to develop methods to analyze and control the risk of water scarcity during drought periods, with the ultimate goal of decreasing the loss before the occurrence of risk.
Many scholars present their understanding about the risk of water scarcity and also develop several indices to evaluate the risk of water scarcity. For instance, Hashimoto et al. [1] proposed three evaluation indices (reliability, resiliency and vulnerability) to evaluate the possible performance of water resource systems. Ruan et al. [3] put forward the indexes including the risk rate, weakness, possibility of recovery, period for reappear and risk level to assess water scarcity risk. Wang et al. [6] defined the risk as the product of the probability and the impact degree due to water scarcity risk. These indices prove to be useful and helpful in giving us an evaluation of water scarcity risk. Nevertheless, the indices do not address water scarcity risk induced by drought. In fact, measuring potential water-supply problems caused by droughts needs to jointly consider severity and spatial extension of droughts, water use relative to reliable water supply, and drought-resistant measures, which few studies are devoted to [8-11]. Furthermore, most of the risk indices established in such studies are based on the evaluation indices proposed by Hashimoto, but these indices reflect the performance of the water resources system, and the nature of risk is not taken into account [12,13]. Therefore, a suitable performance index is necessary to quantify the characteristics of water scarcity induced by drought. In this paper, the integrative risk index, namely water scarcity risk index (WSRI), was built and applied to assess the risk of water scarcity induced by drought in the upper and middle reaches of Xiu River.

2. Risk assessment of drought-induced water security

Water scarcity risk is affected by meteorological factors and non-meteorological factors. So it is difficult to combine all these factors to analyze the risk of water scarcity. In this paper, the drought as the main factor was taken into account on the research of water scarcity risk. Based on the natural disaster risk index established by Mileti [14] and the performance evaluation system for water resources system proposed by Hashimoto, here, water scarcity risk induced by drought is regarded as the consequence of the interaction of drought hazard, exposure and vulnerability of hazard-affected body. In terms of indices of hazard, exposure, and vulnerability, a multiplicative formula is proposed to link these three indices to define water scarcity risk during drought periods.

2.1. Drought hazard index

In this paper, the hazard of water scarcity risk during drought periods is defined as the probability of failure in different drought intensity, including drought severity and the drought probability. The standardized precipitation index (SPI), developed by McKee et al. [8, 15], is employed to detect occurrences of droughts.

The SPI is computed firstly by fitting precipitation data summed over the time scale to a suitable statistical distribution from which probabilities are transformed to the standard normal distribution, which can be expressed as follows:

\[ SPI = \phi^{-1}(F_Y) \] (1)

where \( \phi^{-1}(\cdot) \) is the inverse of a standard normal function; \( F_Y(\cdot) \) is the fitted cumulative distribution function (CDF) of precipitation; \( y \) is the aggregated amount of consecutive monthly precipitation for a fixed time scale of interest (e.g. 1, 3, 6, 9, 12 ... months).

Based on SPI series for multi time scales, cumulative SPI value of a drought event is computed as follows:

\[ S = \sum_{i=1}^{D} SPI_i \] (2)

where \( D \) and \( S \) are the drought duration and severity of a drought event, respectively.

To compare the impacts of droughts at different regions, the probability of all drought events in each region during the analysis period is summed to represent overall impacts of droughts, which is given by
\[ P_k = \sum_{i=1}^{N_k} P(d_i, s_i) \] (3)

where \( P_k \) is the summed probability of all drought events in the \( k \)th region; \( P(d_i, s_i) \) is the probability of a drought event with drought severity \( s_i \) and drought duration \( d_i \), which can be estimated by a copula-based bivariate distribution function; \( N_k \) is the number of drought events of the \( k \)th region.

For easy comparison, the summed probability of droughts at different regions is rescaled between 0 and 1, which is defined as the hazard index of water scarcity risk, that is

\[ HI_k = 1 - \left( \frac{\max(P) - P_k}{\max(P) - \min(P)} \right)^\alpha \] (4)

where \( HI_k \) is the hazard index of water scarcity risk in the \( k \)th region; \( \alpha \) is a rescale parameter.

2.2. Exposure index

The exposure factor of water scarcity risk measures level of assets, resources and populations exposed to threats of water scarcity induced by droughts. Since this study aims to evaluate water scarcity risk induced by drought based on the relationship between water use and water supply, the exposure index of water scarcity risk is defined as the total water use in a region which is a reasonable indicator to represent level of resources exposed to droughts. In this study, water uses mainly involve with agricultural water use, industrial water use and domestic water use. Compared with the agricultural water use, the domestic and industrial water uses have a very limited tolerance to water scarcity. Thus, a total water use is defined as the weighted total water use in which the weight on the agricultural water use is less than one.

\[ U = U_d + U_i + \beta U_u \] (5)

where \( U \) is the weighted total water use; \( U_d \), \( U_i \) and \( U_u \) is agricultural, industrial and domestic water use, respectively; \( \beta \) is the weight on agricultural water use.

Also, the same rescale scheme is adopted to rescale the value of the weighted total water use ranged between 0 and 1, which is defined as the exposure index \( (EI) \) of water scarcity risk in this study. That is

\[ EI_k = 1 - \left( \frac{\max(U) - U_k}{\max(U) - \min(U)} \right)^\alpha \] (6)

where \( EI_k \) is the exposure index of the water scarcity risk of the \( k \)th region.

2.3. Vulnerability index

The vulnerability of water scarcity risk measures the potential loss of water resources under drought stress. In a certain period of water supply, the more serious the water scarcity of drought is, the more vulnerable the water supply system is, which means the more severe the loss of drought is. The ratio of the average water scarcity and the average water demand is an important criterion to evaluate the water scarcity vulnerability of that region. That is

\[ V = \frac{\sum_{i=1}^{m} (D_i - S_i)}{\sum_{i=1}^{m} D_i} \] (7)
where $V$ denotes the ratio of the average water shortage and the average water demand; $D$ and $S$ are the water demand and the water supply, respectively.

A high value of this index $V$ means that the system is not reliable to satisfy its demands and is prone to water scarcity. Also, the value of $V$ is rescaled between 0 and 1, which is called as the vulnerability index of water scarcity risk ($VI$) in this study.

$$VI_k = 1 - \left( \frac{\max(V) - V_k}{\max(V) - \min(V)} \right)^2$$

where $VI_k$ is the vulnerability index of the water scarcity risk of the $k$th region.

2.4. Water scarcity risk index

The water scarcity risk consists of three components: hazard, exposure, and vulnerability. Thus, water scarcity risk index ($WSRI$) is defined as the product of drought hazard index, exposure index and vulnerability index:

$$WSRI_k = HI_k \times UI_k \times VI_k$$

where $WSRI_k$ denotes the water scarcity risk of the $k$th region.

Obviously, the value of $WSRI$ ranges between 0 and 1. A risk-prone region is that water use is significantly affected by droughts, and/or severity of droughts is greater, and/or reliable water supply is lack. Null water scarcity risk occurs only for the case of no water use ($EI = 0$) and/or fully reliable water supply ($VI = 0$).

3. Case study

3.1. Study area

The developed $WSRI$ was applied to assess water scarcity risk during drought periods in the upper and middle reaches of Xiu River, China. The Xiu River basin is located in the west of Jiangxi Province, China. It has a drainage area of 14,797 km², and situated between latitudes 28°40′-29°30′N and between longitudes 113°55′-116°01′E. The length of the main stream is 357 km and the mean annual runoff is approximately $135 \times 10^8$ m³. In view of the representation of sites and accessibility of data, the upper and middle reaches of Xiu River were selected as the study area. The region covers a total area of 9,243.8 km², and includes three counties, namely, Xiushui, Wuning and Tonggu in Jiangxi province. This area is dominated by a subtropical humid monsoon climate. The mean annual temperature is about 17°C, and the mean annual precipitation is approximately 1629 mm, about 40% of which is received from April to July. Because of the impact of high solar radiation and the circulation of monsoon weather patterns, the streamflow in the area varies significantly by season, which makes more precipitation occur during the monsoon period each year, while less precipitation in late autumn and winter. In general, the study area is characterized by abundant precipitation. However, due to uneven spatial and temporal distribution of rainfall, occasional droughts may lead to limited water availability during such periods. With the rapid socio-economic development, demand for water is also increasing in the region. Therefore, effective evaluation of water scarcity risk during drought periods in the upper and middle reaches of Xiu River is of great importance for a sustainable social and economic development in the region.

3.2. Water scarcity risk assessment

According to the available water resources and water consumption in the upper and middle reaches of Xiu River, a model of water resources optimum allocation was built, and the results for 2010 was presented in figure 1. From figure 1, it can be seen that, because of agriculture-based region, the ratio of agricultural water use accounted for a great proportion of total water consumption, which was about 80%, while the ratio for the domesticity and industry sector was low. It also shows that the water
supply basically satisfied the needs of water use for all sectors except for agriculture sector, in which there was slightly water shortage with 3.45 million m³ in the study area, 1.85 million m³ in Xiushui and 1.6 million m³ in Wuning county, respectively. Since the agricultural responses to the drought strongly which is the main factor of agricultural water shortage, here, we employed the WSRI to assess water scarcity risk deduced by droughts in the upper and middle reaches of Xiu River.

Three representative rainfall gauge stations with 52-year (1957–2010) daily precipitation were selected to calculate drought condition of the upper and middle reaches of the Xiu River. Based on the long-term precipitation series of three gauge stations, corresponding SPI series for multi time scales such as 1-, 3-, 6-, 12-month, were calculated for each station. Here, we defined drought events as a period during where SPI values remained below a threshold of -0.5. Thus, the drought duration ($D$) was the number of consecutive days for which SPI was less than -0.5, and the drought severity ($S$) was the cumulative deficit of the absolute value of SPI for that duration. Then, the drought duration and severity were abstracted from the SPI series of each rainfall gauge station’s record. And all paired drought duration and severity from all regions were pooled to construct the joint probability distribution by empirical copula. Figure 2 shows the cumulative probability curve of the joint drought duration and severity based on the Copulas Frank function for Xiushui county. Thus, the probability of each drought event for all regions was estimated. According to equation (3) and equation (4), the hazard index of each region was obtained to evaluate the relative threats to water scarcity (Table 1).

Figure 1. The allocation results of water resources in the upper and middle reaches of Xiu River.

According to the results of water resources optimum allocation, the exposure index of each region was calculated in the upper and middle reaches of Xiu River based on equation (5) and equation (6), and also the vulnerability index of each region was calculated based on equation (7) and equation (8). Finally, according to equation (9), the value of the WSRI for each region was obtained (Table 1). Table 1 shows all risk indices during drought periods in the upper and middle reaches of Xiu River.

The WSRI value of each region demonstrates the status of water scarcity and depicts the real risk conditions (Table 1). Table 1 shows that EI value of each region was relatively close. Compared with HI values in Xiushui county and Tonggu county, HI values in Wuning county was relatively weakest. For the VI values and EI values, there was a large difference among three counties. The calculated EI ranged between 0.03 and 0.93, which the highest was 0.93 in Xiushui county, the minimum was 0.03 in Tonggu county. And the value of VI was ranged between 0 (Tonggu county) and 0.5 (Xiushui county). The WSRI, revealing the risk degree of water scarcity, had a range between 0 (Tonggu county) and 0.17 (Xiushui county), which, in general, implied a low level of water shortage problem in the upper and middle reaches of Xiu River during drought periods. Although Xiushui county and Tonggu
county had similar drought risk, water scarcity risk in Xiushui county was higher than in Tonggu county due to the less vulnerability of water scarcity risk in Tonggu county. Meanwhile, in terms of the WSRI values, there was a certain degree of the water scarcity risk in Xiushui county and Wuning county, but it was at a low level, as long as we take the corresponding measures, the water scarcity risk can be reduced. And the results were in line with the situation about the level of exploitation and utilization and scarcity of water in the study area.

Table 1. Risk indices during drought periods in the upper and middle reaches of Xiu River.

| Zone     | P    | HI  | U      | EI  | V   | VI  | WSRI |
|----------|------|-----|--------|-----|-----|-----|------|
| Xiushui  | 1.345| 0.57| 51199.09| 0.93| 0.04| 0.33| 0.17 |
| Tonggu   | 1.342| 0.57| 12899.66| 0.03| 0.00| 0.00| 0.00 |
| Wuning   | 1.290| 0.50| 27529.86| 0.50| 0.06| 0.50| 0.12 |

4. Conclusion

Although not all water resources systems suffer water scarcity under a given drought situation, drought conditions can impose additional stress on water supply systems, which have to face the risk of water scarcity induced by drought. Therefore, it is still a necessary consideration for sustainable development of water resources to develop methods to analyze and control the risk of water scarcity during drought periods. In this paper, an integrated risk index (WSRI), was proposed using a multiplicative formula of drought hazard index, exposure index, and vulnerability index to quantitatively assess drought-induced water scarcity risk based on relationship between water use and water supply. The proposed approach was applied to assess water scarcity risk during drought periods in the upper and middle reaches of Xiu River, China. The results show that the water scarcity risk of the upper and middle reaches of Xiu River during drought periods was at a low level, which was consistent with the situation about the level of exploitation and utilization and scarcity of water in the study area. Therefore, the proposed approach can provide a tool for drought-induced water scarcity risk analysis, future water-resources planning and economic developments in the Xiu River Basin, and other relevant or similar studies.

Acknowledgements

This work was financially supported by CRSRI Open Research Program (Program SN CKWV20132 18/KY), National Natural Science Foundation of China (51309130) and the Natural Science Foundation of Jiangxi Province (20132BAB213025).

References

[1] Hashimoto, T, Stedinger J R and Loucks, D P 1982 Water Resour. Res. 18 14-20
[2] Rijssberman F R 2006 Agr Water Manage 80 5–22
[3] RUAN, B Q, HAN, Y P, Wang, H and JIANG, R F 2005 J Hydraul Eng 36 906-12
[4] Wang H and Wang J H 2012 Bull Chin Acad Sci 3 351-58
[5] Gleick, P H, Allen, L, Cohen, M J, Cooley, H, Christian-Smith, J, Heberger, M and Schulte, P 2011 China and Water 7 79-100
[6] Wang, H R, Qian, L X, Xu, X Y and Wang, Y 2009 J Hydraul Eng 40 813-21
[7] Zhang, S, Meng, X, Hua, D, Chen, J, Li, J, Zhang, Y and Xia, J 2012 J. Resour. Ecol. 2 362-69
[8] Shiau, J T and Hsiao, Y Y 2012 Natural hazards 64 237-57
[9] Jinno, K, Xu, Z X, Kawamura, A, and Tajiri, K 1995 International Journal of Water Resources Development 11 185-204
[10] Merabtene, T, Kawamura, A, Jinno, K and Olsson, J 2002 Hydrological Processes 16 2189-208
[11] Feng P 1998 Journal of Natural Resources 13 139-43
[12] Qian, L, Wang, H and Zhang, K 2014 Water Resour. Res. 28 4433-47
[13] Renfroe, N A and Smith, J L 2002 Threat/vulnerability assessments and risk analysis (Cambridge: Applied Research Associates Inc)
[14] Mileyti D S 1999 *Disasters by Design: A Reassessment of Natural Hazards in the United States* (Washington D C: Joseph Henry Press)

[15] Łabędzki, L 2007 *Irrigation and Drainage* **56** 67-77