Dynamic risk assessment method of urban drought based on water balance and optimal allocation analysis

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Abstract. Based on the analysis of driving factors of urban drought, this paper adopts different methods of water balance and drought identification for different water supply sources, such as local water storage and transit runoff. By calculating the city water shortage rate and frequency under different water supply conditions and combining with the benefit analysis model of water supply for each water using sectors, the relationship curve between water loss and water shortage rate for each major industry in cities and towns is established. Based on the dynamic optimal distribution of water shortage for each industry and the forecast results of precipitation and runoff, the dynamic loss and risk assessment method for urban drought with different water supply sources is put forward. Taking Qidong County and the towns of Hengyang City along the Xiangjiang River as examples, the model method is validated. The results show that there is a power function relationship between the urban drought loss and the water shortage during the drought period, the models may provide theoretical reference for optimizing urban water allocation management and making urban drought resistance plan.

1. Introduction

In recent years, the problem of city water supply shortage due to drought is prominent in China, which causes serious losses to urban production and life. Statistics show that there are still more than 100 serious water shortages in about 660 cities in China, of which about 35% are in the south, especially in some counties and towns where the water source is relatively single, such as small reservoirs, dams and ponds. Due to the relatively low water supply guarantee rate for these areas, when extreme water shortage occurs, the contradiction of water shortage in industry, life, agriculture and ecology is more prominent. In the emergency plan for flood control and drought relief of China, it is clearly defined that urban drought refers to the shortage of urban water supply sources in dry years, or the destruction of urban water supply sources due to emergencies, which result in water supply capacity cannot meet the normal water demand, thus affecting the industrial production, life and ecological environment of city.

In order to realize the early warning of urban drought, it is necessary to study the loss mechanism of urban water shortage due to drought, that is the response relationship of different industries losses under different levels of drought in different water sources areas. At present, the relevant researches
about urban drought risk are mainly focused on drought early warning index, drought limit water level of river and reservoir, emergency plan for urban drought resistance (Zhao, 2018; Qu, 2012; Aditi, 2013; Patricia, 2016; Feng, 2018; Maria, 2018). From the perspective of drought resistance and water balance between water supply and water requirement, the agriculture drought resistance model in irrigated areas was builded (Jin et al., 2013), the risk of water shortage in city water supply system is quantitatively described from the uncertainty of water supply and water utilization (Han et al., 2003).

In this study, we (1) investigate the loss of water supply system with the development process of urban drought in perspective of economic loss, social impact and damage degree of ecological environment; (2) Based on the analysis results of water balance between water supply and water requirement, the water shortage is optimally distributed among various water consumption sectors, and establish the relationship curve between water shortage loss and water shortage rate index; (3)Explored a general framework about the dynamic assessment method of loss and risk of water shortage due to drought with different situations in different types of water source cities and towns.

2. Material and methods

2.1. Study area

In this paper, Hengyang City, located in hengshao arid corridor, is selected as the research area. Hengyang City is located in the south of Hunan Province, the middle reaches of Xiangjiang River, which belongs to subtropical monsoon humid climate area. It is rainy and cold in spring, hot in summer and early autumn, the winter cold period is short with ice and snow. Due to the influence of monsoon and underlying surface, the spatial and temporal distribution of precipitation is uneven. The annual average precipitation of the whole city is 1240-1470mm, with more than 50% of annual precipitation concentrated from April to June. The precipitation from July to September only accounts for about 18% of the whole year, which does not match the agricultural water demand.

There are numerous rivers in Hengyang city, such as Chongling river, Lei river, et al., the annual average surface runoff is 10.94 billion m$^3$, however, it’s relatively short of water resources, the per capita water resource is 1491 m$^3$, only about 60% of Hunan Province. According to statistics, from 1950 to 2017, drought occurred in different degrees in an average of about 1.5 years in Hengyang city, most of them are agricultural drought and rural people’s drinking difficulties. In recent years, with the increase of the proportion of secondary and tertiary industry, the phenomenon of urban water shortage due to drought has become increasingly prominent, especially in the urban areas which only rely on a single water source of reservoir for water supply. In this areas, the situation of urban drought is more likely to occur due to the lack of transit runoff supply.

![Figure 1. Location of Hengyang city and Qidong county in Hunan Province](image-url)
2.2. Formation mechanism of urban drought
According to the national emergency plan for flood control and drought relief issued in 2006, urban drought is mainly due to the lack of natural coming water or the impact of human activities, which makes the actual water supply capacity in a specific area of the city lower than the normal water demand, and brings potential economic loss, social impact and ecological environment damage to various industries of the city.

2.3. Drought identification method of different water source
The urban water supply source can be roughly divided into storage, diversion and lifting, among which the water supply capacity of water storage and diversion mainly depends on precipitation, and the water supply capacity of river lifting mainly depends on the amount of runoff. For different water supply sources in urban areas, this paper selects precipitation (storage supply sources) and runoff (river lifting and diversion supply sources) as drought identification factors, and puts forward corresponding identification methods of urban drought process (Gabriela, 2018; Pablo, 2018; Qian, 2015; Tao, 2019). As precipitation mainly reflects the water storage of the whole region, using run theroy to identify the drought process (including duration, intensity, etc.); runoff directly reflects the water supply capacity of transit water resources, and can be directly identified by the threshold method.

Run theory is a method to analyze time series, which is widely used in drought identification (Zhou et al., 2011). In this study, we considering that the available water supply is not only related to the current precipitation, but also depends on the water storage generated by the previous precipitation, so the run theory can be used to identify drought in the areas where the water sources is relying on reservoir water storage(for example: Qidong county in this study).

For the area with river water extraction as the main water supply source (for example: riverside town of Hengyang city in this study), the runoff directly reflects the abundance of the incoming water. We set a fixed threshold as the discrimination condition, that is, when the daily runoff in the current month is lower than the threshold, the drought occurs in that month. When the daily runoff in two or more consecutive months is lower than the threshold, the continuous drought occurs. The determination formula of the threshold is as follows:

$$Q_{Ti} = Q_{Ei} + Q_{Di} + Q_{Pi} - Q_{Ri}$$ (1)

Where $Q_{Ti}$ is the critical threshold value of river daily runoff, $Q_{Ei}$ is the river ecological environment water demand, $Q_{Di}$ is the downstream comprehensive water demand, $Q_{Pi}$ is the water intake capacity of the study area, $Q_{Ri}$ is the return water volume corresponding to the water intake, and $i$ is the month.

2.4. Water shortage caculation during drought and optimal allocation
Based on the mechanism of urban drought, this study uses the method of water balance between water supply and demand to calculate the water shortage in dry period. For urban areas with local water storage as the main water source, the water supply capacity during the drought period depends on the current precipitation and the water storage brought by the early precipitation. Therefore, based on the calculation of the annual available water supply, the available water supply during the drought period should be calculated according to the distribution coefficient within the year of available water supply. Considering that there is a power function relationship between annual water supply and precipitation frequency, the calculation formula of water supply during drought period can be summarized as follows:

$$Q_{year} = a_1 \cdot P^2 + b_1 \cdot P + c_1$$ (2)

$$Q_{drought} = Q_{year} \cdot T \cdot X$$ (3)

Where $Q_{year}$ is the annual available water supply in the first 12 months of the drought period (including); $Q_{drought}$ is the available water supply in the drought period, $P$ is the precipitation frequency, $50\% \leq P < 1$; $X$ is the monthly distribution coefficient of available water supply (the percentage of monthly available water supply in the whole year), $a_1$, $b_1$ and $c_1$ are the coefficients.
For urban areas with surface runoff as the main water source, the available water supply during the drought period is directly determined by the amount of river runoff and has little relationship with the amount of early runoff. Meanwhile, considering the water intake capacity of water supply facilities, the calculation formula of available water supply during the drought period can be summarized as follows:

\[ Q_{\text{drought}} = \min\left( Q_{\text{intake}}, Q_{\text{up}}, Q_{\text{down}}, Q_{\text{en}} \right) \]  

Where \( Q_{\text{drought}} \) is the available water supply in the drought period, \( Q_{\text{intake}} \) is the water intake capacity of water supply facilities, \( Q_{\text{up}} \) is the the amount of river runoff, \( Q_{\text{down}} \) is the normal water demand downstream, \( Q_{\text{en}} \) is the water demand of ecological environment.

Urban water demand mainly includes industrial, agricultural, tertiary industry, residential, etc. When agriculture accounts for the majority, the total water demand is a function of population, industrial output value, temperature and month. According to some research results and the verification of historical statistics data, there is a power function relationship between the total normal water demand and precipitation frequency, and the calculation formula is as follows:

\[ W_{\text{demand}} = a_2 * P^{2} + b_2 * P + c_2; 50\% \leq P < 1 \]  

Urban water shortage ratio due to drought refers to the ratio of water shortage to water demand during the drought period, thus the calculation formula is as follows:

\[ WR = \left( [a_1 - a_3] * P^4 + (b_1 - b_3) * P + (c_1 - c_3) \right)/ [a_2 * P^2 + b_2 * P + c_2] \]  

Where \( WR \) is the water shortage ratio due to drought, \( W_{\text{demand}} \) is the total normal water demand, \( P \) is the inflow frequency.

When urban drought occurs, it is necessary to optimize the distribution of water supply for various industries to reduce the loss of drought as much as possible, such as limiting the water for high water consumption industries, compressing the water for agriculture, giving priority to domestic water use and key industrial water use, etc. At present, the commonly used distribution methods include: on-demand proportional distribution method, efficiency distribution method, output value distribution method, optimization model, etc. At the same time, the urban drought plan gives the water allocation rules among industries under different response levels. In this paper, the optimal allocation method of urban drought and water shortage is put forward. The water consumption is divided into industrial water, domestic water, agricultural water and ecological environment water, the optimal allocation model formula is as follows:

\[ \min L(x) = \sum P_i/W^i \times W_{Di} \times f_i (W_{Di}) \times S_i \times E_i \]  

s.t. \( \sum W_{Di} = W \)  

\( 0 \leq W_{Di} \leq W_i \)

Where \( L(x) \) is loss of urban drought, \( P_i \) is the total regional output value of the specific industry, \( W_i \) is the normal water consumption of the specific industry, \( W_{Di} \) is the water shortage of the specific industry, \( W \) is the total water shortage, \( f_i (x) \) is the change coefficient of water supply efficiency, \( S_i \) is the social impact coefficient of the specific industry, \( E_i \) is the ecological environment impact coefficient of the specific industry.

2.5. Urban drought loss caculation and the response relationship with water shortage

In order to describe the proportion of water shortage loss to the total regional output value in normal years, the loss index of urban water shortage due to drought is proposed, and its calculation formula is as follows:

\[ LI = \sum X_i \times E_i \times f(X_i) \times S_i \times \sum P_i; i=1,2,3,4 \]  

\[ E_i = P_i/W_i \]  

Where \( LI \) is the loss index of urban water shortage due to drought; \( X_i \) is the water shortage of industrial enterprise, tertiary industries and agriculture; \( E_i \) is the benefit generated by each cubic meter of water supply; \( P_i \) and \( W_i \) are the output value and total water consumption of each industry; \( f(X_i) \) is the coefficient of change of economic loss. Considering that the economic loss is non-linear growth with the increase of water shortage, the higher the water shortage rate, the faster the economic loss growth. Therefore, \( f(X_i) \) is a function that changes with \( X_i \), which can be determined by fitting
historical loss and water shortage data; $S_i$ is the weight coefficient of social impact; For water shortage loss of ecological environment, considering that water shortage of ecological environment will occupy the comprehensive water demand of downstream, the loss of ecological environment due to drought can be expressed by water shortage loss of downstream industries.

On the basis of the calculation results of water shortage and the corresponding loss of each industry, the relationship curve between the drought loss index and the total water shortage, and the relationship curve between the loss of each industry and the water shortage ratio of each industry can be established. Combined with the rainfall runoff forecast model, the dynamic assessment of urban drought loss can be realized.

2.6. Dynamic risk assessment method of urban drought

In this paper, the expected loss rate caused by drought is used to express the risk of urban water shortage due to drought. The calculation formula is as follows:

$$RD = \sum_{i=1}^{n} L_i \cdot P(L),$$

Where, $RD$ is the risk index, $L_i$ is the loss of water shortage due to drought of the city, and $P(L)$ is the corresponding frequency of drought. When the precipitation and runoff are predicted, the dynamic assessment of water shortage loss and risk can be realized, and the process is shown in Figure 1. It includes drought identification, frequency calculation, water balance analysis, water shortage calculation and allocation rules formulation, the relationship formulation between industrial loss and water shortage, urban drought risk calculation, etc.

3. Results and discussions

3.1. Model validation

In order to reveal the response of different industries to drought loss and water shortage, and to select the appropriate distribution curve, the statistical data of industrial drought loss in Changsha Zhuzhou Xiangtan area from 2000 to 2007 were selected for analysis and verification, the curve is as shown in Figure 3. It can be seen that there is a power function relationship between industrial water shortage...
and the corresponding industrial loss, which can better reflect the change characteristics of industrial water shortage loss. That is to say, because of the drought resistance measures such as proper compression of non important links and high water consumption of enterprises, the industrial loss is relatively small at the beginning of drought. However, with the increase of water shortage, the industrial loss will increase rapidly.

Figure 3. The relationship curve between industrial drought loss and water shortage

3.2. Results of drought process identification

For Qidong County, where the main water source is the storage project that relying on precipitation to recharge, it is suitable to identify the drought with the monthly precipitation anomaly as the index. Table 1 is the drought process with more than 5-year return period identified by the run theory. Considering that the precipitation outside the drought period may be relatively abundant, the frequency of incoming water mainly depends on the precipitation in the early 12 months, and has no direct correlation with the precipitation during the drought period.

Table 1. Drought process in Qidong County from 1960 to 2018

| drought period | duration (month) | drought intensity | return period (year) | average monthly precipitation during drought (mm) | average precipitation in the first 12 months (mm) | inflow frequency (%) |
|----------------|------------------|-------------------|----------------------|--------------------------------------------------|-------------------------------------------------|---------------------|
| 1964.5-1965.1  | 9                | 2.043             | 31.92                | 50.3                                             | 77.3                                            | 90                  |
| 1966.7-9       | 3                | 1.204             | 6.74                 | 27.9                                             | 80.9                                            | 85.53               |
| 1971.9-1972.1  | 5                | 1.846             | 14.90                | 17.0                                             | 71.2                                            | 95.25               |
| 1974.9-11      | 3                | 1.069             | 6.03                 | 19.0                                             | 85.1                                            | 79.12               |
| 1979.10-12     | 3                | 1.606             | 9.74                 | 5.4                                             | 86.8                                            | 76.23               |
| 1988.10-12     | 3                | 1.415             | 8.13                 | 12.0                                             | 94.7                                            | 60.78               |
| 1991.4-7       | 4                | 0.262             | 5.38                 | 89.1                                             | 94.2                                            | 61.72               |
| 1992.8-11      | 4                | 1.618             | 10.99                | 17.8                                            | 111.7                                           | 27.45               |
| 1998.10-1999.2 | 5                | 1.350             | 10.70                | 23.4                                            | 91.0                                            | 68.32               |
| 2003.7-11      | 5                | 1.297             | 10.40                | 29.0                                            | 97.0                                            | 55.98               |
| 2004.9-10      | 2                | 1.129             | 5.39                 | 4.9                                             | 103.2                                           | 42.91               |
| 2005.7-10      | 4                | 1.396             | 9.22                 | 26.4                                            | 101.0                                           | 47.43               |
| 2007.10-11     | 2                | 1.258             | 6.17                 | 1.5                                             | 78.7                                            | 88.39               |
| 2009.8-10      | 3                | 1.114             | 6.25                 | 24.5                                            | 93.5                                            | 63.27               |
| 2010.7-11      | 5                | 1.355             | 10.73                | 33.5                                            | 90.9                                            | 68.4                |
| 2017.8-2018.9  | 14               | 4.151             | 187.85               | 44.7                                            | 46.3                                            | 99.98               |
For the riverside towns of Hengyang City, using the threshold discrimination method to identify the drought process from 1960 to 2018, where the surface runoff of Xiangjiang River is the main water source. The runoff threshold adopts the corresponding flow of normal water demand. According to the calculation results, 11 droughts occurred in 1960-2018, which is relatively rare compared with precipitation recognition results.

3.3. Calculation results of water shortage during drought process and its allocation rules

For different water source types of urban areas, different calculation methods of supply and demand balance and water shortage are adopted. Combined with the relevant planning results and statistical data, the water supply capacity and normal water demand of Qidong County and riverside towns of Hengyang City under different water frequency are calculated respectively. The results are shown in Figure 4, and Figure 5 is the calculation results of water shortage.

(a) Qidong County                              (b) riverside towns of Hengyang City

Figure 4. Available water supply and normal water demand under different frequencies

Figure 5. Calculation results of water shortage under various droughts

Based on the calculation results of water shortage in Qidong County and riverside towns of Hengyang City under various droughts, the model of optimal water shortage allocation is used to calculate the water shortage of industry, life and agriculture under various droughts, as shown in Figure 6.
3.4. Results of Urban drought loss calculation and the response relationship with water shortage
The results of water shortage of each industry is substituted into equation (7) to calculate the total loss value under different water shortage scenarios. In order to compare between different regions and months, the loss index of water shortage due to drought is constructed, that is, the ratio of drought loss to normal output value during the drought period. The relationship curve between the loss index and the total water shortage rate is constructed, as shown in Figure 7.

It can be seen that when the water shortage ratio is less than 40%, considering that most of the water shortage is allocated to agricultural water by the model, the water shortage ratio of urban industrial and domestic water is relatively low, because the proportion of agricultural output value in the region is relatively low, its unit water use efficiency is far lower than that of industrial and tertiary industries, and precipitation has a direct supplement effect on agricultural water demand in the same period, so the total loss index during this period is relatively low; with the continuous growth of the proportion of total water shortage, the water shortage of industry and tertiary industry will increase rapidly, and the corresponding loss will also increase rapidly. This result is consistent with the standard of urban drought classification in the China national emergency plan for flood control and drought relief.

In this paper, the expectation of loss rate caused by drought is used to express the risk of water shortage due to drought in cities. The corresponding risk expectation can be calculated by substituting the loss index and occurrence frequency under each drought into equation (10). The expectation values of water shortage loss due to drought in Qidong County and riverside towns of Hengyang City are 60.8 million yuan/a and 7.1 million yuan/a respectively.
Figure 8 and Figure 9 respectively show the allocation of water shortage due to drought in different industries and the related loss. It can be seen that the drought in summer and autumn is dominated by agricultural water shortage. However, due to the low benefit of water supply per unit of agricultural water consumption, with the increase of water shortage, the water shortage will bring great losses to industry and life. For winter drought, there is basically no demand for agricultural irrigation water during the period, and the loss of water shortage mainly lies in industry and life.

3.5. The characteristics of drought loss under different combinations of drought scenarios
In this paper, drought scenarios in summer, autumn, winter, spring and the combinations are set up, and the response pattern of urban drought loss under different combinations of drought scenarios is studied. The results are shown in Figure 10.

It can be seen that in summer, due to the high proportion of domestic water consumption, with the evolution of drought and water shortage, when the water shortage is small, the water shortage is mainly allocated to agriculture, at this time, the agricultural loss is higher than the industrial loss and the domestic water shortage loss; when the water shortage reaches a certain degree, the domestic water shortage loss (including the tertiary industry) will be higher than the industrial and agricultural loss.

For autumn drought, the response pattern of industrial loss in the initial drought process is the same as that in summer. However, because the industrial water consumption is higher than that in domestic life, when the water shortage reaches a certain degree, the industrial water loss will be higher than that in domestic life and agriculture.

For the case of summer and autumn drought superposition, the total water shortage in summer and autumn is re-optimized in the superposition month by the allocation model, so the total loss of summer...
and autumn drought will be lower than the sum of summer and autumn drought alone. If the allocation of drought and water shortage in each season is planned, the total loss of continuous drought in summer will be higher than the sum of the individual losses of drought in summer and autumn due to the effect of superposition.

![Water shortage loss of various industries](image1)

![Water shortage loss of various industries](image2)

![Water shortage loss of various industries](image3)

Figure10. Response curve of water shortage loss under different combination of drought scenarios

4. Conclusion
In this study, we analyzed the formation mechanism of urban water shortage due to drought, and put forward a calculation model to dynamically assess the urban drought risk based on water balance and optimal allocation of water shortage. Taking Qidong County and riverside towns of Hengyang City as examples, this paper calculates the loss of water shortage due to drought in different water sources and industries, reveals the change rule characteristics of water shortage loss in various industries under the optimized distribution, constructs the index (loss index of urban water shortage due to drought), and calculates the risk of its occurrence. The results may provide theoretical reference for optimizing urban water allocation management and making urban drought resistance plan.

The application results in the study area show that there is a power function relationship between the urban drought loss and the water shortage during the drought period. With the development of urban drought, as the benefit coefficient of unit water supply of agricultural water is relatively low, in the early stage of urban drought, the main loss is in agricultural, when the water shortage increases to a certain extent, the water shortage will bring great loss to industry and life. For different stages of
drought combination superposition, the urban drought loss after superposition depends on the allocation of water shortage, not the direct sum relationship.

Starting from the definition, development process and driving mechanism of urban drought, based on the principle of water balance and optimal allocation method, this paper preliminarily constructs a dynamic assessment framework of urban water shortage risk due to drought, and conducts a preliminary demonstration area study. Considering that the impact of urban drought not only depends on natural factors, but also depends on the human regulation and allocation of water resources, water quality changes, etc., thus further research may use more influencing factors to improve the model. At the same time, compared with agricultural drought and hydrological drought, the statistical data of urban loss due to drought is lack, and the model test and calibration need to be strengthened. In order to refine the model, the industries of urban water shortage due to drought can be further divided into high water consumption industry, general water consumption industry and water-saving industry, or divided into key guarantee and general guarantee water using sector.

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