Risk estimation for flood and drought: case studies

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Abstract The concept of sustainable development not only strengthens but also extends the main principles and policies of water resource management. In sustainable and integrated water resource management, risk analysis/management for floods and droughts has received much attention. Risk and uncertainty in hydrological processes have been intensively studied, and many significant achievements have been made. This paper presents two case studies of risk assessment for flood and drought. A stochastic point process model for flood risk estimation is first derived by using a clustering stochastic point process. Then, several risk indices including reliability, resilience, vulnerability and risk plane for drought assessment are introduced. The proposed methodology is applied to an example water supply system with the combination of a decision support system.

Key words drought; flood; reliability; resilience; risk; vulnerability; water resources

INTRODUCTION

Too much water is a disaster, too little is a calamity as well. Water related disasters, i.e. severe surplus or deficit of water, have been more devastating in terms of deaths, suffering and economic damage, than any other natural hazards, such as those resulting from earthquakes and volcanoes. Despite much progress in science and technology, humans are still vulnerable to floods and droughts. In attempts to deal with floods and droughts the main focus has been to understand the cause–effect components of the physical processes. In particular, risk analysis for flood and drought has been one of the research fields that has received continued attention in recent years. Together with the new concept of sustainable development, it greatly extends the principles of water resource management (Simonovic et al., 1992). However, the difficulties for risk analysis of floods with clustering features, and the risk measurement for drought, are still open for further study. This paper presents an application of flood and drought risk. A stochastic point process model for flood risk is derived in the following section. Then, the development of a performance index for a water resource system and the procedure to assess the drought risk is described. A case study demonstrates the ability of decision support systems (DSS) to provide assistance to the risk analysis of water resource planning scenarios.

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FLOOD RISK MODEL FORMULATION

In flood risk analysis, a basic task is to estimate the design flood with a specified risk of exceedance within a given period. The choice of a suitable design flood requires statistical treatment of observed historical flow data. Common techniques are: (a) the annual maximum series (AMS) method, which consists of fitting a distribution function to the series of largest annual floods; and (b) the partial duration series (PDS) method, which considers all floods that are larger than a given threshold (Rasmussen & Rosbjerg, 1991). This paper will focus on the partial duration series where all floods above a certain threshold level are taken into account.

Let a threshold level, \( q_0 \), be introduced in a continuous flood hydrograph. If a flood peak, \( Q_i \), at a given time point is larger than \( q_0 \), an exceedance is said to have occurred. Let \( X_i \) denote the magnitude of the \( i \)th exceedance of \( q_0 \) in time period \((0,t)\), i.e.:

\[
x_i = Q_i - q_0
\]

The PDS model adopted here assumes that the variables \( x_i, i = 1, 2 \ldots , N \) are independent of each other as well as of their time of occurrence, and follow an exponential distribution. The total number of exceedances in \( t \) years, \( N \), is a Poisson point process with parameter, \( \lambda_t \). The intensity of the Poisson process denotes the occurrence rate and does not depend on time. Statistical analysis performed previously has proved the efficiency of the Poisson process in flood risk analysis (Xu et al., 1998).

In practice, it is quite possible to have a low threshold \( q_0 \) corresponding to a certain preliminary design such as a coffer construction or short-term flood forecasting. When the critical value \( q_0 \) is low, there may be many flood peak values exceeding \( q_0 \). The peak exceedance count process may then present some degree of clustering which would necessitate a new kind of risk model. A point process is said to be a cluster process if it is defined in terms of two components: (a) a process of cluster centres; and (b) a subsidiary process defining the configuration of the members within a cluster. The whole process is then taken as the superposition of all clusters. As one example of the stochastic point process models, the Poisson-Bernoulli model is derived, in which the basic assumptions are: (a) the number of flood peaks in period \((t_0, t_0 + t)\) follows a Poisson process with the following parameter:

\[
p\{N_t = k\} = \frac{(\lambda t)^k}{k!} e^{-\lambda t}
\]

and, (b) let \( n_k \) be the number of flood peaks in \( k \)th cluster, then \( n_k \) is an independently and identically distributed random variable, which follows the Bernoulli distribution:

\[
p\{n_k = l\} = \binom{n}{k} p^l (1 - p)^{n-l}
\]

where \( n \) is the largest number of flood peaks in clusters. The p.g.f. of the Bernoulli distribution is:

\[
H(z) = (pz + q)^n
\]

in which \( p \) is a parameter and \( q = 1 - p \). The p.g.f. of the cluster process may be written as:

\[
F(z) = \exp \{\lambda t [(pz + q)^n - 1]\}
\]
By extending the progression it can be shown that:

\[ F(z) = e^{-\lambda t} \left[ 1 + \frac{\lambda q^n}{1!} (1 + \frac{p}{q} z)^n + \frac{(\lambda q^n)^2}{2!} (1 + \frac{p}{q} z)^{2n} + \ldots \right] \]  

(6)

Then the risk that one or more exceedance floods occur in future \( t \) years may be obtained as:

\[ R(t) = 1 - \exp[\lambda t(q^n - 1)] \]  

(7)

As long as the parameters \( n \) and \( p \) are obtained, it is not difficult to estimate the corresponding risk in the future \( t \) years.

**DROUGHT RISK ASSESSMENT MODEL**

In water supply systems, both water supplies and demands are driven by the variability of climate conditions such as rainfall and temperature. To avoid unacceptable risk of either extreme shortage or lengthy smaller shortages during critical periods, and to evaluate various types of failures for a municipal water system, different kinds of risk criteria should be identified and studied. Quantifying these criteria and incorporating them into mathematical models of planning and operation may result in improved policies for a municipal water system.

**Reliability**

Reliability means the possibility of non-failure of system operations over an \( N \)-year planning period. It is usually defined as the probability, \( \alpha \), of the system being in a satisfactory state:

\[ \alpha = P\{X_t \in S\} \]  

(8)

where \( S \) is the set of all satisfactory outputs. In water supply systems, reliability may be defined as the probability of a system delivering the desired water to users, i.e.:

\[ \alpha = \frac{1}{NS} \sum_{i=1}^{NS} I_{[i]} \]  

(9)

in which \( NS \) is total days of water supply period and \( I_{[i]} \) is a state variable of the water supply system. \( I_{[i]} \) is equal to 1 if no deficit occurs, and is equal to zero if a deficit occurs.

**Resilience**

Hashimoto *et al.* (1982) suggested that resilience can be a measure of the probability of being in a period of no failure. According to this definition a resilient system is one that is capable of recovery from a deficit state to normal operation in a short time. In
this study, resilience is adopted to describe the capability of a water supply system to return to a satisfactory state from a state of failure, which may be defined as the conditional probability, $\beta$:

$$\beta = P \{ X_i \in S / X_{i-1} \in F \}$$

in which $F$ is the set of all unsatisfactory outputs. It may also be expressed as (Jinno et al., 1995):

$$\beta = 1 / E[T_i]$$

where $E[T]$ is the expected failure period. In this paper, resilience is defined as the inverse of the average period of water deficit, that is:

$$\beta = \begin{cases} \frac{1}{NF}, & NF \neq 0 \\ \frac{1}{NF} \sum_{i=1}^{NF} FP_i, & NF = 0 \end{cases}$$

in which $NF$ is the total number of system failures and $FP_i$ is the length of period for the $i$th failure. If $NF = 0$, which means $FP = 0$, then $\beta = 1$. This states that the system is in its satisfactory state during the whole water supply period. In the general situation, $0 < \beta < 1$, which means that the water supply system is in its unsatisfactory state (deficit occurs), and it will return to its satisfactory state. The longer the average water deficit period, the smaller the resilience. This means that if water deficit occurs during a longer period, it is more difficult to satisfy water demand.

**Vulnerability**

Vulnerability is a measure of the severity of a failure. In a water supply system, vulnerability may be defined as the magnitude of the largest deficit of water during the period of operation. In the present study, vulnerability is used to describe the significant consequence of drought:

$$\gamma = E \{ Se \}$$

in which $Se$ is a numerical indicator of drought severity. In combination with the situations of the municipal water system, the indicator used here is the average deficit during the whole supply period divided by the average water demand during the same period:

$$\gamma = \left[ \frac{\sum_{i=1}^{NF} VE_i}{\sum_{i=1}^{NF} VD_i} \right]$$

where $VE_i$ is the $i$th water deficit in $m^3$ and $VD_i$ is the $i$th water demand in $m^3$ during the $i$th deficit period. $\gamma$ is generally less than one and greater than zero, which means that the larger the water deficit, the greater the vulnerability.
**Drought Risk Index (DRI)**

To enable easy identification of the characteristics for different systems or subsystems, an integrated risk index, drought risk index (DRI), as a linear weighted function of reliability, resilience, and vulnerability, is defined as:

\[ v = w_1(1 - \alpha) + w_2(1 - \beta) + w_3\gamma \]  

(15)

where \( w_1, w_2 \) and \( w_3 \) are weights that need to be predetermined. Drought risk may also be defined as the set of triplets as follows:

\[ R = \{(\alpha_i), (\beta_j), (\gamma_k)\} \]  

(16)

Then it may be expressed in the form of a three-dimensional plane, which is further defined as a risk plane in this paper, as shown in the following section.

**DSS FOR RISK ANALYSIS: CASE STUDY**

Recent trends in the solution of water management problems have been to aggregate several models into an integrated decision support system (DSS). A DSS approach focuses on the interaction and interface between the user or analyst, and the data, models and computers (Câmara et al., 1990). In the present study, a daily planning model for a water supply system has been developed using time series technique, a tank model, and a risk assessment model. It uses a master library that includes compatible modules for assisting the integrated water management of river basins. In the DSS, the graphical-user-interface facilitates data entry, operating the model, and producing and displaying time-series plots and statistical analyses of simulation results. The possible daily inflow to reservoirs is first forecast by using time series or the tank model. Secondly, the release and storage schedules of the reservoirs are obtained by using daily operational regulations. Thirdly, with the combined simulation model, the target water demand in the river basin is obtained on the basis of the simulation model. Finally, the risk indices are used to evaluate the feasibility of the predetermined water management policy, which may be used as the guidelines for the selection of planning scenarios.

As one example of the application, the DSS was used to assist the assessment of water supply risk for the city of Fukuoka, Japan (population 1.2 million). The city supply system is composed of eight reservoirs (Fig. 1). Besides these water sources, Fukuoka also withdraws water from the Chikugo River, 40 km away from the city. Groundwater is also used for water supply, but in small amounts. The water supply system of Fukuoka is a typical run-of-the-river system with much dependence on river flow. However, the small river flow and the very limited availability of dam sites seriously hinder the further development of new water sources. Although Fukuoka is located in a typical humid region with an annual precipitation of 1800 mm, water shortage has frequently occurred during the past several decades.

A severe drought in the Kyushu region during 1994–1995 continued for more than 330 days. The importance of developing new water sources in Fukuoka is sufficiently understood not only by local government and water authorities but also by the public and residents. Due to the shortage of an available dam site, methods of increasing sea
water desalination was considered by the local water authorities for several years. Although the cost is much higher than other measures, it is still fascinating for its stability as a water resource. With the combination of water supply data in 1994, the risk to water supply was assessed by using the DSS developed in this study. According to the results, if the amount of desalination increased by 20,000 m$^3$ d$^{-1}$ from January, the water supply risk would be zero up to October. If this supply was increased by another 10,000 m$^3$, the water would be supplied without any risk until November. But
risk still exists in December, as shown in Fig. 2. For the 1994–1995 drought, the water supply risk would become zero if Fukuoka increased its daily seawater desalination capability to 35 000–40 000 m$^3$. Considering the sustainable development of economics and industrialization in Fukuoka in the near future, a daily capability of sea water desalination of 50 000 m$^3$ is therefore suggested.

CONCLUSIONS

In water resources management, any decision or action, including in-action, carries risk. People are usually risk averse. It is hard to say how much the acceptable risk is. But risk is truly an inherent character of hydrological processes. Risk analysis for floods and droughts needs to find more reasonable strategies and mechanisms that make the control of this risk economically efficient and socially tolerable. Additional criteria like equity and sustainability also need to be included. The integration of risk analysis and geographical information systems (GIS) is another new trend. Floods and droughts are all spatially distributed problems. GIS is an efficient tool for the capture, manipulation, processing, and display of spatial data. GIS and its capability to map risks is clearly a powerful tool for risk analysis. It appears that the use of GIS and spatial display of the results for flood and drought risk analysis is an area that merits investigation in the future.

REFERENCES


