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# An Early Warning System of Water Shortage in Basins Based on SD Model

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**Abstract**

The water resource system, related to society, economy and environment, is a compound feedback system. Supply and demand of the water resources in basins interacts with the development of social economy as well as the aquatic ecosystem. Therefore once suffering crisis of water shortage, not only the socioeconomic system will be confronted with large financial loss, but also the original aquatic ecological equilibrium in basins will be broken. This paper constructed an early warning system of water shortage by using Stella software based on the system dynamics (SD) model, which has been believed to delineate clearly the coupling correlation between the water resource and the social economic system and aquatic ecosystem. The ecological flow was considered as an indispensable element in the water demand. So the calculation model of ecological flow was involved in the SD model, which distinguished it from traditional model of water resources supply and demand. Moreover, the supply and demand ratio was chosen to predict the variation of supply and demand of the socioeconomic water as well as ecological flow by means of simulation under a given scenario of water shortage.



*Keywords:* Water shortage; Early warning; System dynamic; Ecological flow; Stella

## 1. Introduction

Water resources is a concept with twin attributes involving society and natural environment. Obviously, that means the system is complex and large scale, involving numerous factors including social economy, population, resources, environment, ecology, etc. (Giupponi et al., 2004). These factors interact as both cause and effect, restrict each other and act as a positive feedback as well as a negative feedback (Feng and Huang, 2008). However, Along with the fast development of the society and economy and acceleration of urbanization process, the problem of water resource shortage in basins has extremely increased. When such a water shortage event occurs, not only the socioeconomic system will be confronted with large financial loss, but also the original aquatic ecological

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equilibrium will be broken. Therefore, it is crucial to establish an early warning system to forecast the occurrences of water shortage for minimizing the socioeconomic and environmental loss.

However, scholars often estimated some selected indicators in a district by establishing some linear relationship to achieve the purpose of the drought early warning (Chou and Chen, 2007). Yet it is not proper for the early warning of water shortage, which is a nonlinear, time varying and coupling problem. And some researches proved that the established system dynamics (SD) model was useful to delineate clearly the coupling correlation inside the complicated water system (Han et al., 2006; Elshorbagy, 2005). Just based on this, the SD model will be introduced to construct an early warning system of water shortage in this paper. But applications of the SD model on the water management focused mainly on socioeconomic water demand, such as irritation water, indoor water or wastewater (Krystyna, 2003), rarely considering ecological flow which directly influences degradation of basins (Kashaigili et al., 2005). However, it is essential to consider ecological flow in early warning system for maintaining ecological security in basins. Hence, in the study, the calculation model of ecological flow will be embedded in the SD model, which can make the result more scientific and reliable. Furthermore, the supply and demand ratio will be forecasted as the most comprehensive index of water shortage, considering the relationship between all sorts of water supply and demand.

## 2. Early Warning Model for Water Shortage

In this paper, the SD software Stella version9.0.1 (Isee systems.inc., 2006) was applied to establish the early warning system based on its practical operation and powerful design tools (Costanza et al., 1998). The SD model was constructed from two aspects, that is, water supply system and water demand system.

The early warning system for water quantity was established based on the relationship between supply of basins and demand of socioeconomy and aquatic ecosystem. Therefore, the crisis of water quantity could be directly diagnosed through whether the water support and demand in basins came into balance. Figure 1 shows a general water supply system that includes all of the modeled surface water supply and ground water supply. For planning purposes, calculations are performed on a monthly time step. Alternative time steps can also be examined.

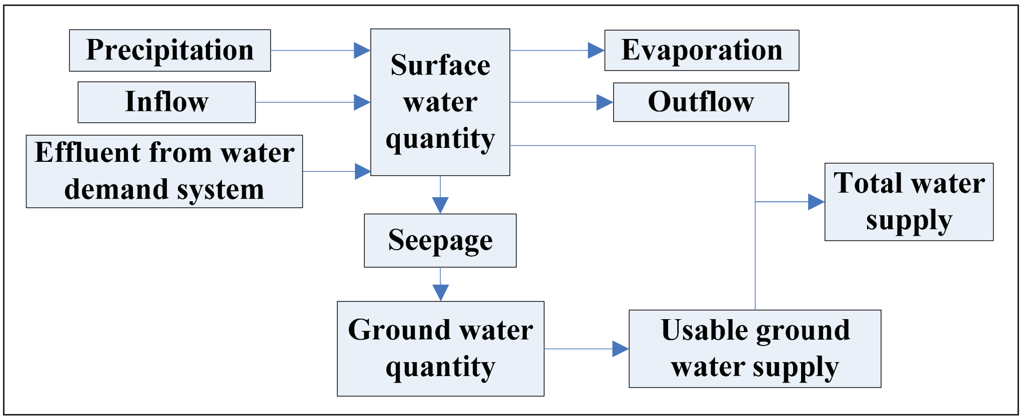


**Figure 1**. Schematic of a generic water supply system.

Water enters the system as precipitation or from the upper river and leaves the system as evaporation/transpiration or outflow downstream. On the other hand, surface water flows down slowly to recharge groundwater. Water in the system is provided to users around for daily use unless surface water level fall down to the lowest point which means the water system is on the verge of drying up. In reality, however, surface water level in some basins may drop below the lowest point for nobody can accurately control the surface water supply and seepage when the water level closes to the limit point. Depending upon the use, surface water can be sent directly to users or through a water treatment plant. According to the water supply system mentioned above, the following equations, added several parameters in the mass-balance mathematical equations (Mitsch and Gosselink, 2000), are used to determine the structure of the dynamic simulation model for monthly water supply:

$$SW(t) = SW(t-\Delta t) + [I(t) + P(t) + Ed(t) - E(t) - O(t) - SS(t) - SE(t)] * \Delta t \quad (1)$$

$$TS(t) = SW(t) + SS(t) + GS(t) \quad (2)$$

where $t$ is simulation time, $SW$ is surface water quantity; $I$ is monthly inflow; $P$ is monthly precipitation; $Ed$ is monthly effluents from the water demand system; $E$ is monthly evaporation; $O$ is monthly outflow; $SS$ is monthly surface water supply; $SE$ is monthly seepage; $GS$ is monthly usable groundwater supply; $TS$ is monthly total water supply. Most of the parameters can be fixed according to the statistical data except for $SE$. Because it is theoretically impossible to accurately measure the temporal fluctuation of $SE$. But it is almost certain that change of surface water quality affects $SE$. Therefore, in the model, a graphic function is defined to describe the relationship between $SE$ and $SW$. And the graphic function is estimated by calibrations.

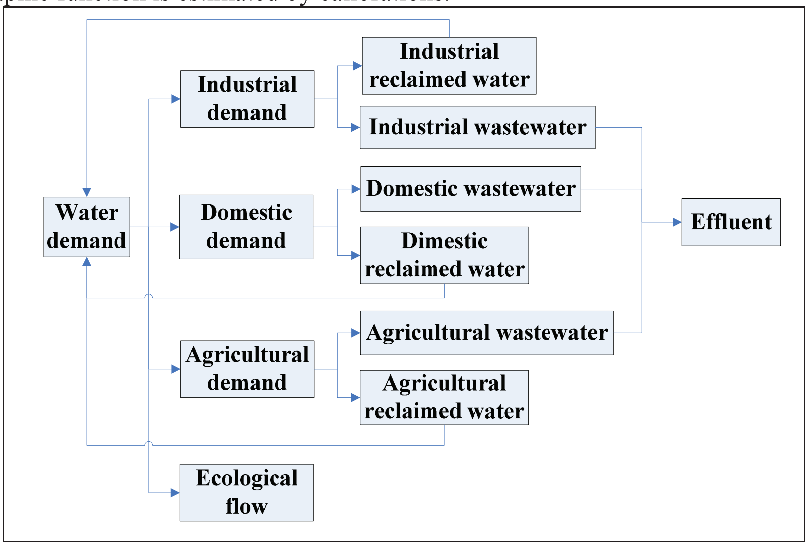


**Figure 2.** Schematic of a generic water demand system.

Fig.2 shows a general water demand system that includes all of the modeled industrial demand, agricultural demand, domestic demand and ecological flow. The industrial demand is based on industrial output value and industrial water use per 10,000 Yuan output value. Depending on the specific study region, some part of industrial use is consumed in the industrial production; some part is reused as reclaimed water and the remainder discharges from the industry area as wastewater. Each part is computed by the following equations:

$$IV(t) = IV(t-\Delta t) + K_I(t) * \Delta t \quad (3)$$

$$D_I(t) = IV(t) * A_I \quad (4)$$

$$IR(t) = D_I(t) * ratio1 \quad (5)$$

$$IW(t) = D_I(t) * ratio2 \quad (6)$$

where $IV$ is monthly industrial output value; $K_I$ is industrial growth; $A_I$ is industrial water use per 10,000 Yuan output value; $D_I$ is monthly total industrial water demand; $IR$ is industrial reclaimed water; $ratio1$ is repeated utilization ratio; $IW$ is industrial wastewater; $ratio2$ is discharge ratio of industrial wastewater. Along with the development of manufacture technology, consumption and wastewater of industry will reduce while reclaimed water will increase.

Agricultural demand varies by land use type and season. Typical classification (including arable land, grass land and woodland) is available in the model. And the arable land need to be further classified into several specific parts according to different plants. Furthermore, it is worth mentioning that the agricultural water demand significantly changes in different seasons for various water demands of plants. And consequently selecting the time step of a month in the early warning model is the most suitable. Agricultural demand is computed by:

$$D_A(t) = \sum S_n * A_{An}(t) \tag{7}$$

$$AR(t) = D_A(t) * ratio3 \tag{8}$$

$$AW(t) = D_A(t) * ratio4 \tag{9}$$

where $D_A$ is monthly total agricultural water demand, $A_{An}$ is monthly water use per square meter of each category of land (n = 1, 2…) and $S_n$ is the area of each category of land (n = 1, 2…); $AR$ is agricultural reclaimed water; $ratio3$ is repeated utilization ratio in agriculture; $AW$ is agricultural wastewater; $ratio4$ is discharge ratio of agricultural use. Demanding water of breeding industry and fishery should be considered to add into the equation according to the specific condition of the study area selected.

Domestic demand is assumed to be proportional to an area's population and water consumption per capital. The population is undoubtedly the primary driving factor for water demand. And population growth is estimated by a monthly percentage increase, which is involved with birth, death, immigration and emigration. In general, domestic demand is computed by:

$$NP(t) = NP(t - \Delta t) + K_D(t) * \Delta t \tag{10}$$

$$D_D(t) = NP(t) * A_D \tag{11}$$

$$DR(t) = D_D(t) * ratio5 \tag{12}$$

$$DW(t) = D_D(t) * ratio6 \tag{13}$$

where $NP$ is the number of people; $K_D$ is rate of population growth; $A_D$ is water use per capital; $D_D$ is monthly total domestic water demand; $DR$ is domestic reclaimed water; $ratio5$ is domestic repeated utilization ratio; $DW$ is domestic wastewater; $ratio6$ is discharge ratio of domestic use.

Ecological flow has been a central issue in sustainable water resources management (Kashaigili et al., 2007; Bunn and Arthington, 2002). Now there has formed a consensus that the ecological flow is a certain amount of water be purposefully left in or released into an aquatic ecosystem to maintain it in a condition that will support its direct and indirect use values (King et al., 2002; Dyson et al., 2003). Once the quantity of surface water fails to ensure the ecological flow, along with ecological deterioration, the crisis of water shortage will become inevitable. Thus, it is apparently indispensable to add the ecological flow into water demand.

Considering the differences in structures, functions and regionalization of ecosystems, various methods are used for estimation of ecological flow worldwide which range from simple to more comprehensive approaches, such as hydrological index, hydraulic rating, habitat simulation and holistic ones (Tharme, 2003). As for basins, the method of ecological water level (Cui and Yang, 2006) is used to estimate ecological flow in this paper. Ecological flow in each month can be determined by the following equation (Zhao et al., 2005):

$$\lambda = \frac{1}{\mathrm{m}} \sum_{i=1}^{n} \frac{E(\eta_i)}{E(\varepsilon_i)} \tag{14}$$

$$D_{\mathrm{E}} = \lambda \frac{\sum_{i=1}^{n} D_{\mathrm{E}i}}{n} \tag{15}$$

where $\lambda$ is ecological water coefficient, which means similarity of minimum ecological water level and yearly average water level; m is number of indicators for ecological status; $\eta_i$ is all the yearly minimum ecological water level variable during the period when indicator $i$ changes most greatly, $\varepsilon_i$ is all the yearly minimum ecological water level variable during the other period; $E(\eta_i)$ is the mathematical expectation of $\eta_i$ ; $E(\varepsilon_i)$ is the mathematical expectation of $\varepsilon_i$ ; $D_{\mathrm{E}}$ is the monthly minimum ecological flow; $D_{\mathrm{E}i}$ is the monthly average ecological flow for years; $n$ is number of year.

To sum up, the total water demand in socioeconomic system can be figured out by the equation:

$$D = D_I + D_A + D_D + D_{\mathrm{E}} - IR - AR - DR \tag{16}$$

Then, the early warning level for water shortage can be classified according to the supply-demand ratio ( $R_{sd}$ ) as follows:

$$R_{sd} = TS / D \tag{17}$$

where $R_{sd}$ is the supply-demand ratio.

Based on it, a five-level, color-coded water shortage warning system, ranging from "green" to "red", was classified in line with any specific value of $R_{sd}$ (see Table 1).

**Table 1.** Responses to water shortage alert level and signal.

| Alert level | Signal | Standards | Description |
|---|---|---|---|
| Safety | Green | $R_{sd} \geq 1$ | Water supply is more than water demand. |
| Level Ⅳ | Blue | $(D - D_E) / D < R_{sd} < 1$ | Water supply can't meet ecological flow requirement. |
| Level Ⅲ | Yellow | $(D_A + D_D - AR - DR) / D < R_{sd} < (D - D_E) / D$ | Water supply is less than industrial water demand and ecological flow. |
| Level Ⅱ | Orange | $(D_D - DR) / D < R_{sd} < (D_A + D_D - AR - DR) / D$ | Water supply can't meet ecological flow and industrial and agricultural water demands. |
| Level Ⅰ | Red | $R_{sd} < (D_D - DR) / D$ | Water supply is not even enough for the domestic water demand. |

## 3. Application

To demonstrate the model's utility, a scenario is considered for a year planning period (12 months of the year of 2000). And data requirements were populated using real and representative data for Baiyangdian basin, Hebei province. Detailed input datum is from yearbook of Hebei, chorography of Anxin and chorography of Baiyangdian basin. It is necessary to state that the main land use type in Baiyangdian basin is arable land, so other types were excluded when simulating the agricultural demand. And the arable land is specifically divided into four classes, that is, rice, corn, wheat and broom land. Water shortage condition of Baiyangdian basin during the whole year was predicted with the datum of January as the initiate value.

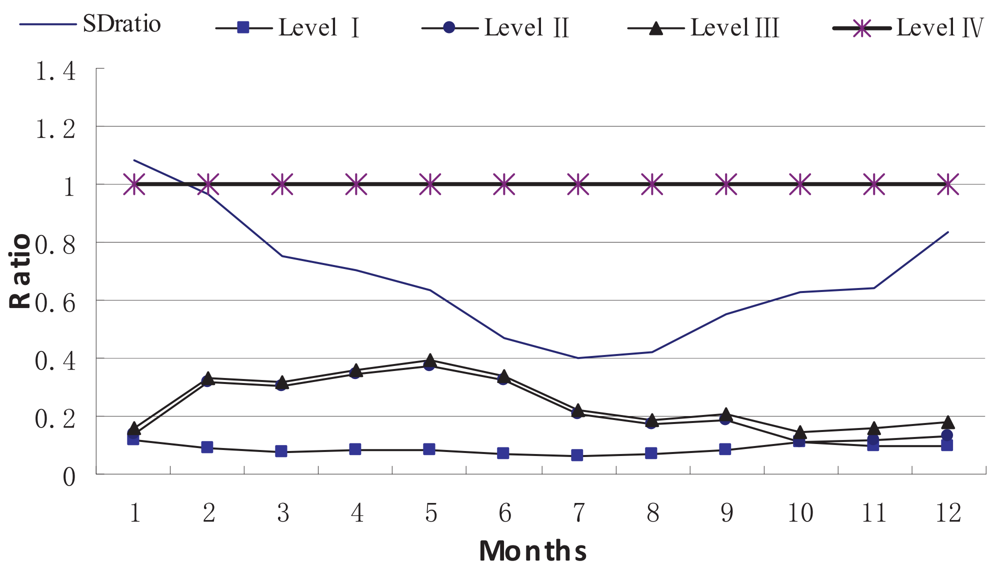


**Figure 3.** Alert level and monthly supply-demand ratio of Baiyangdian basin.

Figure 3 shows the alert level and changes of $R_{sd}$ in the 12 months. When the ratio is higher than 1, which corresponds to level Ⅳ, the water resource is in a safe condition. The ratio is computed according to the relationship between total water supply and actual water demand. It can be stated that water supply can meet the socioeconomic water demands all the year round though, there still exists water crisis. Ecological flow of Baiyangdian basin exceeds the available water sustained by the basin for most of the year except January. From Figure 4, it can be found that agricultural demand and ecological flow account for the major part of water demand in Baiyangdian basin, especially the latter, which consumes twice the water resources of all the socioeconomic demands combined. And the two parts need more water in summer than in winter, so the lowest value of $R_{sd}$ appears in July. However, excessive exploitation of groundwater may be the reason why water supply can maintain the socioeconomic demands all along.

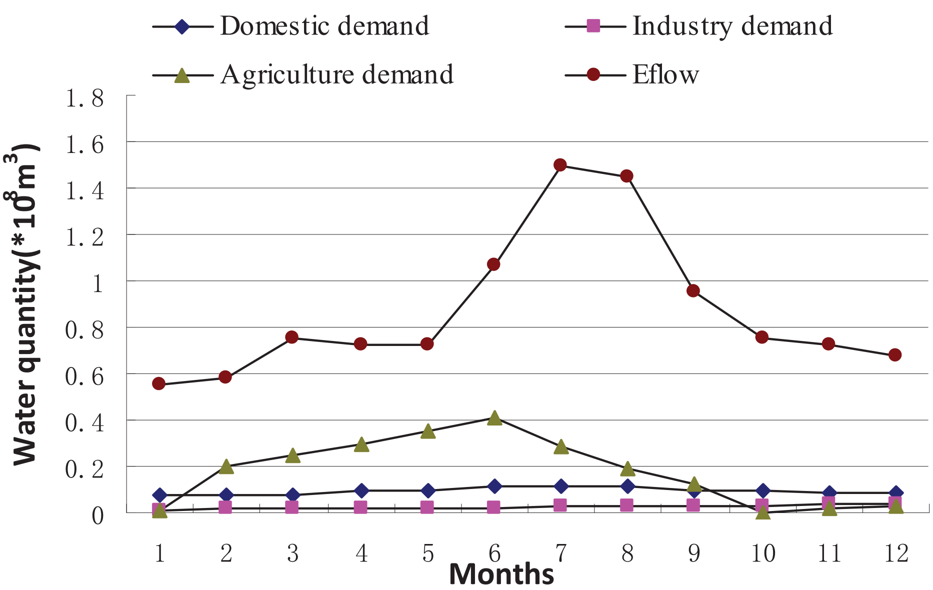

**Figure 4.** Monthly agricultural, industrial, domestic demanding water and ecological flow in Baiyangdian basin

Hence, we can come to a conclusion that aquatic ecosystem in Baiyangdian basin faces a serious water shortage throughout the entire year. Nevertheless, socioeconomic system doesn’t actually suffer water shortage in the year. It may result from serious overextraction of groundwater when prohibited from drawing water directly from the basin, which induces more and more water table depression cone. And the surface water level drops down below the ecological water level as a result. And finally, the simulation results demonstrate that there exists warning of level Ⅳ in Baiyangdian basin.

## 4. Conclusion

Given the complexity of water resource systems, decision makers may have difficulty in giving an early-warning of water crisis effectively in advance based on current information and policy. To predict the changing trend of water supply and demand in a basin when suffers a water shortage, a modular early warning system has been developed. The modular structure allowed a general system model to be constructed as well as coupled with calculation model of ecological flow. Many parameters were involved in the model, such as domestic, industrial, agricultural, multiple supplies, effluents, and seepage, and so on. It almost included most of the typical elements related to water quantity. Since ecological flow plays a key role in ensuring the continued availability and sufficiency of water resource, it was also considered into water demand system. Furthermore, a more scientific and practical alert level system was put forward based on the supply and demand ratio. Simulation is performed on monthly time steps at critical periods.

An application in Baiyangdian basin demonstrated the ability to predict the water crisis. The results were reasonable. In detail, the supply and demand ratio refered to the condition of water shortage in Baiyangdian basin. Since the water demand of society could be generally met because of exploiting groundwater regardless of sustainable development, it would make more sense to take ecological flow into consideration of water demand. These results would assist decision makers in understanding the origin of water crisis and determining to implement some measures.

A general procedure and method of early warning system of water shortage in basins was shown in this paper, which could extend to other basins. The simulation results will be more accurate if taking into account the interaction between groundwater and surface water. So the problem will be further studied in future.

## Acknowledgements

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