Stochastic Analysis of Water Supply and Demand at the River Basin Level

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EXTENDED ABSTRACT

Quantitative analysis techniques have gained a great deal of popularity with decision-makers and analysts in recent years, this is also the case in hydrology. Since conjunctive water use for agriculture is turning out to be a major environmental challenge in some river basins, there is an urgent need to quantify the future water availability and water demand to identify whether there is a surplus or deficit of water. This is of great importance in developing water management plans for a basin or a state. In this paper, the Basin-wide Holistic Integrated Water Assessment (BHIWA) model developed by International Commission on Irrigation and drainage (ICID) was used in an attempt to simulate the water balance of the study basin, Qiantang River Basin in China, as well as to analyse the impacts of land and water use on return flows of this basin. Four water situation indicators were propounded in the model to depict the level of water use (withdrawals) and potential risks (due to return flows) to water quality. Stochastic analysis was also done in this paper using Monte Carlo Simulation Method, by randomly selecting sets of values for the probability distributions in the cell values and formulas to quantify the risks in terms of water quantity and water quality resulting from climate change and return flow. "Quantifying risk" means determining all the possible values a risky variable could take and determining the relative likelihood of each value.

BHIWA can be used to simulate and analyse the impacts of land use and climate change on water resources and eventually optimize the water allocations among agricultural, industrial, domestic, and environmental sectors within a basin context.

A decision support tool called @RISK has been used to perform stochastic analysis on water supply and water demand. This allows the relationship between the reliability of the supply system and the capacity of its storage tank(s) to be quantified using Monte Carlo analysis. There are two basic approaches to quantitative risk analysis. They are simulation and analytical approach. Both have the same goal — to derive a probability distribution that describes the possible outcomes of an uncertain situation — and both generate valid results.

A major strength of @RISK is that it allows users to work in a familiar and standard model building environment — Microsoft Excel. Variables are the basic elements in the Excel worksheets that have been identified as important ingredients to the analysis. @RISK uses probability distributions to describe uncertain variables in Excel worksheets and to present results.

The estimated water budgets simulated from BHIWA model were in general in good agreement with the estimated water balance by the provincial water conservancy department. The model provided reasonable estimates for current water recharge to groundwater and potential for the sustainable development of surface and groundwater as well as export of water from the basin. However, the surface water withdrawals for irrigation are relatively high, ranking from 2,903 million cubic meters to 6,523 million cubic meters with 90% of probability. Therefore, expansion of irrigation infrastructure and improvement of soil and water management measures should be adopted to increase the efficient use of irrigation water. In addition, the contamination threat to the groundwater is significantly high due to high proportion of return flow to groundwater (varying from 0.18 to 0.58); this might result in poor groundwater quality in future.

Given the water situation in the basin, the model amply demonstrates the scope for enhancing the present storage and regulation capacity of water resources. Besides a possible opportunity for inter-basin transfer of water from Qiantang basin to other water short areas also came to light.

1. INTRODUCTION

As more of the developing world's river basins become 'closed' with all their available water used, it becomes increasingly important to plan water resources development, allocation, and management in the context of multiple uses of water (International Water Management Institute (IWMI), 2002). Improvement of water use efficiency in all sectors at all scales has become the focus in the present irrigation practices and in future water developments. However, savings from one part of the system may lead to higher water use in another part of the system and the overall improvement may be negligible (Khan et al, 2005). Therefore, to effectively manage and develop water in ways that advance sustainable development, an Integrated Water Resources Management (IWRM) approach must be adopted in a process of change in political, social, economic and administrative systems (Lenton, 2004). In addition, the quantified water budget can give decision makers a clear view of water availability in a river basin through accounting of the inflow, outflow, and storage changes of water.

China is a relatively water scare country where the average per capita water resources is only 2240 m^3 per year, around one fourth of the world's average. To provide for the increasingly growing population and rapidly developing economy, there will be a greater water demand in near future. Therefore, the adoption of a simultaneous and a viable approach of water supply management and water demand management is desirable to ensure sustainability. The conjunctive use of surface and groundwater is definitely one of the strategies of water supply management which has to be considered to optimize the water resources development, management and conservation within a basin, and artificial recharge of aquifers is certainly one of the tools to be used for that purpose (FAO, 1993). Meanwhile, since the groundwater use affects the base flow in rivers besides causing depletion of aquifers, separate water budgets are needed for the river-surface and ground water systems to quantify the water availability and demand and to identify whether there is a surplus or deficit (a deficit of water would indicate insufficient water availability to meet present or future demands) in the basins and ultimately to achieve integration of supply sources.

A hydrologic model called, Basin-wide Holistic Integrated Water Assessment (BHIWA) developed in ICID for the basin level integrated water assessments caters to this broader need and for the integration of water and land resources for sustainable use (ICID, 2005a and 2005b; China Institute of Water Resources and Hydropower Research 2004). The results of this study would be incorporated into the five-year update of the Zhejiang Province Water Management Plan in China.

The forecasting of water demand is critical to those involved in water resources planning. These forecasts help managers assess the adequacy of the present resources to meet future demands (Steiner et al, 2000). However, because of the current uncertainty and magnitude of impact of the potential effect of climate change on resources, future water demand and water availability will be uncertain. Therefore, there is a need to quantify the risks of experiencing extreme droughts and pollutions.

This study examines the water resources in the context of development and management of water, land and related resources, integrating the needs of various human uses including vital needs of terrestrial and aquatic eco-systems. Stochastic analysis is made later on to depict the risks in both water quantity and water quality in a term of probability distribution and their likelihoods of occurrence. Recommendations on optimal policy interventions on integrated and sustainable water resources management in this river basin are made eventually.

2. THE STUDY AREA

The study basin, Qiantang river basin, is a part of the drainage area of Yangtze River Basin and lies between east longitudes 118° to 121° and north latitudes 28° to 31°. While the catchment area of the basin is 55,558 km^2, the drainage area of the basin considered in the study is 35,500 km^2 in the upstream of Hangzhou gate. The hydrologic components such as surface water and groundwater resources and land uses in this study basin are calculated proportionally on the basis of area.

This basin is divided into two sub-basins in this study which allows segregation of areas having similar hydrological and water use attributes as follows:

- Sub Basin 1 (SB 1): Upstream of Fuchun River (Drainage area 25,200 km^2)

- Sub Basin 2 (SB 2): Downstream of Fuchun River (Drainage area 10,300 km^2).

Qiantang River basin comes under sub-tropical monsoon climate with well marked four seasons. The average annual rainfall in the basin varies between 1200 mm and 2200 mm. The average annual evaporation ranges between 800 mm and 1000 mm and the average annual temperature between 16.2º C and 17.7º C. Qiantang river basin has favourable natural conditions supporting rich agricultural resources. The cultivable area of the basin in the year 2000 was 0.424 million hectares accounting for 11.9% of the total land area and the area covered under the horticulture was 0.131 million hectares, 3.7% of the total land area. The forest area in the basin was 1.42 million hectares. The irrigated area was about 0.393 million hectares, which is 93% of the cultivable area. Paddy, wheat, barley, maize, soybean and potato are the staple crops and tea, cotton, sugarcane, medicinal plants are the cash crops grown in this basin. Paddy is a major crop in the basin which covers about 85% of the total cultivated area. The area under rapeseed cultivation is about 12% of the total cultivated area.

The population of the basin in the year 2000 was 10.7 million comprising urban population of 3.56 million and rural population of 7.11 million. It is projected that population of the basin in the year 2025 will be 11.4 million. The per capita availability of water resources in the year 2000 was 3,621 cubic meters and projected to be 3,389 cubic meters in the year 2025.

The total water resources in Qiantang river basin (within Zhejiang province) are estimated at 38.64 km^3including 7.71 km^3 of unconfined groundwater resources (Provincial Irrigation and Drainage Technological Development Company 1999; Provincial Institute of Water Conservancy and Hydropower Reconnaissance and Survey 2003). Forty eight large and medium reservoirs and over 200 small reservoirs have been constructed in the basin. The live storage capacity of medium and large reservoirs in the basin is 1,224 million cubic meters and storage capacity of small reservoirs is 886 million cubic meters. There are a number of reservoir projects that are under construction and are proposed to be constructed. The live storage capacity of on-going and future projects is 985 million cubic meters.

3. METHODOLOGY

3.1. Environmental/Water Cycle Approach

The BHIWA model specifically addresses the future water scenarios for food and rural development, water for people as well as water for nature, in order to achieve sustainable development and use of the water resources. The model was designed to be simple and flexible. The conceptual diagram of the model is given in Figure 1. The model can be calibrated for the present conditions and applied to derive water fluxes for future scenarios at monthly intervals. The basin can be divided into a number of sub-basins to allow the segregation of areas with similar hydrologic and water use attributes.

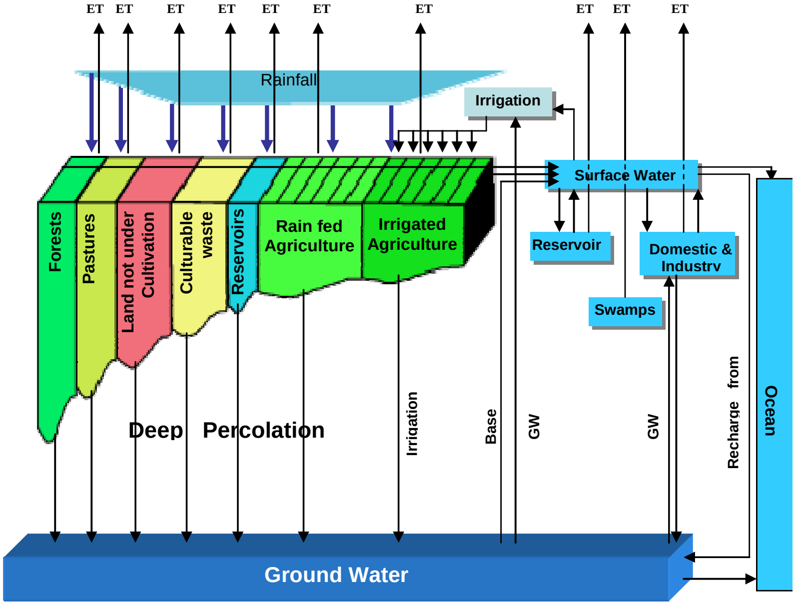

Figure 1 Schematic of Hydrologic Model

Four water situation indicators propounded in the model to depict the level of water use (withdrawals) and potential risks (due to return flows) to water quality, were as follows:

Indicator 1: Total surface water withdrawal/ Total surface water inputs

Indicator 2: Total returns to surface water/ Total surface water inputs

Indicator 3: Total groundwater withdrawals/ Total groundwater inputs, and

Indicator 4: Total returns to groundwater/ Total groundwater inputs

The indicators were further categorized into 3 to 4 classes each to represent the degree of water stress (Indicators 1 and 3) and the water quality threat (Indicators 2 and 4) as shown in Table 1. It is believed that such indicators will enable better appreciations of the sustainability of a scenario of development envisaged.

Table 1 Description of water situation indicators

Indicator	Water source and type	Category	Value
1	Surface water withdrawal	Very high stress	>0.8
		High stress	0.4-0.8
		Moderate stress	0.2-0.4
		Low stress	<0.2
2	Surface water quality	High threat	>0.2
		Moderate threat	0.05-0.2
		Low threat	<0.05
3	Groundwater withdrawal	Very high stress	>0.8
		High stress	0.4-0.8
		Moderate stress	0.2-0.4
		Low stress	<0.2
4	Groundwater quality	High threat	>0.8
		Moderate threat	0.4-0.8
		Low threat	0.2-0.4

3.2. Stochastic Analysis Approach

Risk derives from our inability to see into the future, and indicates a degree of uncertainty that is significant enough to make us notice it. In this paper, a decision support tool for stochastic analysis called @Risk was applied. Risk analysis in @RISK is a quantitative method that seeks to determine the outcomes of a decision situation as a probability distribution. In general, the techniques in @RISK Analysis encompass four steps: developing a model; identifying uncertainty; analysing the model with simulation; and making a decision.

@RISK uses the technique of Monte Carlo simulation for risk analysis. Over thirty types of distributions are available in @RISK for describing distributions for uncertain values in the Excel worksheets. In this paper, normal distribution *Normal (μ, σ)* has been adopted in the input variables and its density and cumulative functions can be expressed as:

$$f(x) = \frac{1}{\sqrt{2\pi\delta}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\delta}\right)^2} \qquad (1)$$

$$F(x) \equiv \Phi\left(\frac{x-\mu}{\delta}\right) = \frac{1}{2}\left[erf\left(\frac{x-\mu}{\sqrt{2}\delta}\right)+1\right] \quad (2)$$

where μ is mean; σ is deviation; Φ is called the Laplace-Gauss Integral and erf is the Error Function.

4. SIMULATED RESULTS

Based on the present conditions and average rainfall, the modified model response for sustainable water use conditions is briefly described as below:

The model indicates that the present average flows to the sea are as follows:

- SB1: 23,300 million cubic metres;
- SB2: 9,230 million cubic metres;
- total basin: 32,500 million cubic metres.

The total flow computed by the model fairly matches with the observed one, which is 32,700 million cubic metres.

For the present condition, the withdrawal required for sustaining agricultural (irrigation) uses, which is entirely from surface water, is 4,500 million cubic metres. The withdrawals for D&I uses are 1,300 million cubic metres from surface water and 110 million cubic metres from groundwater, respectively. Therefore, there is huge potential for groundwater development in this basin. To sustain these current withdrawals, the surface storage filling and depletion of 7,680 million cubic metres contributes considerably.

The current total natural recharge from rainfall in the basin as computed by the model is 5,140 million cubic metres, which is about 8.9% of average annual rainfall of 58,000 million cubic metres. As there is no groundwater use in irrigation in this basin so far, exploiting groundwater for both agricultural and D&I uses inevitably is a priority plan for local Integrated Water Resources Development and Management (IWRDM) so as to achieve sustainable development and use of water resources. Therefore, 20% of groundwater is planned to be developed in the envisaged scenarios ‘Future III’, ‘Future IV’ and ‘Future V’.

Moreover, water export, which is 180 million cubic metres from the upstream and 90 million cubic metres from the downstream, together with better water management is also adopted in Future IV even though there is no current plan for water export from this area.

5. STOCHASTIC ANALYSIS

There are many factors significantly affecting the simulated results from BHIWA model, such as surface water and groundwater conveyance and distribution efficiency representing the plenitude of irrigation infrastructure, and proportion of return flows evaporating through water logged areas and swamps from surface irrigation and proportion of residual return flows returning to surface/ground water from surface/groundwater irrigation indicating the water management levels. Five inputs with normal distribution as shown in Table 2 is defined in this paper to make the uncertainty analyse.

Table 2.Distribution of some selected input data

Input data	μ	σ
Proportion of return flows evaporating through water logged areas and swamps from surface irrigation	0.15	0.05
Proportion of residual return flows returning to ground water from surface irrigation	0.7	0.1
Proportion of residual return flows returning to ground water from ground water irrigation	0.95	0.05
Surface water conveyance and distribution efficiency	0.65	0.15
Ground water conveyance and distribution efficiency	0.75	0.15

From the simulation results as shown in **Figure 2**, there is 90% of probability that the surface withdrawals for irrigation is between 2,903 and 6,523 million cubic meters, 5% of probability less than 2,903 million cubic meters, and 5% of probability more than 6,523 million cubic meters. The maximum surface water withdrawal for irrigation can reach 10,000 million cubic meters, the minimum can be 2,540 million cubic meters, and the mean value is 4234 million cubic meters.

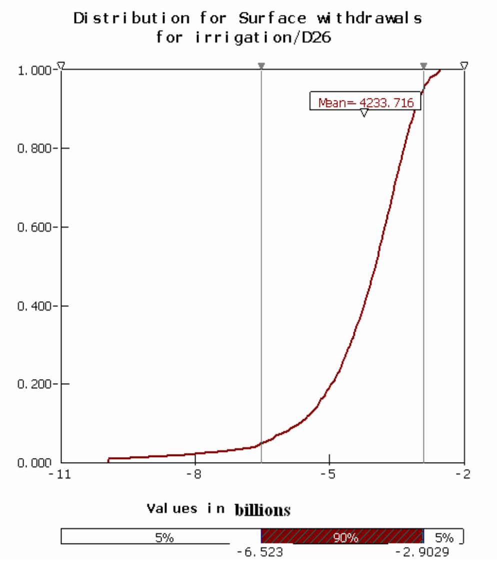

Figure 2 Simulation results for surface withdrawals for irrigation

The standard deviation is 1195 million cubic meters. Furthermore, the surface water withdrawal for irrigation is 100% of sensitivity to surface water conveyance and distribution efficiency, 14.7% of sensitivity to proportion of return flows evaporating through water logged areas and swamps from surface irrigation, 11.8% of sensitivity to proportion of residual return flows returning to groundwater from groundwater irrigation.

It can be seen from the **Figure 3** and **Figure 4** that surface water withdrawals are only a small part of the total surface water inputs, varying from 0.15 to 0.22 with 90% of probability. In groundwater withdrawal, the ratio varies from 0.009 to 0.018, 90% of probability between 0.012 and 0.017. However, it should be specially noted that groundwater return flow is very high, varying from 0.18 to 0.58, indicating a high risk of groundwater pollution due to high return flows to groundwater. Therefore, efforts should be made to reduce the threat to groundwater quality.

Among the four water situation indicators, all of them are very sensitive to surface water conveyance and distribution efficiency, which are 99.7%, 97.3%, 84.7% and 84.7% of sensitivity respectively to it. In addition, indicator 3 and indicator 4 are still very sensitive to proportion of residual return flows returning to ground waters from surface irrigation and proportion of return flows evaporating through water logged areas and swamps from surface irrigation, both are 52.8% and 25.2% respectively of sensitivity to them. The correlations between inputs and outputs are shown in **Table 3**.

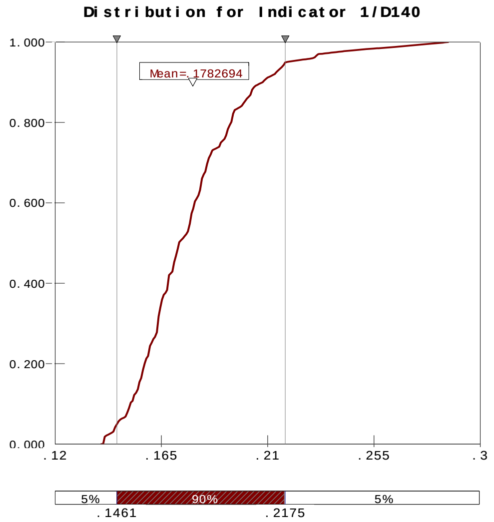

Figure 3 Distribution for Indicator 1 – total surface water withdrawals/ total surface water inputs

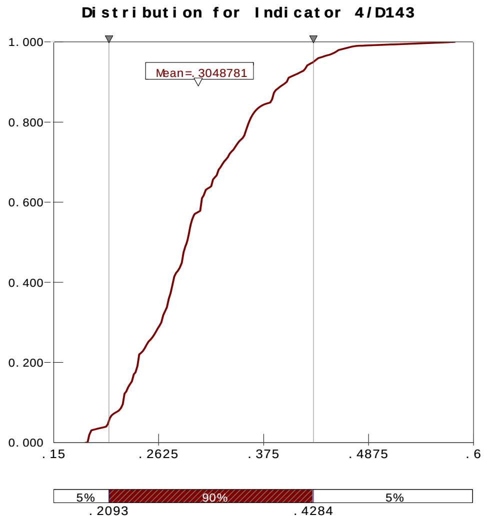

Figure 4 Distribution for Indicator 4 – total returns to groundwater/ total groundwater inputs

Table 3.Correlations between inputs and outputs

Input data	Distribution	Indicator 1	Indicator 2	Indicator 3	Indicator 4	Surface withdrawals for irrigation
Surface water conveyance and distribution efficiency	RiskNormal (0.65, 0.15)	-0.997	-0.973	0.847	-0.847	1
Proportion of residual return flows returning to ground waters from surface irrigation	RiskNormal (0.7, 0.1)	0.028	0.004	-0.528	0.528	-0.081
Proportion of return flows evaporating through water logged areas and swamps from surface irrigation	RiskNormal (0.15, 0.05)	-0.126	-0.326	0.252	-0.252	0.147
Ground water conveyance and distribution efficiency	RiskNorma l(0.75, 0.15)	0.022	0.003	-0.07	0.07	-0.025
Proportion of residual return flows returning to ground waters from GW irrigation	RiskNormal (0.95, 0.05)	-0.118	-0.127	0.017	-0.017	0.118

6. CONCLUSION

BHIWA model was successfully calibrated using average monthly flows at the end of the river system. Application of this model in the Qiantang river basin shows that this basin is rich in its water resources. The estimated water budgets were in general in good agreement with the estimated water balance by the provincial water conservancy department. The model was able to provide current status of water availability and water use and able to depict the interaction between surface and groundwater system. The model provided reasonable estimates for current water recharge to groundwater and potential for the sustainable development of surface and groundwater as well as export of water from the basin. The surface water withdrawals for irrigation is relatively high, ranking from 2,903 million cubic meters to 6,523 million cubic meters with 90% of probability. Therefore, expansion of irrigation infrastructure and improvement of soil and water management measures should be adopted to increase the efficient use of irrigation water. In addition, the contamination threat to the groundwater is significantly high due to high proportion of return flow to groundwater (varying from 0.18 to 0.58); this might result in poor groundwater quality in future.

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7. ACKNOWLEDGEMENS

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