Modeling Water Futures Using Food Security and Environmental Sustainability Approaches

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EXTENDED ABSTRACT

Global water scarcity is becoming a constraint for human development. Therefore there is a need to enhance water productivity of the irrigated and rainfed agriculture to meet the increasing food demand due to the population growth. This paper describes modeling efforts to assess present and future water needs for food, people and environment. This exercise is being carried out by the International Commission on Irrigation and Drainage (ICID) in five countries, China, Egypt, India, Mexico, and Pakistan, which together cover 51% of irrigated area and 43% population in the world. This paper presents two modeling frameworks including the food security approach of the International Water Management Institute (IWMI) through policy dialogue model (PODIUM), an environmental approach i.e. the Basin wide Holistic Integrated Water Assessment (BHIWA) model and its system dynamic version using VenSim environment.

The two modeling approaches i.e. the BHIWA and PODIUM can be used to simulate and analyze the impacts of land use and climate change impacts on water resources and eventually optimize the water allocations among agricultural, industrial, domestic, and environmental sectors within a basin context.

Both approaches described in this paper have shortcomings for exploring water futures of a country. BHIWA is not a distributed hydrologic model and cannot deal with each land use geographically distributed throughout the basin. All such parcels need to be conceptually lumped into a single land use unit. BHIWA model does not depict the spatial variations in rainfall, potential evapo-transpiration, intensities of cropping or irrigation as well as slow horizontal groundwater movement, from under one area to another.

The PODIUM model is based on accounting of more or less fixed contemn of “utilizable” surface and ground water resource. The changes in the hydrology due to land use changes, and the resultant changes in the utilizable water are important when considering longer term scenarios.

This paper highlights the benefits and disadvantages of using these approaches through model applications in the Qiantang River basin in China. The Qiantang River basin lies in the southeast of China and comes under a subtropical monsoon climate with four well-marked seasons. The average annual precipitation is between 1200 mm and 2200 mm, with annual evaporation ranging between 800 mm and 1000 mm.

On the basis of the model simulations presented in this paper it is concluded that the PODIUM model is strong at representing basin/country’s food needs and associated use of “utilizable” surface and ground water resources but it does not depict the inter-relations between different hydrologic components e.g. surface and ground water. The BHIWA model developed by ICID aims to quantify water use by three sectors (i.e. nature, food and people), therefore allows better understanding of impact of land use changes as well as soil and water conservation policies and programmes through the simulation of overall hydrologic cycle. A system dynamics based representation of BHIWA model allows users to conceptualize, document, simulate, analyze, and optimize water management. It can help to understand the most sensitive parameters for improving the water use efficiency at system scale.

1. INTRODUCTION

The world's demand for freshwater is one of the most critical issues in the 21st century. The world's primary water supply will need to increase by 22% to meet the population needs in 2025. At the 2nd World Water Forum in 2000, it was decided to formulate the World Water Vision 2025 on "Water for Food and Rural Development" (WFFRD) to assess water for Food, water for People, and water for Nature. The WFFRD projected substantial increase in the global water withdrawal, water storage and irrigation expansion that by 2025. However, the "Overview Vision" of the 2nd World Water Forum considerably scaled down these findings. The International Commission on Irrigation and Drainage (ICID), therefore decided to develop a common framework through an initiative called Country Policy Support Program (CPSP) in 2002 (ICID, 2002). The CPSP aims to assess and integrate water needs for three sectors, i.e. food, people, and nature, for the present and for the year 2025, with a goal to evolve policy interventions. The CPSP program is currently being carried out by the ICID in five countries, China, Egypt, India, Mexico, and Pakistan, which together cover 51% of irrigated area and 43% population in the world (ICID, 2002). As part of the project, two modeling approaches i.e. simulation of food security and environmental/water cycle were developed and tested. This paper discusses how these modeling approaches were applied in China.

The Basin wide Holistic Integrated Water Assessment (BHIWA) model uses an environmental and water cycle simulation approach. It was developed by ICID in 2004 (ICID, 2004 a and b; China Institute of Water Resources and Hydropower Research 2004). The original BHIWA model is a semi-lumped model with a Microsoft Excel interface. It is able to account for the whole land phase of the hydrologic cycle, including the consideration of hydrologic changes due to changes in the land use and agriculture use. The model is capable of depicting surface and groundwater balances separately and allowing interaction between them as well as impacts of storage and depletion through withdrawals.

Khan et al (2005) have provided an overview of system approaches in water management. A system dynamics version of the BHIWA model was developed by the authors under the VenSim environment which allows users to conceptualize, simulate, analyze, and optimize models for the complex systems.

The PODIUM modeling approach to address food security was developed by the International Water Management Institute (International Water Management Institute 2003). This model can generate food security scenarios at catchment, national and global levels (Seckler et al., 1998). The model maps the complex relationships between numerous factors that affect demand and supply of the water and food. It enables users to set goals, such as food production for an adequate level of per capita consumption, and explore ways of reaching these goals through expanding irrigated area or rainfed area, increasing cropping intensity, or importing more food. Likely scenarios can also be developed in terms of population growth, diets, and developments in agriculture and water resources; which will help to determine the necessary steps for ensuring food security and sustainable water use.

The primary aim of this study is to provide a capability analysis of the food security and the watercycle/environmental approach to assess the current (year 2000) and future (year 2025) water use in Qiantang River Basin of China.

2. MODELLING WATER FUTURES

2.1. Environmental /Water Cycle Approach

The BHIWA model specifically address 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. The BHIWA model was imported into a system dynamics environment using the VenSim system (Ventana Systems, Inc., 2004). This approach allows users to conceptualize, simulate, analyze, and optimize models for the complex systems. Most importantly, it has the powerful functions for the sensitivity testing compared to the above two models and it gives the opportunity to users to identify the most sensitive parameters affecting the water cycle. By connecting words with arrows, relationships among system variables are entered and recorded as causal connections. This information was used by the Equation Editor to help users to form a complete simulation model.

The sensitivity analysis can be done based on the change of constant values of different variables e.g.

irrigation efficiency, and proportion of quick runoff from rainfall into sub-basins and deep percolation rate of paddy rice, etc. The effects of change of the values are checked on the ground water recharge and river balance.

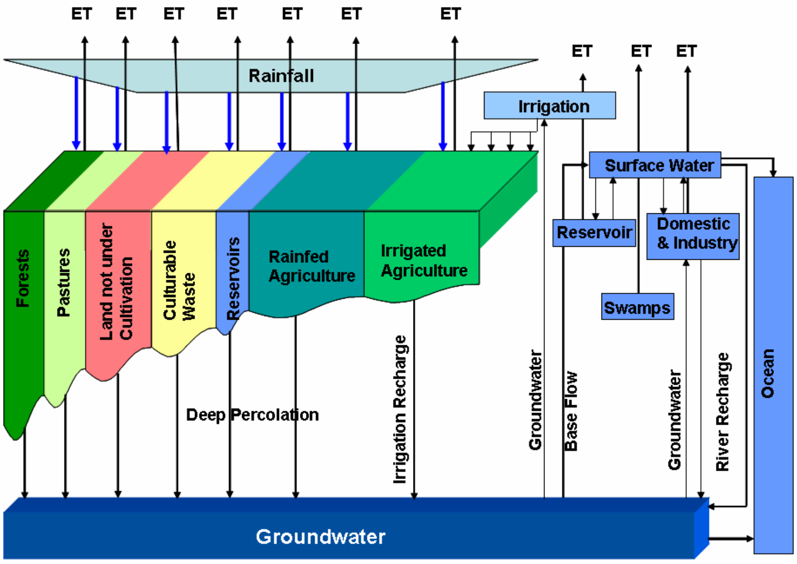

Figure 1 Schematic of Hydrologic Model

The optimization of the model is based on combination of different variables effect to river flow such as the irrigation efficiency, proportion of quick runoff from rainfall into sub-basins, proportion of return flow from surface irrigation to river, and deep percolation rate of paddy rice. The observed river flow and model forecasted river flow was compared based on the optimization to find the best coefficients for the above mentioned variables.

2.2. Food Security Approach

PODIUM calculates the area of the crops needed to meet the food consumption needs. Different scenarios can be developed in for the food consumption and demand with an interval of five years. The food demand scenarios are simulated in the model on the basis of population and per capita dietary consumption for the basin or country. Similarly, the scenarios for food production are simulated on the basis of rainfed and irrigated area in the basin or the country. Policies can then be developed to improve the water use efficiency of the cultivated area, the possibility of expansion of irrigated area or rainfed area, and increasing cropping intensity or importing more food in order to meet the future food security for the population of the basin. Projections for future years are determined in relation to base year by the expected changes in the key variables over this period. PODIUM does not represent complete water flows in a hydrological system but it represents system water demands (current or forecasted) and remaining water balance as environmental or the return flow.

3. EXAMPLE APPLICATION OF TWO APPROACHES

3.1. Description of the Case Study

The Qiantang River basin lies in the southeast of China and comes under a subtropical monsoon climate with four distinct seasons. The favorable average hydrologic conditions endow this basin with rich agricultural production and ensuing rapid economic development. However, this basin is also plagued by escalating flood disasters in wet seasons and serious drought in dry seasons due to uneven spatial and temporal distribution of rainfall. The total area of the catchment is 35,500 Km^2 and the total population of the Basin is 10.67 million. Location of the Qiangtang River Basin in China is shown in Figure 2. The annual precipitation varies between 1200 mm and 2200 mm, with annual evaporation ranging between 800 mm and 1000 mm. The total volume of water resources of Qiantang River basin (upstream of Hangzhou Gate) is 38.64 billion m^3 (BCM) which includes 7.71 BCM of unconfined groundwater resources that accounts for 20% of the total volume. The cultivatable land area is 0.424 million hectares (Mha) which includes 0.360 Mha of paddy field and 0.064 Mha of upland crops. The per capita cultivated area in the river basin is 0.04 Mha and total horticultural area is 0.1309 Mha which accounts for 3.7% of the total land area. In addition, there is also a variety of cash crops such as tea-tree oil, oranges, bayberries, grapes, persimmons, young trees, and loquats.

Figure 2 Location of Qiantang River basin in China

3.2. Environmental/Water Cycle Approach

In Qiantang river basin, the major source of water for agricultural, domestic, and industrial use is the surface water while groundwater has not been used for irrigation so far, except in small quantities for domestic and industrial use (Provincial Institute for Water Conservancy and Hydropower Reconnaissance and Design, 1998, Provincial Irrigation and Drainage Technological Development Company 1999; Provincial Institute of Water Conservancy and Hydropower Reconnaissance and Survey 2003). Studies were done at the sub basin level. The two sub-basins studied are:

SB1 : Upstream of Fuchunjiang Reservoir (two thirds of surface water storage and land area)

SB2 : Downstream of Fuchunjiang Reservoir (one third of surface water storage and land area)

The soil moisture capacity varies according to each land use type, and values consistent with the likely root zone depths and field capacities were taken into account. Paddy rice is the major crop in the basin, making up for 85% of the total cultivated area. The cash crops like fruit and rapeseed etc., are also very common. The cropping area of rapeseed in 2000 was 733 Km^2, amounting to 12% of the total cropping area. The land use types in the model are shown in Table 1.

The BHIWA model was calibrated and validated by comparing the monthly outflow (surface runoff plus base flow) and the total groundwater recharge and withdrawal computed by the model and estimations made by Qiantang Basin Management Bureau as well as the percentage of rainfall (with an annual rainfall of 1632 mm for the year 2000), percolating into groundwater (the natural recharge rate from the precipitation) with the generally adopted norms. In terms of monthly outflow to sea, this model matched the present conditions fairly accurately, where the difference between the total outflows computed by the model and data observed by local hydrological stations was only around 0.5%. Figure 3 shows the computed and observed average monthly values of river flow for the year 2000. The total annual observed river flow is 3.6 BCM which is little bit less than the annual average computed river flow for 2000. The model calibration is achieved by manually changing a number of parameters such as runoff from rainfall, irrigation efficiency, and deep percolation from paddy. This is a tedious process and it does not allow parameters optimization, sensitivity analysis and dynamic economic integration.

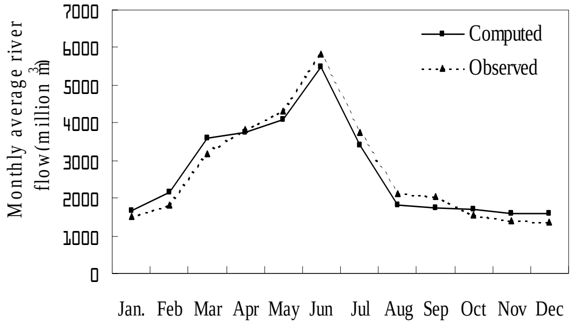

Figure 3 Comparison of Computed and Observed Average River Flow

Table 1 Land Categories Used in the Model

Forest and miscellaneous trees
Permanent pastures
Land not available for cultivation, waste, & fallow
Land under reservoirs
Rain-fed soybean and wheat
Rain-fed fruit
Irrigated double cropping of rice
Irrigated early rice and autumn maize
Irrigated single cropping of rice and rapeseed/vegetable
Irrigated sugarcane and barley
Irrigated cotton and wheat
Irrigated sweet potato and vegetable
Irrigated vegetable
Irrigated fruit

The original BHIWA is written as an EXCEL spreadsheet which is not suitable for dynamic analysis and optimization. The BHIWA model was imported into the Vensim environment which is a powerful systems visualization tool. It is capable of developing the causal and use graphs, and reviewing equations of the workbench variables in its Structural Analysis Tools. It can perform sensitivity analysis and compare the behavior of variables.

Sensitivity Analysis with VenSim

Vensim allows mutli-variable sensitivity analysis using the Monte Carlo Simulation Method by simultaneous changing the desired parameters. The important parameters, for determining water savings in this basin, are deep percolation rate for paddy rice and irrigation efficiency. The default values of these parameters at the beginning of the simulation were 90 mm and 45% respectively. In this paper, two parameters i.e. the deep percolation rate of paddy rice (50-150 mm) and surface irrigation efficiency (20%-90%) were used in this model to test the sensitivity of surface and ground water balance with 50%, 75%, 95% and 100% probabilities respectively for 2000 time series data.

Figures 4 shows the sensitivity analysis of the end of system river balance with the change in surface irrigation efficiency in a range of 20% to 90% respectively. It can be that the end of system river balance is very sensitive to the change of irrigation efficiency particularly at the peak of main irrigation seasons i.e. the months of May and August.

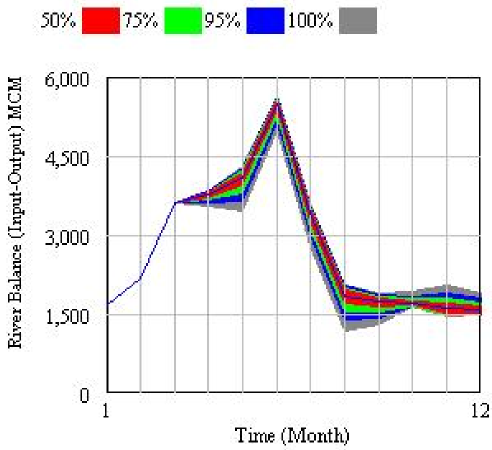

Figure 4 Sensitivity testing result of end of system river flow with the change of irrigation efficiency (20%-90%)

Figure 5 shows the sensitivity testing of the indicator 1 ratio (withdrawals/total runoff) with the change of deep percolation rate of the paddy rice for the whole basin. The sensitive periods for the deep percolation rate parameter are July, August and September.

3.3. Food Security Approach

One of the main features of the PODIUM model is that all main variables and assumptions are made explicit and can be changed easily by the user. This feature makes the model an excellent tool for scenario testing. The PODIUM model includes the following four modules: Crop consumption; Crop production; Water Demand (Agriculture, Domestic, Industrial, Environment); and Water Supply (Surface, Groundwater).

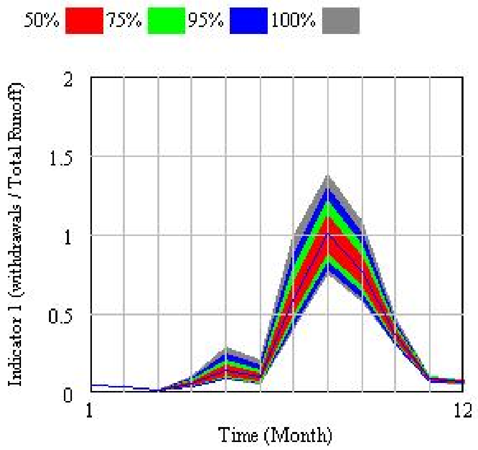

Figure 5 Sensitivity testing result of Indicator 1 (withdrawals/total runoff) with the change of percolation rate (50 – 150 mm)

The total grain demand depends on the amount of population and per capita grain consumption, which is affected by the income, urbanization level, development level of agricultural production market and grain consumption policies. It is estimated that the total population in Qiantang River Basin will increase from 10.67 million in 2000 to 11.4 million in 2025.

Figure 6 shows the crop production, consumption, and surplus/deficit (in terms of economics) for year 2000 and the simulated results for year 2025.

With per capita grain consumption at the national level scaled down as the average value at the basin level, the total grain demand in 2025 needs to be increased to 4.37 million tons according to the simulation results of PODIUM. In terms of economics, the food production in 2025 for all the crops will be 1.5 Billion US$ higher than the food production in 2000 for the basin as shown in Figure 6.

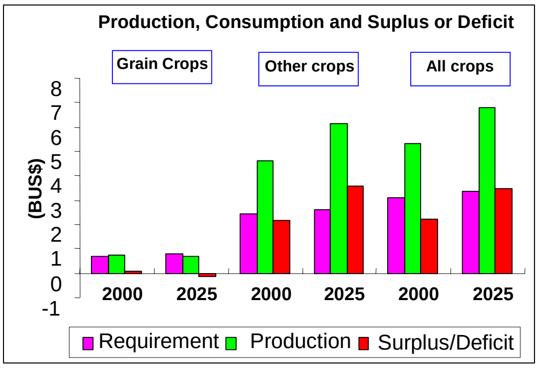

Figure 6 Crop Production, Consumption and Surplus or Deficit Simulated with PODIUM

According to the simulation results, the cropped area will be decreased from 0.771 Mha to 0.59 Mha in 2025 which can be explained to the adjustment of cropping pattern and implementation of the policy of returning cultivated land to forest and pasture. Out of total area, the areas for the paddy rice and wheat will be dramatically reduced while the maize area will increase slightly. This is due to assumed increase in the water productivity of rice, wheat and maize due to the improvement of irrigation technology and adoption of comprehensive agricultural measures. Therefore, even though the cultivated area of rice and wheat is reduced, however the grain production in year 2025 will still reach around 6 Mt, increased by 1.92 Mt than that in 2000. Figure 7 shows the lumped water balance of the whole basin for the year 2000. In 2000, agricultural water diversions are 4.50 BCM and return flow is 28.89 BCM. Where as agricultural water use in 2025 will be reduced to 3.34 BCM due to high water demand for industrial and domestic sectors. While, the return flow in 2025 will be 28.61 BCM which shows a very little reduction as compared to return flow of 2000. Water balance for year 2000 suggest there are is potential for the development of groundwater in the Qiantang basin. The total natural recharge computed by the model for the basin from rainfall is 5.143 BCM, which is about 8.9 percent of average annual rainfall of 57.958 BCM. With the absence of groundwater use for irrigation in this basin so far, exploiting groundwater for both agricultural and D & I uses inevitably has been a priority for local Integrated Water Resources Development and Management (IWRDM) in order to achieve the sustainable development and use of water resources.

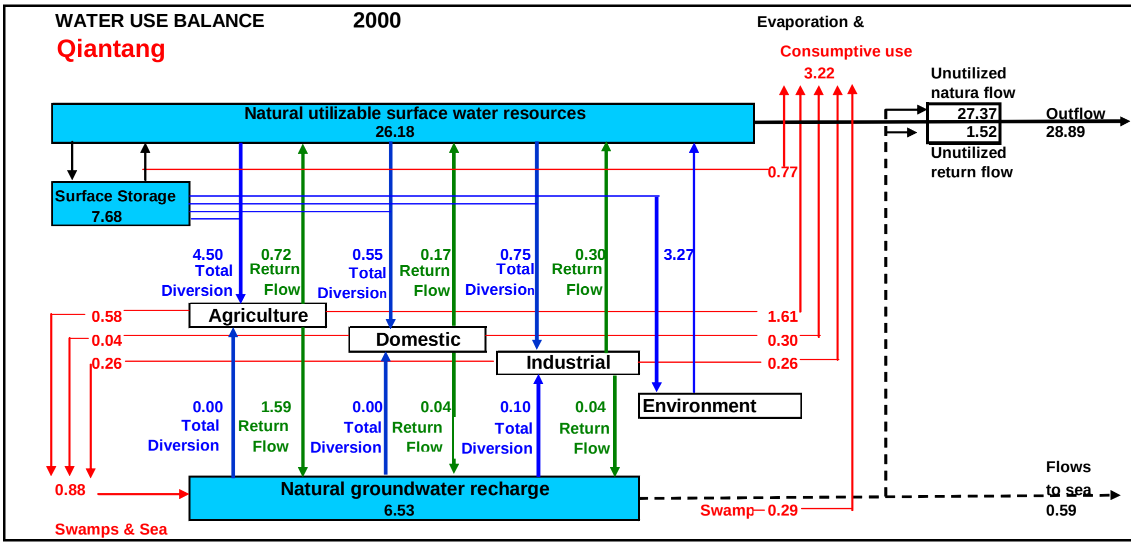

Figure 7 Lumped water balance of the whole basin with PODIUM (BCM)

4. COMPARATIVE ANALYSIS OF TWO APPROACHES

It is very difficult to have absolute comparison of modeling approaches presented in this paper. Each model has its own limitations and advantage for analysing sustainable water management of a basin or a country. The PODIUM model is strong at representing country's food needs and associated used of "utilizable" surface and ground water resources, it does not depict the inter-relations between surface and ground water. The BHIWA model developed by ICID aims to quantify water use by three sectors (i.e. nature, food and people), therefore allowing better understanding of impact of land use changes as well as soil and water conservation policies and programmes through the simulation of overall hydrologic cycle. BHIWA model in VenSim in system modeling environment allows users to conceptualize, document, simulate, analyze, and optimize dynamic models. It can help to understand the most sensitive parameters for improving the water use efficiency at system scale.

5. CONCLUSIONS

Using a food security approach the PODIUM model indicated total grain demand for the Qiantang River Basin needs to be increased to 4.37 million tons by 2025. In terms of economics, the food production in 2025 for all the crops will be 1.5 Billion US$ higher than the food production in 2000 for the Qiantang basin even though the cropped area will be decreased from 0.771 Mha to 0.59 Mha in 2025 which can be explained to the adjustment of cropping pattern and implementation of the policy of returning cultivated land to forest and pasture.

PODIUM is strong on food security but does not address the water management problem and it is best applicable for a country. BHIWA model is useful for understanding the water cycle and associated intervention but does not address the food security. BHIWA is best applicable for a basin. BHIWA divides area into sub units where as PODIUM treats areas as weighted average. System dynamic model can be helpful to understand the most sensitive parameters for improving water use efficiency and it can also be used to optimize unknown parameter. The VENSIM model has indicated that the end of system river balance very sensitive to the changes in irrigation efficiency.

6. POSSIBLE WAY FORWARD

The authors recommend that PODIUM and BHIWA models may be integrated using a system dynamics such as VENSIM . This should be linked with a cost benefits analysis at the basin and country level. Podium can not deal with the externalities such as virtual water trading within and outside the country to evaluate production and environmental tradeoffs. The authors propose a global food security, virtual water trades, and environmental stress analysis using an integrated PODIUM-BHIWA approach.

7. ACKNOWLEDGEMENTS

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