Water resource allocation modelling to harmonise supply and demand in the Malaprabha catchment, India

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Abstract

Malaprabha River has a catchment area of 11,549 km^2 that accounts for 5 percent of the Krishna basin. The catchment area of the sub-basin lies entirely in Karnataka state. It has diversified hydro-climatic zones ranging from humid (annual rainfall - 3047 mm) to semi-arid (annual rainfall - 447 mm) with an average annual rainfall of 766 mm. The 75% dependable flow is 1,857 MCM and is declining over years due to reduced rainfall and upstream catchment development. The basin has predominantly agriculture and drinking water demands. The basin serves the drinking water demand of 3 million people in three districts and primarily to major twin cities, Hubli and Dharwad.

The demand for water in the Malaprabha catchment will change in the next twenty years due to population growth and changes that occur in different sectors. Historical hydrologic analysis and stream flow simulation were assessed using a monthly conceptual rainfall-runoff model SYMHYD. The Resource Allocation Model (REALM) was used to build the water allocation model and analyse alternate policy scenarios and investigate possible water allocation options. These are used to investigate historic, current and future developments in water demand in the catchment. The paper presents a detailed analysis of security of supply for the main water users in the basin: agriculture, urban and industry. The results highlight the intense competition for water between the alternative uses. The impact of proposed inter-basin import of water into the catchment is also analysed.

Introduction

The effective management of available water in the semiarid regions has increased in importance, due to limited water availability. With growing scarcity and increasing inter-sectorial competition for water the need for efficient and sustainable water allocation policies has also become more important. Finding ways to meet the competing demands, while also achieving positive economic and environmental outcomes, requires the aid of modeling tools to analyze the impact of alternative water allocation policy scenarios.

Malaprabha catchment is located in the semi arid region in India. Rainfall in this area is highly seasonal (Monsoon) and the base flow contribution is also low resulting in the need for reservoirs to meet the agricultural demand during the dry season. The

Malaprabha catchment has several water users, which are in conflict with one another. The major water users are irrigation; domestic and industrial water use and environmental water demand. These uses have resulted in the commitment of a large percentage of the catchments mean annual runoff. The intense agricultural practices and absence of reasonable water resources management have led to an increase in water demand which is currently unmet. Therefore, there is a need for better management of water resources in this area. Due to complexity of the physical processes in the catchment, it is difficult to make informed decision on water allocation and development.

The complexity and magnitude of many water resources problems require the assistance of computer models in order to obtain reliable and timely solutions. Allocation models are typically divided into two categories, simulation and optimization models. Linear and non-linear programming models for integrated hydro-economic modeling have been used in many rivers basins like Mekong, Murray, Yellow river etc (Ringler & Huy, 2004, Rosegrant et al. 2000, Rodgers et al. 2002). Those tools will provide the optimum solution for a particular problem. Simulation models are widely used by managers for planning and management of complex systems. Simulation based water allocation models use mass balance principles to allocate resources in a river system, as in MODSIM-DSS (Fredericks et al. 1998), Mike Basin (DHI, 2001), WEAP (Yates et al. 2005), REALM (Perera et al. 2005) etc. A simulation model is not intended to provide optimum solution to a specific problem. Rather, its aim is to evaluate changes managers might like to make to a complex system.

The main aim of this paper is to analyse alternative allocation scenarios in the Malaprabha sub basin, which forms part of the Krishna Basin.

Malaprabha

Malaprabha River has a catchment area of 11,549 km^2 that accounts for 5 percent of the Krishna basin. The river originates at Kankumbi near the Chorla Ghats in the Western Ghats at an altitude of 793 meters, 16 km from Jamboti village in Khanapur taluk. The catchment area of the sub-basin lies entirely in Karnataka state. It has diversified hydro-climatic zones ranging from humid (annual rainfall - 3047 mm) to semi-arid (annual rainfall - 447 mm) with an average annual rainfall of 766 mm. The Malaprabha dam was constructed between 1962 and 1974 near the famous "Naviluteertha" or peacock gorge near Manoli in Parasgad taluk of Belgaum district. The reservoir has a storage capacity of 1250 MCM. The 75% dependable flow is 769 MCM and is declining over years due to reduced rainfall and upstream catchment development. The basin has predominantly agriculture and drinking water demands. The basin serves the drinking water demand of 3 million people in three districts and primarily to major twin cities, Hubli and Dharwad.

Malaprabha reservoir has a storage capacity of 1250 MCM. Inflow at 75% dependability is about 769 MCM (due to scanty rainfall in recent years). The first priority is for meeting drinking water demand as the reservoir fulfils drinking water demand of 3 million people in four districts. The reservoir evaporation loss is approximately 85 to 115 MCM/year which is approximately 10% of total storage capacity. Groundwater use is low in this command. Soils of this region are black or red loamy type.

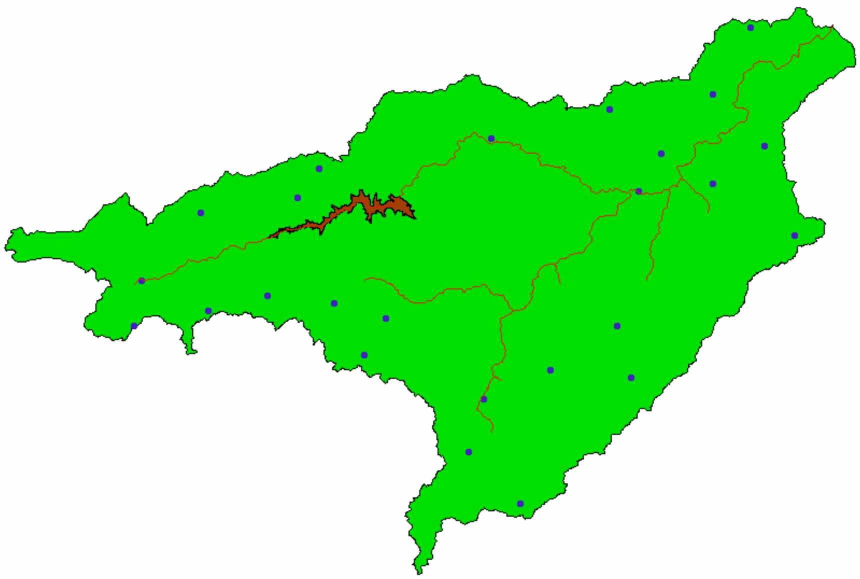

Figure 1. Map of Malaprabha Catchment (Image Source: IWMI Hyderabad)

There are 11 lift irrigation schemes in operation in the catchment and command of the Malaprabha system. There are two cropping seasons in a year Kharif and Rabi. Rabi depends entirely on irrigation. Main crops are Sugarcane, cotton, Groundnut, Jowar, maize, sunflower, and vegetables. The command area is mainly designed for semi-arid crops and the cropping pattern is slowly changing to sugarcane due to market value. The design discharge of the right bank canal is 39 m^3/sec and left bank canal is 47 m^3/sec. The water that is released through right bank canal is used for producing hydro-power before irrigation.

Kolachi weir is constructed 40 km's downstream of main canal to collect the return flow and reuse it for irrigation. The design discharge is 4.2 m^3/sec. About 7.1 m^3/sec of water is released twice in early kharif and Rabi through the river to start the irrigation.

Modelling Framework

In this study the aim is to evaluate the potential of surface water resources of the catchment to supply future water demands and the impacts this has on different sectors within the region. A better understanding of water supply, demand and its value in different sectors is very much essential in developing any alternate policy. The complexities involved in water allocation and use in the Malaprabha catchment requires a holistic approach to achieve a positive allocation outcome, which is sustainable, efficient, and equitable (Rogers & Fiering, 1986). The modelling framework for this catchment consisted of: (1) a hydrologic assessment of the surface water resources and an estimation of water demand; (2) allocation modelling to allocate water to different nodes, and (3) an economic assessment that, includes the calculation of the net benefits water uses derive by sector, demand site and catchment (see Figure 2). In the economic model the output from allocation model is combined with price data and used to assess the outcome of each of the allocation scenarios.

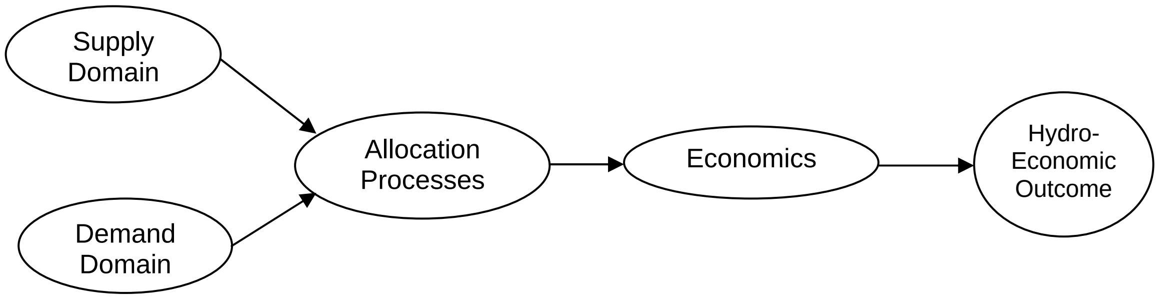

Figure 2. Conceptual modelling framework

Hydrologic Analysis

The allocation model REALM requires surface water inputs to allocate these resources among competing uses. The main aim of the hydrologic analysis is to simulate the flows required to run the allocation model. Historical hydrologic analysis and stream flow simulation was carried out to identify the most important components of the water balance at the sub basin scale and how those components have changed over time. A monthly conceptual rainfall-runoff model SYMHYD was used to model the rainfall-runoff process at key supply nodes in the catchment (Chiew 2002). SYMHYD works on a daily time step. The model uses a pattern search technique to optimise its seven parameters. The parameters are infiltration storage capacity, maximum infiltration loss, infiltration loss exponent, soil moisture storage capacity, constant of proportionality in interflow, constant of proportionality in groundwater recharge and base flow linear recession parameter The simulation period was 1993-2003 (except 2002). The simulations show on average 40% rainfall is contributing to surface and subsurface flow and 60% to ET. The efficiency and coefficient of determination during the calibration and validation period were in acceptable limits. The comparison of simulated and measured runoff during simulation period is given in Figure 3 and 4. The calibrated model was used to generate the monthly runoff from 1972-2003.

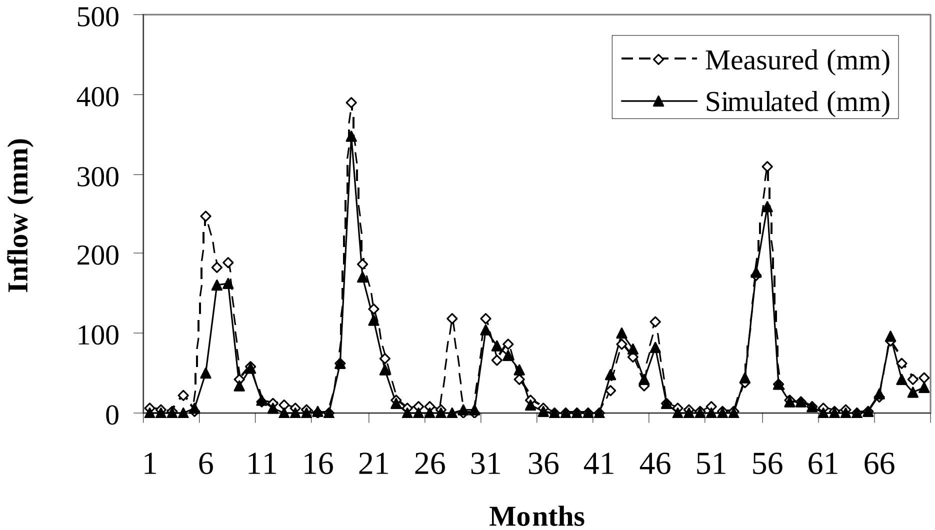

Figure 3. Comparison of simulated and measured runoff in Malaprabha during calibration period.

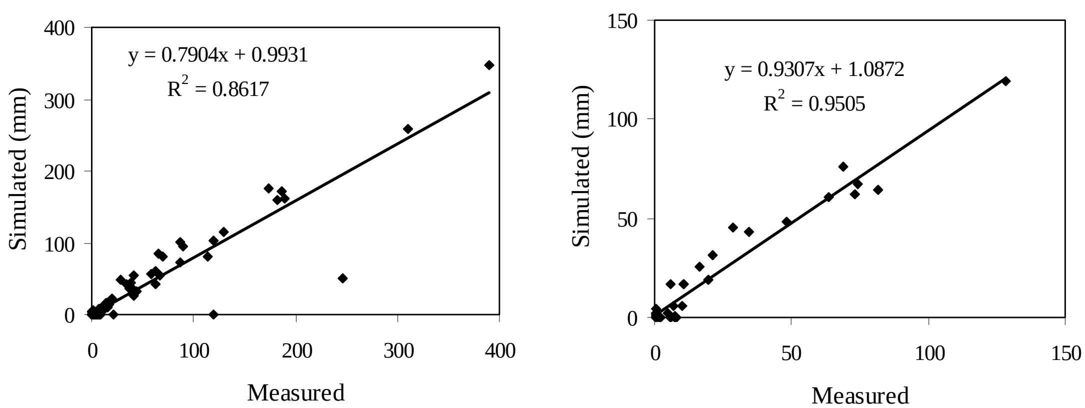

Figure 4. Scatter plots of monthly simulated versus recorded stream flow.

Water Allocation Modelling

The modelling approach is based on integrating resource availability and use through a network allocation model. The Resource Allocation Model (REALM), which is a well-proven tool to aid water resource planning, and management in both urban and rural water supply systems was used to represent the system network. REALM has been developed in close collaboration with a diverse range of users in the water industry (James et al. 1996; Perera et al. 2005). REALM is a network allocation model based on a combination of water balance combined with a linear optimisation algorithm that enables the use of user-defined penalties to impose constraints and preferential resource use. This model capability is particularly useful to generate a large number of alternative policy scenarios reflecting legal, physical and other constraints as well as favoured uses of the resource.

REALM applications generally involve the following steps:

- Defining the problem and developing system components and simulation
- Simulating current scenario which includes actual water demand, resources available and supply,
- Building new scenarios based on future population trends, climate change, cropping pattern etc.,
- Evaluating the economic and environmental impact of future scenarios.

The model uses a node-link network to represent the river basin where nodes represent the physical entities such as rivers, pipelines and canals and links represent the connection between them. The nodes include (1) source nodes such as rivers, reservoirs, aquifers, etc. (2) demand nodes includes urban and irrigation and are connected by either river or pipe carriers. The careers got the capacity to model minimum flows and transmission losses. The model also got the capability to model complex operating rules. In most of the planning models user-defined priorities are used to allocate water to different uses but in REALM it is possible to model preferred distribution of flow by user-defined penalties in the carriers. The allocation of water within the physical water supply network is controlled through user-assigned relative penalties assigned to the various carriers, with low or negative penalties assigned to force water through operationally preferred carriers. It is also possible to move water from one node to another by changing the user-defined penalties.

The model uses a combination of water balance with a network linear program algorithm RELAX (Bertsekas, 1991) to transfer water from various sources (storages and inflows) to various demand centres. The relative penalties assigned to the various carriers dictate the distribution or allocation of flows within the network such that the objective function representing the overall total penalty for the network is minimum. This model capability is particularly useful to generate a large number of alternative policy scenarios reflecting legal, physical and other constraints as well as favoured uses of the resource.

The REALM consists of three major components namely input processing, simulation and output processing (Pereira & James, 2003). Input processing dealt with the preparation of input files. The model requires three input files namely stream flow, demand and system files. The stream flow file contains the stream flow and climatic data (temperature, rainfall etc). The demand file contains the urban, rural and environmental demands for each demand node in the system. The system file contains the information on node and carriers and long-term operating rules. The model output includes reservoir end storage, volume supplied, unrestricted and restricted demand, spillage, shortfalls, carrier flows etc.

REALM modelling tool was used to develop the planning model for Malaprabha System (Figure 5). The system consisted of two sources: Malaprabha reservoir and Kolachi Weir and six demand centres of which three are irrigation demand and two urban demands. The main demand centres are urban, industry, irrigation-left bank canal (LBC), irrigation-right bank canal (RBC), lift irrigation.

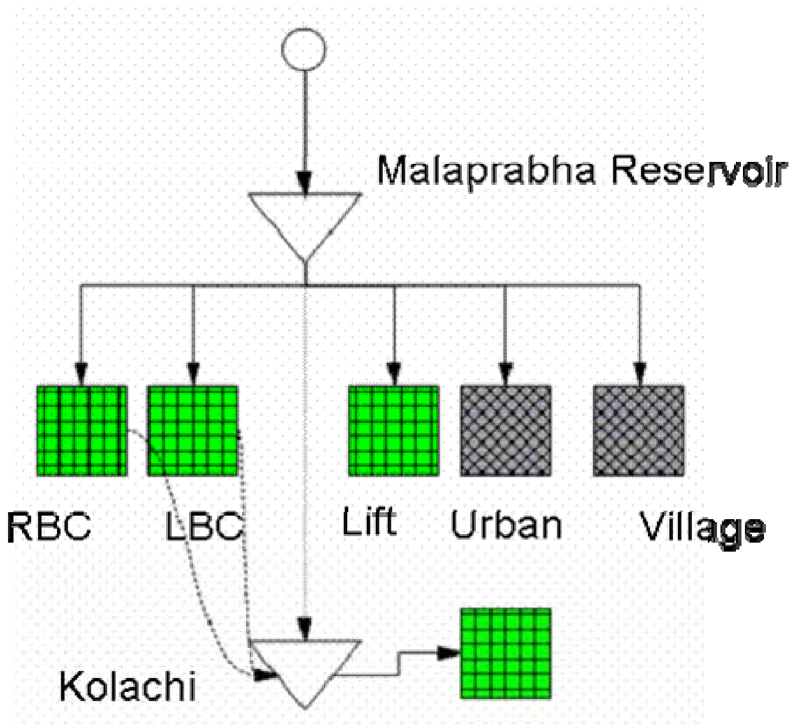

Figure 5. Schematic layout of the Malaprabha River Basin

Economic Modelling

As the competition for water increases in a mature water economy, the effect of different allocations will have an economic impact. Shunting water around for its own sake provides little insight into the needs in a competitive economy. Analyzing water allocations in terms of its economic impacts is more insightful. The principal gap with the current modeling capabilities to analyze water productivity under various allocation scenarios is REALM's (and other hydrological techniques) inability to reflect the economic value of water allocated to alternative demand nodes and uses. A major focus in this research is to enhance REALM model capability by providing an economic assessment tool to quantify the economic output that results from different water allocation scenarios (Davidson et al. 2007). The model will also be used to assess the impact on system performance due to additional commitments on the system such as Hyderabad water use and environmental flows to improve the in stream ecosystem and river health. Since water distribution schemes in Musi involve massive public investment, the model is based on a social benefit cost methodology. Social Benefit Cost Analysis is a well-established and accepted method of assessing society's returns from an investment, and then to attach it to a water allocation model.

Water Demand

Urban & Industrial

The amount of water that people in a city use depends on minimum needs, availability, the level of economic development and the extent of urbanization. In a given city, water consumption varies from season to season and from hour to hour. The total water consumption may be estimated by adding domestic consumption, water required for public use, and the water needed by industry. As more people share the same amounts of fresh water, there is less available to each person. The higher living standards can affect the demand for fresh water as it increases per capita water consumption. Rapid growth of population will lead to more future water scarcity. The current population of the Hubli-Dharward City is approximately 0.8 million and it has expanded at a rate of 3 per cent per year. Based on the projected population (3% growth rate) and an average per capita demand of 100 litres, the gross yearly demand for 2010 is estimated to be 47.1 MCM and is expected to cross 88 MCM in 2031 (Figure 6). To meet the drinking water demand of 0.2 million population down stream of reservoir (Villages), 8.5 MCM of water is released two times in a year (last week of March and May). This water is stored in 74 tanks downstream and is used for drinking in summer months. The industrial demand is assumed as zero.

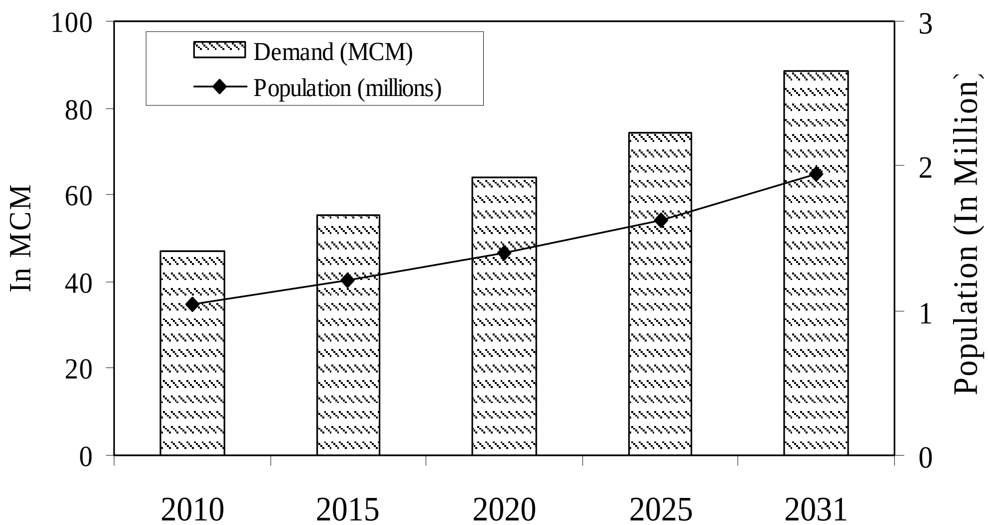

Figure 6: Water demand projections in Hubli-Dharward at 3% population growth rate.

Agricultural Demand

The quantity of water used in agriculture is a function of crop area, type of crop and climatic conditions. The main economy of the Malaprabha catchment is agriculture and the irrigated area is 279,072 ha. Major crops grown are maize, wheat, cotton, pulses, sorghum, sugarcane and groundnut.

The cropping data collected from district level statistical handbook was used to estimate crop area. The water requirements of crops were estimated using the Penman-Monteith approach based on climate and crop culture. The quantity of water required at each demand centres is adjusted using average irrigation efficiencies. The average effective rainfall was estimated using the average monthly rainfall for the whole catchment and adjusting the value to reflect the potion of rainfall to meet crop water requirements. To estimate the effective rainfall we have used a fixed percentage of 80%. The availability of irrigation water is a major constraint on agricultural development in the catchment. The variability of rainfall from year to year is the major constraint for rain-fed areas.

The main irrigated areas in Malaprabha are the Right Bank Canal, the Left Bank Canal, Lift Irrigated Area and the Kolachi Irrigation area. The details of these irrigated areas are given in Table 1.

Table 1. Demand sites and their details.

DEMAND SITES	TYPE OF DEMAND	AREA IRRIGATED (HA)	MAJOR CROPS	AVERAGE ANNUAL DEMAND (MCM)
Hubli-Dharward	Urban water supply	-	-	45
Village	Urban water supply	-	-	8.5
Left Bank Canal	Agricultural	41364	ID crops, Sugar cane	285
Right Bank Canal	Agricultural	202708	ID crops, sugarcane	410
Lift Irrigation	Agricultural	35000	Wheat, ID crops, sugarcane	60
Kolachi irrigation	Agricultural	25000	Wheat, ID crops	60

Environmental Demand

Dams and reservoirs, aqueducts, river diversions, major irrigation projects, industrial and domestic diversions, groundwater pumping etc have a major hydrological impact which could affect both present and future generations and wildlife. The same applies to the disposal of wastewater and contamination of water bodies through agricultural runoff, industrial effluent and unprocessed sewage. In India traditionally no water has been allocated for environmental demand, as enough surface water was available to meet these demands. The Malaprabha River remains dry below the reservoir during summer months, as most of the water is stored and diverted to agriculture.

Scenario Modelling Results

Model Testing

Calibration and validation of water allocation models poses difficulties due to many factors including the complexity of system under study, lack of data and other drivers of water allocation in the system, which cannot be modelled (Jakeman and Letcher, 2003; Letcher et al. 2006; Mainuddin et al. 2007). Calibration was carried out by comparing the reservoir end storages, as spill data is not available. Actual releases were used as the demand and evaporation losses were adjusted. The comparison of actual and modelled reservoir end storage at Malaprabha reservoir is given in the figure 7. The simulated and measured storages followed a similar pattern except for few months with low storages. The differences in the low storage period is mainly because of the under estimation of evaporation from reservoir.

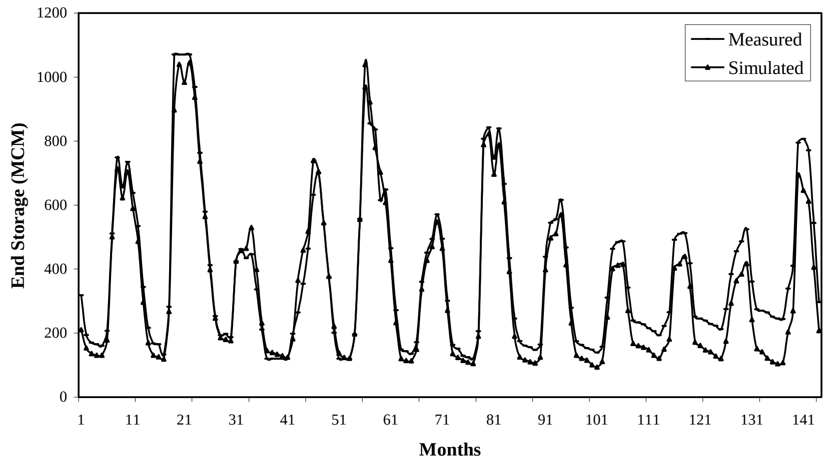

Figure 7. Comparison of measured and modelled end storages in Malaprabha Reservoir

Baseline Scenario

The model was used to simulate selected future scenarios. A baseline scenario was developed using the demand data from 1993-2031 and simulated stream flow data from 1993-2004 assuming that similar trend of stream flow situation will exist in future. Agricultural demand and hydrological condition is assumed as unchanged into the future. There is no restriction to meet the urban and village drinking water demand. Deficit is shared between the agricultural zones.

The analysis of the result shows that the current storage would not be sufficient to meet the demand and the demand deficit is estimated to grow from 52 MCM in 2007 to 294 MCM in 2031. The demand deficit in the agricultural zones: Left Canal (LC) and Right Canal (NSRC) and Lift irrigation were more than 50% of the allocated volume in 6 years out of 38 years of simulation. The demand deficit in Left Canal varied from 0 to 200

MCM in different years. The shortfall in the urban area varied from 0 to 25 MCM in different years. The volume supplied at different assurance level is given in Table 2.

Table 2. Baseline scenario with simulated supply (MCM) at different levels of assurance

% of Assurance	Urban Water	Left Bank Canal	Right Bank Canal	Lift Irrigation
99.5	5.0	6.0	30.0	0.0
99	9.9	29.0	59.0	1.1
95	11.5	92.0	140.0	14.0
90	16.5	126.0	184.0	22.0
80	22.6	166.0	275.0	33.0
70	26.9	196.0	307.0	40.0
50	35.0	245.0	337.0	53.0

Scenario with stream flow decline

The agriculture in the catchment is developing quickly. Also the cropping pattern is changing from rainfed to irrigated crops in the catchment. A series of dry years in recent times has had a significant impact on the annual average stream flows into the reservoirs. The yield is reduced to 736 MCM (26 TMC) from 1250 MCM (44 TMC) due to scanty rainfall. Therefore security of inflows into the reservoirs is not guaranteed in the future. Scenarios were analyzed with a 10% and 20% decline in stream flow in all the supply nodes in the future with demand unchanged.

With a reduction of inflows by 10% from the current situation, water withdrawals for agriculture and urban sites decline sharply. The return period of demand deficit of more than 100 MCM in left bank and right bank canal is 5 and 3 years respectively. In Lift Irrigation area the demand shortfall of more than 50% of the demand will occur once in every 25 years. The situation is more worst if the stream flow declines by 20%.

Scenario with Crop Diversification

Crop diversification is defined as the strategy of shifting from less profitable to more profitable crops by changing of crops, variety and cropping system. In Malaprabha the command area is mainly designed for semi-arid crops and the cropping pattern is slowly changing to sugarcane due to market value. Therefore a scenario was analysed with 20% of cotton & maize is replaced with sugarcane. Sugarcane is a water hungry crop and swapping of other crops with sugarcane may lead to increased use of water by irrigation. The analysis of the result shows that this will put more stress on the reservoir and the irrigation requirement increases drastically by diversifying more area into sugarcane. The demand deficit in Left Canal varied from 46 to 350 MCM in different years. The shortfall in the Right Canal varied from 84 to 520 MCM in different years. Therefore there is a need to use groundwater and surface water conjunctively or transfer water from other basins to meet this deficit.

Scenario with Inter Basin Transfer

Inter-basin transfer of water from surplus to deficit regions could be an option for achieving more equitable distribution of India's water wealth and its optimal utilisation. Inter basin transfer is planned from Mandovi river in Goa to Malaprabha (214 MCM). A scenario was analysed with original cropping pattern and with diversified with sugarcane. The analysis of the results suggests that the current supply together with the inter basin transfer would be sufficient to meet the water demand by 2031 if population grows at a rate of 3%. Moreover the shortfalls are in the LBC and RBC demand centres are reduced (Figure 8).

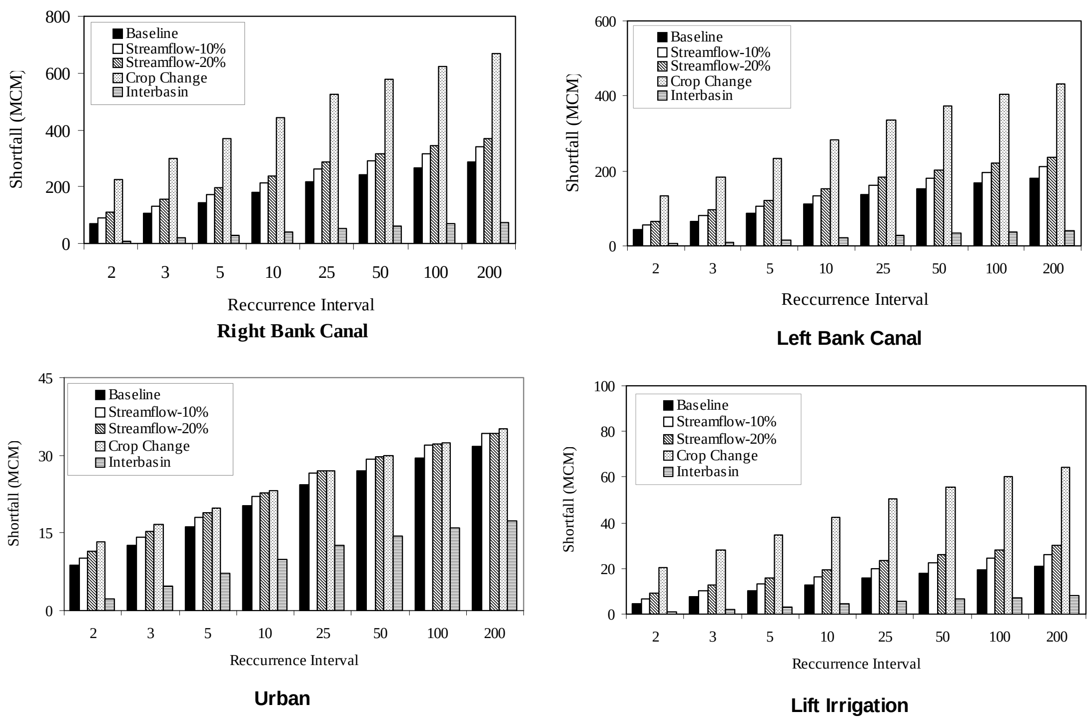

Figure 8. Comparison of unmet demand in each sector for different scenarios

Conclusions

Rapid economic and population growth has driven increasing demand of water from the industrial and urban sectors, which put pressure on resources available for agricultural production. With growing scarcity and increasing inter-sectorial competition for water the need for efficient and sustainable water allocation policies has also become more important. Finding ways to meet growing demands and also achieve positive environmental and economic outcomes requires the aid of modelling tools to analyse the impact of alternative policy scenarios. This paper investigates water availability and use in the Malaprabha catchment, India.

The modelling approach is based on integrating resource availability and use through a network allocation model (REALM) integrated with an economic model. The comparison of historical supply with the irrigation demands showed that there is considerable shortfall in supply in many years. The upstream watershed development and climate change will reduce the inflows and therefore security of inflows into the reservoir is not guaranteed in the future. With a reduction of inflows by 20% from the current situation, water withdrawals for agriculture sites decline sharply. The increase in sugarcane cultivation will alleviate the shortfall in the agricultural sector. It was found that inter-basin transfer of water from Mahadayi river basin to Malaprabha will improve the water supply and will reduce the irrigation shortfall considerably.

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