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Hydro-economic modelling of the Upper Bhima Catchment, India

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Abstract: Water resources development has played a crucial role in the expansion of agriculture and industry in the Upper Bhima Catchment, Maharashtra, India. However, sustainable water resources management has become a challenging issue in this catchment in recent years as there is an increasing demand for renewable, yet finite water resources. Finding ways to meet this growing demand and also to achieve positive environmental and economic outcomes requires the aid of modeling tools to analyze the impact of alternative policy scenarios. Water resources management modeling at a catchment scale can provide policy makers with essential information needed to make rational resource allocation decisions.

Rainfall in this 46,066 km^2 catchment ranges from 450mm-2500mm, and is monsoonal by nature. As a result of the seasonal distribution of rainfall, a large portion of the catchment is often subjected to water stress conditions. With anticipated population and industrial growth, together with increased environmental concerns, demand for water in this catchment is expected to increase in the next thirty years. In this study, the economic impacts of multiple water redistribution scenarios will be assessed against present day conditions based on hydrological principles using a water allocation model combined with a social cost-benefit framework. Resource assessment was conducted at key control nodes in the catchment. Historical hydrologic analysis and stream flow simulation were assessed using the semi distributed hydrologic model Soil Water Assessment Tool (SWAT). The Resource Allocation Model (REALM) was used to build the Upper Bhima water allocation model and then to simulate the resource allocation with constraints. Social Cost-Benefit Analyses using appropriate rates was then applied to water allocated to each sector (agriculture, urban, industrial, and hydro-power generation). A scenario approach was used to investigate security of supply associated with possible future changes in demand. Hypothetical water allocation alternatives representing future development scenarios, including increased water consumption and different water allocation strategies, were developed in consultation with the stakeholders and then evaluated.

Presented in this paper are the results of the hydrologic and economic analysis. The most affected sector, in terms of priority and allocation, was urban use. In the water allocation model, it was found that although supply and demand remained largely heterogeneous throughout the system, response to change in resource allocation was consistent from one demand node to the next. Unmet demands were observed throughout the catchment, indicating a need for policy-makers to explore options for future water allocation policies. Economically speaking, agriculture is likely to suffer the greatest impacts. With expected high level of water shortage, it was found that using economic criteria for assessing the effects of water sharing provides a clear, objective and transparent form of decision support to policy-makers in the Upper Bhima catchment. When using hydrologic principles in conjunction with economics of water resources, this framework was capable of critiquing potential scenarios from a multi-disciplinary perspective, most notably quantifying the economic impact of alternative water allocation policies.

Keywords: *Water allocation, irrigation, water resources economics, urban, Upper Bhima, Krishna.*

1. INTRODUCTION

World population continues to increase and so is the demand for water. Growing pressures to meet urban, agricultural and environmental demand will have an impact on available resources. Globally around 70% freshwater is used in agriculture, 22% in industries and 8% domestically. About 2 billion people worldwide have no access to potable water and this figure is projected to rise as high as 3.5 billion by 2025. Producing enough food and providing safe drinking water to a growing population is going to be a difficult task in the years ahead. More and more extraction of water to meet the growing demands has resulted in the closing of many river basins and depletion of water tables. As the resources are becoming scarce, we will be forced to use our existing available supply water more efficiently, and to investigate options for water recycling (and reuse) in order to keep up with demand. Greater efforts in effective water resources management will be necessary if demands across all sectors continue to increase as expected.

Water resources management has morphed from a technical discipline in the past to a more multi-disciplinary endeavor today. The aim of this study is to assess the wider economic effects of water redistribution in the Upper Bhima catchment (Maharashtra, India) based on the principles of Integrated Catchment Management. This paper focuses on the hydrologic and water allocation analysis of the basin and the economic consequences of different water allocation policies. Both current management practices and several hypothesised scenarios to meet future demands in the system are assessed.

Figure 1. Upper Bhima Catchment

The framework developed for the Upper Bhima catchment (Figure 1) draws on previous hydrologic-economic projects (George et al. 2007). The aim of integrating these constituents is to analyse plausible water sharing scenarios in the basin and to better understand the impacts of future actions. This integrated approach to analysing water allocation can provide policy-makers with a tool that allows them to enhance their decision making capacity. Furthermore, this framework could be used as a template for future evaluations of similar projects, regardless of scale.

2. UPPER BHIMA – PHYSICAL CHARACTERISTICS

The Upper Bhima River and its catchment are located primarily in the state of Maharashtra, India. Located in the upper reaches of the Krishna Basin, the Upper Bhima is the second largest sub-catchment in the basin, covering an area of 46,066 km^2. Running north-south on the western side of Maharashtra is the Sahyadri Range (known as the "Western Ghats") with an average elevation of 1,000 m. This range quickly transitions through the Mawal area before it flattens out into the Deccan Plateau. Streamflows in the catchment are generated predominantly in the Western Ghats.

The catchment has a highly diverse climate mainly caused by the interaction between the monsoon and the Western Ghat mountain range. The mean annual rainfall of the catchment is 642 mm and is unevenly distributed. The Western Ghats zone is covered with thick forests and receives heavy rainfall reaching a maximum of 5,000 mm/year. Rainfall decreases rapidly down the eastern slopes and plateau areas to less than 500 mm/year. It again increases slightly in the east of the catchment; therefore, the central part of Upper Bhima receives the lowest rainfall. Although rainfall is abundant during monsoon season (June-September), often flooding the plains of the Deccan Plateau, water stress conditions are common at other times of the year.

Population plays an integral role in water resources management and development in a catchment. The stresses imposed on water resources by population growth is not a new problem; however, it is becoming a far more pressing issue today (Dinar et al., 1997). Currently, the basin serves a population of 15 million (2001 census) of which 6 million live in urban areas. It is an important catchment in the context of serving inter-sectorial demands including drinking and agricultural water supply, where agriculture has been a mainstay in Maharashtra's economy, and hydropower generation (363 MW). There are 6 major and more than 30 medium reservoirs in the catchment with a gross storage capacity of 7,800 Mm^3 (Million Cubic Metre).

3. MODELLING FRAMEWORK

The aim of this modelling exercise is to evaluate the potential of surface water resources of the catchment to supply future water demands and to assess the impacts this has on water security and different sectors within the region. The modelling framework for this catchment consisted of: (1) a hydrologic assessment of the surface water resources and an estimation of water demand; (2) water allocation modelling to allocate water to different nodes, and (3) an economic assessment that includes the calculation of the net benefits from water uses derived by sector, demand site and whole of catchment. 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.

3.1. Hydrologic Analysis

The allocation model requires surface and groundwater water availability to allocate the resource among competing uses. The main aim of this analysis is to generate the flows required to run the allocation model. The Soil and Water Assessment tool (SWAT) is used for this purpose. SWAT is a process based continuous hydrological model that predicts the impact of land management practices on water, sediment and agricultural chemical yields in complex watersheds with varying soils, land use and management conditions (Arnold et al., 1998). The main components of the model include: climate, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing.

SWAT requires three basic files for delineating the catchment into sub basins and Hydrological Response Units: Digital Elevation Model (DEM), Soil map and Land Use/Land Cover (LULC) map. A 90 m spatial resolution Shuttle Radar Topographic Mission (SRTM) DEM was used in this analysis. A soil map of Maharashtra State was used to derive basic soil hydraulic properties. Land Use/Land Cover were derived for year 2004-05 using IRS P6, LISS III remote sensing images of October '04 and February '05 months with a spatial resolution of 23.5 m. In this study, daily rainfall data from 44 rain gauge stations, spread spatially across the entire catchment, was used. Further, records of meteorological parameters such as daily maximum and minimum temperatures, wind speed, solar radiation and relative humidity for three meteorological stations were provided for estimating reference evapotranspiration in catchment. Daily discharge data from 8 monitoring stations and recorded flows at all reservoir sites were used for calibration and validation purpose.

The SWAT model development involves calibration and validation phases. In this study, the data for the period from January 1998 to December 2001 was considered for model calibration, and data for the period from January 2002 to October 2005 was considered for model validation. In the calibration phase, the runoff was simulated at a daily time scale and was compared with that observed at the gauging stations and inflow at reservoir locations.

3.2. Water Allocation Modelling

The allocation modelling approach is based on integrating resource availability and use through the REALM (Resource Allocation Model) network allocation model. REALM is a useful tool to address allocation issues in water-stressed basins and can help managers in complex decision-making. It can be applied to both urban and agricultural systems and can address a diverse range of issues such as sectorial water allocation, water trading, water rights, environmental flows, climate change, restrictions, and supply and demand management. The model is 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 (Perera et al. 2005; James et al. 1996).

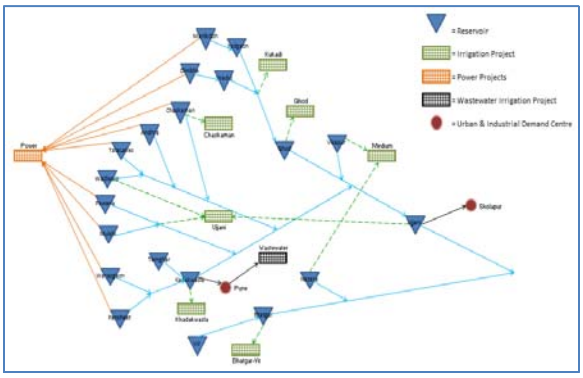

Figure 2. Schematic of the Upper Bhima in REALM

The model uses a node-link network approach to represent the river basin where nodes represent the physical unit such as reservoirs, aquifers, townships, agriculture, industries etc. and links represents the carriers which connects the nodes (rivers, pipelines, canals etc). The model has 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.

In building the REALM model for Upper Bhima, 18 supply nodes were included in the network which includes: Manikdoh, Waduj, Dhimbe, Yadgaon, Chaskaman, Ghod, Bhatgar, Vir, Khadakwasala, Warasgaon, Panshet, Temghar, Ujjani, Wadiwale, Pawana, Mulshi, Tata Lakes and Andhra (Figure 2). At this stage, ground water is not included in this model as its availability is very limited and data is unavailable. Twelve demand nodes were included in this model: two urban centres (Pune & Sholapur), seven agricultural zones (Kukadi, Chaskaman, Ghod, Vir Bhatgar, Khadakwasala, Ujjani and medium irrigation projects) which irrigates 0.6 million ha, and three hydro-power generation projects (Tata, TataHydel and Andhra). To accommodate for urban demand, the projected population and existing consumption rate of 200 L/person/day was used.

3.3. Economic Modelling

Applying economic concepts to evaluate alternative allocation scenarios incorporates a social perspective to the analysis. An impartial economic notion should be a mainstay in water resources management, especially with growing demands for the resource and ever-increasing constraints to supply. Economic assessments can help determine whether the implementation of particular schemes will result in an overall net benefit (or loss) to society.

Although water allocation is at the core of water resources planning and development, deriving the economic value of water in an allocation regime is fundamental to assessing its viability. At present, a widely accepted and heavily utilized water market does not exist for doing so in this catchment. Of interest in this economic assessment is the value of water only. To determine the value of water, all additional costs (operational, social, environmental and opportunistic) must be evaluated and subtracted. The value of water used in urban centres and industry is determined based on price paid and own-price elasticities of demand. For water used in hydro-power generation, its value is directly correlated to electricity price because power generation is a conjunctive use of water resources.

A basic approach for calculating the value of water in agriculture is to disaggregate the total price of the crop into individual components, whereby all known prices and quantities of the system are used to determine the remaining unknown value of water. This can be done by determining the net income received by the farmer per unit of water applied. Equation 1 displays, in simple terms, how this was done:

$$Price\ of\ Water = \frac{(Price_{Output\ Goods})(Quantity_{Output\ Goods}) - (Price_{Input\ Goods})(Quantity_{Input\ Goods})}{(Quantity\ of\ Water\ Used)} \qquad (1)$$

Once all water within the catchment was valued, an economic assessment of the current regime was conducted. In order to determine economic value of alternate water resource allocation scenarios, relative economic variation between the baseline and each scenario was calculated. In a model recently developed by Davidson and Hellegers (2008), Social Cost-Benefit Analyses (SCBA) were conducted on allocation outputs from the REALM allocation model.

A Cost-Benefit Analysis is a well established and accepted method used to assess relative desirability of competing alternatives to society by their economic worth from present day forward. The overall idea behind conducting an SCBA is to add up all benefits that will be seen from a project, subtract all costs (using shadow prices and including all externalities), and account for timing over the prescribed life of the project. Accounting for timing, or discounting, is required because future benefits are worth less today than their face value. This is achieved by converting all costs and benefits to a net present value (NPV) so that economic potential of varying scenarios within the catchment can be compared without an existing accepted water market.

4. DATA

The data used for this study was primarily collected from secondary sources and validated by comparing data collected from different sources.

Population growth has been rapid in most of India's urban centres over the past few decades, and is expected to continue to do so. When using available population data from 1991and 2001, population growth rates for Pune and Sholapur were approximated at 4.2% and 3.5% respectively. Urban demand is based on the existing consumption rate of 200 L/person/day (PMC, 2007) which was assumed to remain constant until 2031. Overall urban demand increased in line with the estimated 3.5% growth rate in population. Industrial demand was estimated and calculated as being an additional 20% of urban demand. It was assumed that with an increase in population in the urban centres, a similar increase will be observed in industry. The urban nodes in REALM represent both domestic and industrial demands.

There are three significant hydro-electric power generation projects located in the Upper Bhima catchment (363 MW). The majority of the projects located in the upper reaches of the river network within this catchment contribute a known volume (thus demand) to these projects. In agriculture, demands are ideally determined based on land-use planning, incorporating cultivable area, crops, crop area, irrigation requirements, etc. The water requirements of crops were estimated using the Penman-Monteith approach based on climate and crop culture (FAO 56, 1998). The quantity of water required at each demand centres is adjusted using average irrigation efficiencies and effective rainfall (80% chance occurrence). In the baseline scenario, it was assumed that net irrigation requirement will remain constant for project duration (2031).

No information was available on wastewater irrigation schemes that are likely take place downstream of Pune City. However, there is reliability in perennial flows generated from the urban wastewater stream. A wastewater irrigated area of 10,000 ha has been assumed for this study. It was also assumed that the area produces two crops a year, paddy and jowar; these crops have been found to thrive in wastewater irrigated zones downstream in the Krishna Basin. Determining requirements for environmental demand (e.g. environmental flows) is a relatively new component in modelling catchments in India and at present environmental flow is assumed to be zero. Present system conveyance efficiency of determined supply was estimated at 60%.

5. PRELIMINARY RESULTS

The model described in Section 3 was applied to present day conditions in the Upper Bhima catchment. This will be used as a baseline scenario, a basis by which selected future scenarios can be developed from and simulated in order to derive benefits from this framework in terms of potential relative change.

5.1. Baseline Scenario

A baseline scenario was developed using the demand data from 1993-2031 and simulated stream flow data assuming that similar trend of stream flows will replicate in future.

The analysis of the results shows that the projected supply would be sufficient to meet the demands from power projects, Ujjani, Bhatgar-Vir, Ghod, Sholapur and the Wastewater Irrigation Scheme showed as no deficit in required demands in the baseline scenario were present. Pune's first year of unmet demand occurred in 2014, with an 8% deficit and almost continuously thereafter, with the greatest unmet demand in 2028 at 22%. Khadakwasla irrigation project shows its first year of unmet demand in 2011 (20%), and almost continuously thereafter, with the greatest deficit seen in 2031 at 59%. The Kukadi projects displayed deficits for the entire life of the project, ranging from 64% to 83% of demands not being met. The Medium Projects also suffered from consistent unmet demand until 2031, averaging 20%. Chaskaman saw its first year of unmet demand in 2010 (15% unmet), and again for 9 other years, peaking at 24% in 2029. The volume supplied at different assurance levels is given in Table 1.

The economic evaluation of surface water allocations to different sectors, assessed over a 30-year time horizon from 2001, shows a return of Rs. 380,641 million. It should be noted that this figure can only be used as a reference with which different scenarios will be compared. Of more interest are the average net values placed on water used for different purposes in each region. These ranged from Rs. 0.62/m^3 in the agriculture sector to Rs.38.97/m^3 in Pune City. The value of water in agriculture varies from Rs 0.40/m^3 for rice to Rs 19.8/m^3 for vegetables. A sensitivity analysis was conducted on the baseline with regards to the original discount rate (of 8%) to assess impacts on results when rates of 4% and 16% were used.

Table **1.** Baseline scenario with simulated supply (Mm^3) at different levels of assurance

% of Assurance	Pune Urban	Sholapur Urban	Irrigation Kukadi	Irrigation Chaskaman	Irrigation Kadakwasla
99.5	74	36	24	104	146
99	118	43	32	118	162
95	240	71	55	168	214
90	305	94	68	202	249
80	384	130	83	254	298
70	441	165	94	300	340
60	489	202	103	345	380
50	535	244	111	393	421

Although the SCBA display great sensitivity to changes in discount rate, all changes seen were relatively consistent across all sectors and for total NPV.

5.2. Environment - Stream Flow Decline

A series of dry years in recent times has had a significant impact on the annual average stream flows into the reservoirs. Therefore this scenario was run to represent potential changes in climate. In order to represent such changes, stream flows were reduced by 10% system-wide. Based on REALM generated allocations for this scenario, areas in the Upper Bhima catchment suffered from very large unmet demands.

However, the Power Projects, Ujjani, Bhatgar-Vir, Sholapur and the Wastewater Irrigation Scheme had their demands met for the entire simulation period. With a 10% reduction in available flows, water withdrawals for Pune City were affected significantly. Figure 3 shows that the first deficit occurs in 2011 with 9% of demand unmet and almost consistently thereafter, with the greatest unmet demand of 27% in 2028.

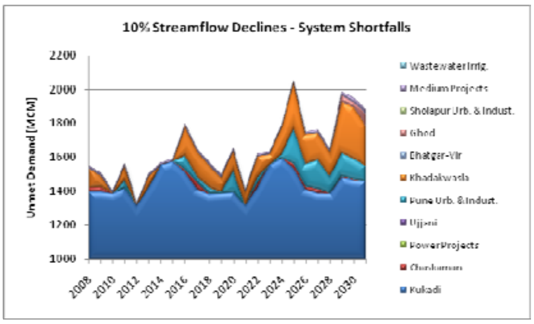

Figure 3. Comparison of unmet demand in each sector for streamflow decline scenario

Water available for diversion for irrigation in the Khadkwasala irrigation area decline sharply. Khadakwasla shows an unmet demand of 30% in 2008, and demand remains unmet for the majority of the simulation period. The return period of demand deficit of more than 180 Mm^3 is once every 10 years. In the Kukadi irrigation project the supply shortfall of more than 1500 Mm^3 will occur once in 5 years.

The economic assessment of this allocation scenario indicated that the agriculture sector will suffer losses in terms of its NPV and value of water (Table 2). A decrease in overall water supply will result in reduced production and therefore reduced economic value. Reduced stream flows had a negative impact on both industrial and urban sectors, reducing both of their NPVs.

Table **2.** Comparison of economic results

Scenario	Economic Assessment			
	ΔNPV (agri)	ΔNPV (urban/ indust)	ΔNPV (total)	ΔWater Value (agri)
#1 – Stream flow Declines	-6%	-1%	-1%	-1%
#2 – Technological Improvements	-73%	+1%	-1%	+2%
#3 – Management Changes	+53%	+2% / 0%	+2%	+50%
#4 – Tech. Impr. & Mgmt Changes	-11%	+1%	+1%	+51%

5.3. Technology - Improvement in Conveyance for System Efficiency

The irrigation efficiency in surface water irrigation projects in India is very low (40-60%). Most of the surface water irrigated land uses furrow and border type applications. As the resources become scarce and expensive, water saving irrigation practices spread fast. United Nations estimates show that the bulk of the increase in food production will need to come from irrigated land in the future. There exists both a need and the potential to improve efficiency in the irrigated agriculture. Increased efficiency can be achieved through price incentives, infrastructure refurbishment and improved agricultural management techniques, including greater precision in the timing and volume of water applied to crops and sustainable agriculture techniques. Therefore a scenario was analyzed by assuming that an improvement of irrigation efficiency by 10% is achievable.

The analysis of results shows that under this assumption the shortfall can be reduced significantly. Relative to the baseline, the agricultural sector saw a huge decrease in NPV, indicating overall devaluation of this sector. However, because of an increase in met demands, the weighted average for the value of water in agriculture increased. Overall results generated from the economic model indicated any spending from present day conditions will result in less desirable outcomes (Table 2). Although positive results for this scenario were seen in REALM, its cost might not justify its feasibility.

5.4. Management - Crop Diversification

Crop diversification is defined as the strategy of shifting from less profitable to more profitable crops or water intensive to low water intensive crops by changing crops, variety and cropping system. In an attempt to match the supply and demand the cropping pattern was diversified by changing 15% and 10% of less profitable crops (rice and sugarcane) in summer and winter seasons to more profitable crops.

With this particular crop diversification regime, overall unmet demand decreased slightly from the baseline. With respect to economics for this scenario, a large increase in water value was realized in agriculture compared to the baseline. Overall benefits were seen in this scenario, with increases for urban, industrial and overall system NPV.

6. DISCUSSION AND CONCLUSIONS

The practice of water resources management within a basin has always been challenging. With the continual trend of increasing demand and a finite supply, effective management of water resources will be needed to meet these needs in a sustainable manner. In this study, the Upper Bhima catchment was modeled in terms of water resources availability, demand, allocation, with the aim of assessing effects of water redistribution from an economic perspective.

Unmet demands in a catchment are indicative of a need for policy-makers to strategize and explore options with respect to alternate water allocation schemes. In this study, scenarios to address potential environmental, technological and management changes that could improve the allocation of water were developed and analyzed. Findings from this study indicated that:

- A framework whereby integrating water allocation modelling and economic assessments can provide policy-makers with a tool that allows them to make more appropriate decisions with respect change of management and operations strategies;
- This framework was found to be capable of assessing each scenario relative to the baseline in terms of net present value, as well as quantifying the changes in value of water in each sector arising from each hypothesized allocation; and,
- When used in conjunction, these models were capable of critiquing potential scenarios from a multi-disciplinary perspective, most notably quantifying their economic potential in order to enhance results generated from water resources allocation modelling simulations.

The combined results from modeling allocation and economics in a catchment enabled the assessment of wider economic effects of water redistribution in the Upper Bhima catchment (Maharashtra, India). The potential of surface water resources of the catchment to supply future water demands were assessed, including their economic potential with any simulated change, indicating any potential impacts on different sectors within the region.

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