Integrated Water Allocation-Economic Modelling at a Catchment Scale

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EXTENDED ABSTRACT

Rapid economic and population growth has led to increased demand for water from the industrial and domestic sectors and 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 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.

The Musi catchment in India is facing serious challenge to meet the growing demand due to rapid population growth and decline of resources. The intense agricultural practices and absence of reasonable water resources management have led to an increase in water demand which is currently filled by extracting groundwater resources and importing from sources outside the basin.

In this paper a modeling framework is introduced that accounts for the interactions between hydrology, water allocation and economics to asses the economic impacts of redistributing surface and ground water at a catchment scale. The modelling approach is based on integrating resource availability and use through a network allocation model integrated with an economic model based on social benefit cost techniques. Resource Allocation Model (REALM) is a simulation model, based on a combination of water balance combined with a linear optimisation algorithm that enables the application of user-defined penalties and priorities to impose constraints and preferential resource use. The economic model will be used to assess the monetary outcome of different water allocations and is in a developmental stage.

Resource assessments were conducted at key control nodes in the catchment. Historical hydrologic analysis and stream flow simulation were assessed using a monthly conceptual rainfall-runoff model SYMHYD. REALM was used to build the Musi water allocation model and then to simulate the water supply system that integrates the Musi catchment and the Nagarjuna Sagar project in Krishna and Singur and Manjira in Godavari, which lies outside the catchment but is one of the water sources for Hyderabad city. A scenario approach was used to investigate possible changes. Hypothetical water allocation alternatives representing future development scenarios that would increase water consumption and different water allocation strategies were formulated after consulting the stakeholders in the catchment.

Results from the scenario analysis indicate that competition for Musi water is very high. For each scenario levels of assured supply were estimated for each node. The results shows that the transfer of water from agriculture to the urban users may grow over years and that water must come from Nagarjuna Sagar in the future. Hence, the allocation to irrigation is likely to fall over time unless other sources of water such as runoff recycling and water harvesting are used to meet part of the urban demand. Given this, improvements in the productivity of available water, in irrigation efficiency and in crop diversification are essential.

1. INTRODUCTION

Population growth and economic development have placed stress on the water resources of the Musi River, a tributary of the Krishna Basin. The City of Hyderabad, which lies in the basin, has experienced water scarcity for a number of years. The available water resources are being exploited to meet this increasing demand. Water demands for domestic and industrial needs have historically been met from surface water sources. Currently, water is being imported from sources outside the basin to meet the drinking water demands. Water from these outside sources has traditionally been used for agricultural operations in these adjoining basins and is also becoming stressed. This transfer is also creating considerable conflicts between water users in the catchment and has complicated policy tradeoffs in allocating water among competing users.

If anticipated economic development and population growth over the next 30 years eventuates the catchment will experience serious water quantity and quality resources issues. The allocation of available water resources, in light of uncertain rainfall and depleting ground water table, is one of the serious challenges in the catchment. An important question for policy makers centres on is the economic impact of restricting irrigation water supplies, and its accompanying losses to farmers, to supply growing urban demand. Finding ways to meet the competing demands, while also achieving positive economic outcomes, requires an integrated approach that links the allocation of water with the economic impacts. Governing this linked model are the underlying hydrological principles of the catchment.

Effective water allocation and management requires an understanding of water availability and reliability. The complexity and magnitude of many water resources problems require the assistance of computer models in order to obtain reliable, quantifiable and timely solutions. Models can be divided into two categories according to their function. They either simulate or optimize. Optimization models use an objective function and a set of constraints to find the optimum solution for a particular problem (Ringler & Huy, 2004, Rosegrant et al. 2000). Simulation models are widely used by managers for planning and management of complex systems. Simulation based water allocation models use a network linear program with user-defined penalties and 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.

In this paper an integrated water allocation-economic modeling framework that accounts for the interactions between hydrology, water allocation and economics is introduced. The intention of this modeling exercise is to asses the hydrological and economic impacts of redistributing surface and ground water in the Musi system, which is a component of the Krishna basin in India.

2. MUSI – GENERAL CHARACTERISTICS

The Musi River, a tributary of Krishna, originates in Anantha Hills approximately 90 km to the west of Hyderabad and flows from west to east. The Musi River is 110 km long and joins the Krishna River at Wazirabad in Nalgonda district in Andhra Pradesh. The River has a catchment area of 11,000 sq km. The major sources of water into the River are the runoff, sewage from Hyderabad city and irrigation return flow from Nagarjuna Sagar Left Canal (NSLC).

The climate of the Musi catchment is typical of the semi-arid rain-fed conditions found throughout the Deccan Plateau. Summers are hot and winters are pleasant. The mean annual rainfall of the catchment is 760 mm and is not distributed evenly in space and time. The region as a whole is characterized by a higher degree of inter-annual variability of rainfall. The land use consists of agriculture, forest, and urban, barren and rocky areas. The total cropped area is 870,000 ha. The major crop in the sub-basin is rice; followed by vegetables, ground nuts, cotton, chillies, sugar cane, jowar, bajra, maize and gram.

3. MODELLING FRAMEWORK

In this study the aim is to evaluate the potential of surface and ground water resources of the catchment to supply future water demands and the impacts this has on different sectors within the region. The modelling framework for this catchment consisted of: (1) a hydrologic assessment of the surface and groundwater 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 1). 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 REALM requires surface and groundwater inputs to allocate these resources among competing uses. The main aim of this analysis is to simulate the flows required to run the allocation model. There are five tributaries joining the Musi River before it joins the Krishna. There are three gauging stations maintained by the State Government at each reservoir sites and one station maintained by Central Water Commission at Damerchala, a few kilometers upstream of the confluence of Musi and Krishna rivers. 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. 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 catchment is divided into four sub-basins based on stream network and the model was calibrated at two gauging stations (Himayath Sagar and Musi Medium). The calibrated model was used to generate the monthly runoff from 1972-2002.

Due to intensive agricultural development, more than 50% of the groundwater basins in Musi are categorized as being in either a critical or semi critical state. This is the main reason for the groundwater table to deplete as deep as 60-90 meters in certain areas. Therefore, majority of the rainfall falling into the catchment is first used to recharge the depleting groundwater table and hence reducing the excess runoff. Detailed ground water modeling was performed using MODFLOW (Massuel, 2007).

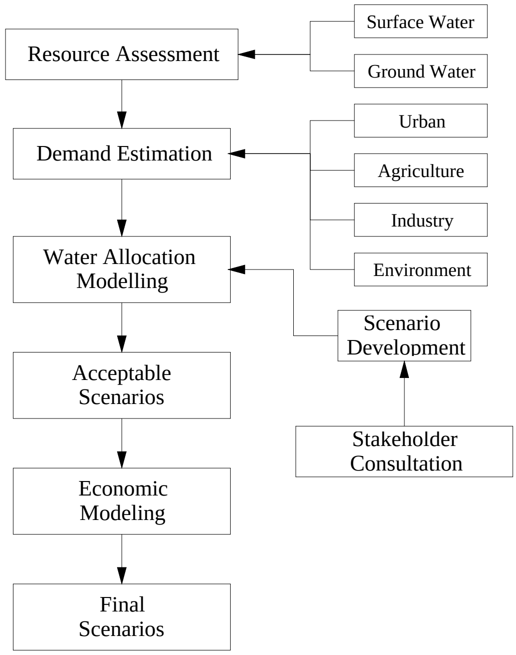


Figure 1. Conceptual modelling framework

3.2 Water Allocation Modelling

The allocation modelling approach is based on integrating resource availability and use through a network allocation model. REALM is a useful tool to address complex water allocation issues in water stressed basins and can help managers in complex decision-making. The model has been developed in close collaboration with a diverse range of users in the water industry. 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 carriers 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 model uses a combination of water balance with a linear optimisation algorithm that enables the use of user-defined penalties to impose constraints and preferential resource use (James et al. 1996; Perera et al. 2005). 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. It requires three input files namely stream flow, demand and system files. The model output includes reservoir end storage, volume supplied, unrestricted and restricted demand, spillage, shortfalls, carrier flows etc.

REALM was used to build the Musi water allocation model, and simulate the water supply system that integrates the Musi catchment, the Nagarjuna Sagar project, Singur and Manjira which lies outside the catchment but is one of the water sources for Hyderabad City (Figure 2). Eleven supply structures and fourteen demand centres are included in the model. The main storages are Osman Sagar, Himayath Sagar, Manjira, Singur, Nagarjuna Sagar, Musi medium, wastewater, Musi ayacut and four groundwater zones and main demand centres are Hyderabad urban, industry, wastewater irrigation, suryapet urban, Musi Ayacuts, medium irrigation area, Nagarjuna Sagar left and right canals, the Krishna delta and four groundwater zones. The ground water usage is modelled indirectly by considering the storage as the reservoir and the inflow (recharge) is modelled as a percentage of the rainfall. The groundwater reservoir is connected to different demand centres (groundwater irrigated areas) with sustainable yield as the maximum capacity of the carrier.

3.3 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. 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.

3.4 Stakeholder Consultation

A project advisory panel was formed and is serving two main purposes – to implement an on-going consultative process whereby new allocation scenarios will be developed and the results from the proposed scenarios will be exposed and discussed with key stakeholders and augment the capacity of the participating staff in the process of participatory research.

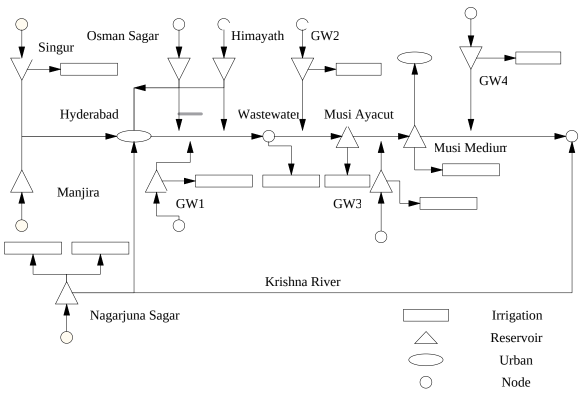


Figure 2. Schematic of Musi Model

Using the project Advisory Panel as a formal institutional mechanism to coordinate inputs and response, extensive discussions were carried out with stakeholders like the state irrigation departments, urban water boards, groundwater department and social and environmental groups on various options for changing the current allocation policies to achieve the intended performance improvement goals. Face-to-face interviews were carried out to collect basic data and information relating to the basin. Refined water allocation scenarios that lead to improved outcomes are shared in workshops based feedback sessions. The modelling framework would assist in developing allocation policies in thirteen other similar river basins in India, all of which face increasing levels of water competition. The project also consists of a capacity building component and the officials from State Irrigation Departments, Hyderabad Metro

Water Supply and Sewerage Board and Jawaharlal Nehru University will be trained in using the model. The model will be used to generate future allocation scenarios and levels supply reliability under the variable climatic conditions which will help the Managers to make appropriate decisions to plan for the future. By combining economic data with simulated estimates of allocations to different users, it is possible for the decision makers to determine the most productive water allocation strategies.

4. DATA

The data used for this study is primarily collected from secondary sources and validated by comparing the data collected from different sources. The current population of the Hyderabad City is approximately 6.2 million and it has expanded at a rate of 32.3 % in the last decade, and more recently the population has increased at about 3 % per year. Based on the projected population (3% growth rate) and an average per capita demand of 140 litres, the gross yearly demand for 2011 is estimated to be 520 Mm^3 and is expected to cross 780 Mm^3 in 2031. The industrial demand is estimated as 20 percent of the Hyderabad requirement based on the discussion with Urban Water Board.

The main economy of the catchment is agriculture and the gross cropped area is 870 000 ha. The cropping data collected from district level statistical handbook was used to estimate crop area. The major crops grown are rice, fruits, vegetables, cotton, chillies, maize, jowar, gram and groundnut. 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. At present environmental flow is assumed as zero and there is provision in the model to run scenarios with environmental requirement.

Economic data was collected on the quantities and prices of all inputs (labour, seeds, fertilizers, water, power etc.) and the prices of the major crops grown for 2001-02. From this information it was possible to derive the net value of water to each crop grown in each agricultural zone. This average net value was multiplied by the quantities of water supplied to each zone to determine the total returns from water employed in agricultural uses. The total value of water used for industrial and domestic pursuits was determined by multiplying the quantity employed by the ruling price. Summing the values across all zones and uses and subtracting the costs of distributing the water will yield the net returns from the whole water allocation process.

5. PRELIMINARY RESULTS

5.1. Baseline Scenario

The model can be used to generate future demand scenarios and levels of assurance for supply under the different conditions. Developing different scenarios are of value because they provide a basis for discussion and a framework for strategic planning by evaluating different options for meeting possible future water demand. 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. The maximum supply from Nagarjuna Sagar into the city is restricted as 450 Mm^3 (Current allocation). Agricultural demand and hydrological condition is assumed as unchanged into the future.

The analysis of the result shows that the projected supply would be sufficient to meet the urban demand until 2014 and the demand deficit is estimated to grow from 12 Mm^3 in 2014 to 336 Mm^3 in 2031. The demand deficit in the agricultural zones: Nagarjuna Sagar Left Canal (NSLC), Nagarjuna Sagar Left Canal (NSRC), Musi Medium and Musi Ayacuts are more than 50% of the allocated volume in 6, 6, and 7 years out of 38 years of simulation. The demand deficit in Musi Medium varied from 0 to 78 Mm^3 in different years. The volume supplied at different assurance level is given in Table 1. The demand in the Musi wastewater area was fully satisfied during the whole span of simulation as more water is coming to the city due to increased urban demand. The demands from the groundwater zones were never met since the maximum capacity of the carrier to these demand centres were restricted with the sustainable yield. The deficit was more in Zone 1 (upstream of Hyderabad).

At the time of publication the only results available from the economic component of the model related to this baseline scenario. What was found was that the economic impacts of both surface water allocations and ground water extractions on five regions of the Musi sub basin assessed over a 38 year time horizon from 1993 yielded a return of Rs.

2,250,370 million. It should be noted that this figure can only be used as a base for comparing different scenarios with. Of more interest are the average net values placed on water used for agricultural purposes in each region. These ranged from Rs.23.68/m^3 in the waste water region to Rs.55.44/m^3 in the region upstream from Hyderabad. The disparity in results is a function of the cropping pattern in each region. Where rice dominates the cropping pattern the returns are low and where vegetables dominate the value is high.

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

% of Assurance	Urban Water	Musi Medium	NSLC	Musi Ayacut	NSRC	Ground Water	Waste Water
99.5	261.2	16.7	704.8	45.9	314.4	849.6	86.8
99	283.4	22.7	797.9	48.2	643.7	893.7	87.9
95	344.6	39.1	1120.1	55.6	1543.4	1005.1	95.3
90	377.1	47.8	1342.1	59.9	2023.2	1059.3	103.1
80	416.8	58.4	1670.8	65.7	2204.3	1119.7	118.7
70	445.3	66.0	1956.7	70.2	2723.3	1160.4	136.2
60	469.7	72.5	2239.2	74.3	2881.2	1193.1	157.4
50	492.5	78.6	2539.5	78.3	3015.0	1221.9	184.5

5.2. Scenario with meeting future urban demand from Nagarjuna Sagar alone

Construction of new water storage facilities to meet the growing urban demand appears to be no longer feasible. Cost effective sites are already developed and recent resistance from environmentalist effectively prohibit new large construction. Water transfers from agriculture have historically being suggested as a solution to meet the growing urban demand. This scenario shows that if Hyderabad is going to draw most of the growing demand from Nagarjuna Sagar in the future, the situation may well get worse over time. The analysis of the result shows that the shortfall in the urban sector is very little as urban dwellers receive priority to agriculture. Since irrigation is given low priority, irrigation in Nagarjuna Sagar (NSLC and NSRC) suffers most from the shortfalls. Since the allocation to irrigation is likely to fall over time other sources of water such as runoff recycling, water harvesting and wastewater recycling can be used to meet part of the urban demand. The relative impacts of Hyderabad's water supply on the irrigation are less significant in humid years as the Hyderabad demand is only 10% of the total allocation to irrigation. The drying up of Osman Sagar and Himayath Sagar and a reduction in diversion from Godavari is going to put more pressure on Nagarjuna Sagar reservoir in the future. Therefore, to improve the productivity of available irrigation water improvement of traditional irrigation efficiency and crop diversification is essential.

5.3. Scenario with stream flow decline

The urban areas and industries in the upstream of the basin are also growing quickly. A series of dry years in recent times has had a significant impact on the annual average stream flows into the reservoirs. The runoff coefficient has decreased to 6 percent from 20 percent in a span of 20 years. Therefore security of inflows into the reservoirs is not guaranteed in the future. A scenario was analyzed with a 10% decline in stream flow and groundwater availability 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 sites decline sharply. The return period of demand deficit of more than 2000 Mm^3 (50% of the allocation) in Nagarjuna Sagar left and right canal is 3 and 5 years respectively (50% assurance). In Musi medium the demand shortfall of more than 50% of the demand will occur once in every 10 years (see Appendix).

5.4. Scenario with 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 by changing of crops, variety and cropping system. In an attempt to match the supply and demand the cropping pattern is diversified by changing 15% and 10% of Rice in summer and winter seasons to dry crops.

The comparison of unmet demand in each of the agricultural nodes for the baseline scenario and with diversified cropping pattern and its return period is given in the Appendix. Shortfalls occur in all the demand centers in both of the scenarios but it was less for the scenario with diversified cropping pattern. More over the greatest shortfalls are in those demand centres with high irrigation demand (NSLC& NSRC). The economic impacts of all these allocation scenarios need to be assessed to do proper planning for the future and to ensure sustainability.

Since urban sector is drawing more water from traditional irrigated areas, the wastewater outflow is going to increase to 500 Mm^3 (100% increase by 2031). Therefore more area downstream of Hyderabad can be brought under irrigation. Due to huge outflows from the city the river may have perennial flows down to the Musi medium irrigation project. The rapid increase in the quantity of sewage generated and disposal of this sewage into the Musi River is going to create a huge problem of water quality in the future. As there is no freshwater flowing into the river from upstream to dilute this untreated wastewater, the impacts are huge. Urban, peri-urban farmers for cultivation of mainly fodder grass, leafy vegetables, coconut palms and banana plants currently use this untreated wastewater. As part of the wastewater irrigation is recharged into the groundwater, it is indirectly polluting aquifers as well. More over water quality impacts on yield due to long term accumulation of salinity and heavy metals is going to be a major concern to ensure the sustainability in longer term.

6. CONCLUSIONS

The aim in this paper was to present a generic process for modelling alternative allocation scenarios in Musi, one which can be applied in other catchments of the Krishna Basin. The modelling approach is based on integrating resource availability and use through a network allocation model (REALM) with an economic model. REALM 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. The economic approach used in this study is based on a benefit cost analysis.

The analysis of the scenarios indicates that the competition for Musi water is very high. The baseline scenario shows that the projected supply would be sufficient to meet the urban demand until 2014 and the demand deficit is estimated to grow from 12 Mm^3 in 2014 to 336 Mm^3 in 2031 assuming that population will grow at rate of 3%. The demands from agricultural zones were not fully met in many years. If the City is going to draw most of the growing demand from Nagarjuna Sagar in the future, the situation is going to be worst for agriculture in the coming years. Therefore to improve the productivity of available water improvement of traditional irrigation efficiency and crop diversification is essential.

7. REFERENCES

Danish Hydraulic Institute (DHI) (2001), MIKEBASIN 2001: A versatile decision support tool for integrated water resources management planning.

Fredericks, J.W., J.W. Labadie and J.M. Altenhofen (1998), Decision support system for conjunctive stream-aquifer management. *Journal of Water Resources Planning and Management*, ASCE, 124(2), 69-78.

James, B., N. Kesari and W. Hansen (1996), Modeling of Capacity Shared Water Entitlements, International Hydrology and Water Resources Symposium, I.E. (Aust.), Hobart, Australia, 31-36.

Massuel, S. 2007. Ground water modeling in the Musi catchment, India. ACIAR Project Report. ACIAR, Canberra.

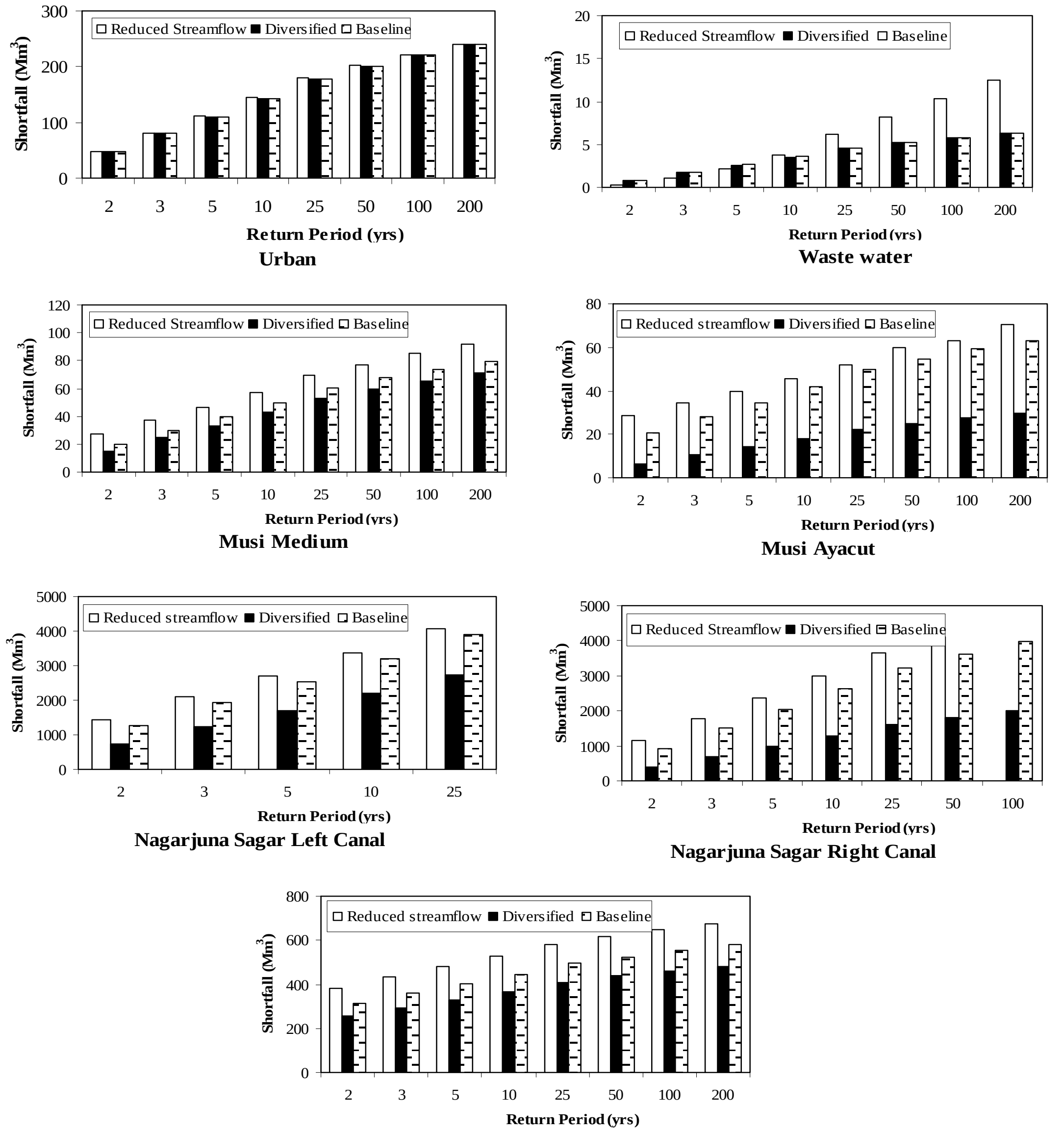
Perera, B. J. C., B. James and M.D.U.Kularathna (2005), Computer software tool REALM for sustainable water allocation and management. *Journal of Environmental Management*, 77 (2005), 291-300.

Ringler, C. and N V. Huy (2004), Water allocation policies for Dong Nai River basin in Vietnam: An integrated perspective. EPTD disussion paper No. 127. IPTRI. Washington, D. C.

Rosegrant, M. W., C. Ringler, D. C. McKinney., X. Cai, A. Keller and G. Donso (2000), Integrated economic-hydrologic water modelling at basin scale: The Mapio river basin. *Agricultural Economics* (24)1, 33-46.

Yates, D., J. Sieber, D. Purkey and A. Huber-Lee (2005), WEAP21-A Demand-, Priority and Preference-Driven Water Planning Model: Part 1, Model Characteristics, *Water International*, 30 (2005), 487-500.

APPENDIX



Comparison of unmet demand in each sector for different scenarios