Utah State University

DigitalCommons@USU

All Graduate Theses and Dissertations

Graduate Studies

5-2010

Water Allocation Challenges in Rural River Basins: A Case Study from the Walawe River Basin, Sri Lanka

D. K. Neelanga Weragala
Utah State University

Follow this and additional works at: https://digitalcommons.usu.edu/etd

Part of the Civil Engineering Commons

Recommended Citation

Utah State University
MERRILL-CAZIER LIBRARY

WATER ALLOCATION CHALLENGES IN RURAL RIVER BASINS: A

CASE STUDY FROM THE WALAWE RIVER BASIN, SRI LANKA

by

D. K. Neelanga Weragala

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

Approved:

_____   _____

Dr. Jagath Kaluarachchi   Dr. Mac McKee
Major Professor   Committee Member

_____   _____

Dr. Gilberto Urroz   Dr. Wynn Walker
Committee Member   Committee Member

_____   _____

Dr. Vladimir Smakhtin   Dr. Byron Burnham
Committee Member   Dean of Graduate School

UTAH STATE UNIVERSITY
Logan, Utah

2010

ABSTRACT

Water Allocation Challenges in Rural River Basins: A Case Study from

the Walawe River Basin, Sri Lanka

by

Neelanga D.K. Weragala, Doctor of Philosophy

Utah State University, 2010

Major Professor: Dr. Jagath J. Kaluarachchi
Department: Civil and Environmental Engineering

This dissertation evaluates the water allocation challenges in the rural river basins

of the developing world, where demands are growing and the supply is limited. While

many of these basins have yet to reach the state of *closure*, their water users are already

experiencing water shortages. Agricultural crop production in rural river basins of the

developing world plays a major role in ensuring food security. However, irrigation as the

major water consumer in these basins has low water use efficiency. As water scarcity

grows, the need to maximize economic gains by reallocating water to more efficient uses

becomes important. Water allocation decisions must be made considering the social

economic and environmental conditions of the developing world. The purpose of this

dissertation is to identify water allocation strategies that satisfy the above conditions, in

the example of the Walawe River basin in Sri Lanka.

In this dissertation three manuscripts are presented. The first manuscript takes a

broad view of the current water allocation situation. The second manuscript develops a

methodology to analyze water allocation under a priority-based approach with the use of network flow simulation techniques. The third manuscript analyzes the water supply-demand situation in the basin under future climatic conditions. The major findings of this study suggest that: (1) while up to 44% of water is still available for use, seasonality of inflows, poor water management, physical infrastructure deficiencies, and other socio-economic factors contribute to the irrigation deficits in the Walawe basin; (2) prioritizing irrigation over hydropower generation increases supply reliability by 21% in the Walawe irrigation system IRR 1. The corresponding annual loss in power output in less than 0.5%. Prioritizing the left bank irrigation area in system IRR 2 increases the economic gains from crop yields by US $1 million annually; (3) an increase of water use efficiency between 30-50% in agriculture can mitigate all water deficits in agriculture, urban water supply and industrial sectors; (4) the predicted 25% increase of rainfall over the Walawe basin in the 2050's allows for 43% increase in hydropower generation (with changes to power generation mode) and 3-16 % reduction in irrigation requirements; (5) network flow simulation techniques can be successfully used to evaluate different demand management strategies and improvements to the priority-based water allocation method.

(175 pages)

ACKNOWLEDGMENTS

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

In the developing world the processes of population growth, urbanization and industrialization are occurring at an ever increasing phase. These processes result in an increased demand for water in the sectors of agriculture, power generation, industry and urban water supply. As water resources in the rural river basins are exploited to their limits, issues of water pollution and resource degradation arise. To mitigate the damages to water resources and their environment additional limits are imposed on water abstraction. As demands exceed the limited supply, the objectives of water resources development and the water allocation criteria are brought in to focus.

Traditionally the water resources development activities in the developing world were related to improving irrigated agriculture. Even today irrigation consumes more than 80 % of the water abstracted (Rosegrant and Gazmuri 1994). In most developing countries the high capital investments required for water resources development have been borne by the state sector. The tendency to identify the state as the custodian of water resources (Rees 1996), the ability of state to formulate and enforce legislation regarding use of water, the obligation of state to control certain aspects of water activities such as control of floods and water borne diseases, have all resulted in the government sector playing a key role in administration of water allocation (World Bank 1993).

The quantity based administrative allocation is the most common water allocation mode in the developing world today (Meinzen- Dick and Mendoza 1996). This mode of allocation guarantees supplies to irrigation, domestic water supply and ecosystem water demands which improves national /regional food security, public sanitation,

environmental health etc. In general, state managed administrative allocation (public allocation) has multiple objectives and is more concerned with equity, sovereignty and satisfying greater public good (Dinar et al. 1997). The presence of multiple objectives in a public allocation necessitates the assigning of a priority order.

In the context of a river basin, allocation priority becomes important when the full water rights of all water users cannot be supplied. A prioritized system allows the water managers to take control over the water use in a river basin by allocating water in a preferential order. This preferential order could be based on regional or national objectives. In an analysis carried out in 14 developing countries in the Asian and Asia-Pacific region, domestic water supply retained the highest priority. The sectors of Irrigation, Industry, and Hydropower were named at the next levels of priority in the given order. The sectors of fisheries, aquaculture, recreation and navigation received the least priority according to this survey (UN 2000).

Although widely spread, the priority based publicly administered allocation has come under criticism for being unable to enforce efficient water use. Meinzen-Dick and Mendoza (1996) points out that the absence of an incentive structure as the main reason. The sectoral nature of responsibilities in the implementing agencies, influence of politics, unclear decision-making mechanisms for inter-sectoral allocations, inefficient pricing schemes and scope for rent-seeking by agency staff have been identified as other possible reasons (Meinzen-Dick and Mendoza 1996; Dinar et al. 1997). The farmer managed (self governing) irrigation systems as an alternative, have produced better results in irrigation water allocation according to some studies (Tang 1992; van Koppen et al. 2007).

As water becomes economically scarce, "efficient" aspect of water allocation receives prominence over "equity." An efficient water allocation aims to maximize the net economic benefits from all water uses in a basin. Such an allocation can be realized by allocating water to the most beneficial water uses. The transfer of water rights from less efficient water uses to high efficient water use can be facilitated through voluntary exchange and market pricing of water (Howe et al. 1986). Unfortunately, due to the transaction costs, technological constraints, political constraints and many other reasons the real-world water markets do not attain first-best allocations. The absence of properly defined water rights is also seen as a major obstacle in formulating water markets in the developing world (Rosegrant and Gazmuri 1994). Accordingly the instances of market based water allocations in the developing world river basins are very few (Young 1986). Therefore it can be expected that the current priority based allocation system will continue to function in many of these basins for a number of years. This dissertation describes a methodology that utilizes network flow simulation technique to investigate the possible improvements to water allocation under the priority based system.

The proposed methodology is tested on the water allocation in a test river basin. This is a rural river basin in the developing world where multiple water users compete for limited water resources. Water allocation in this basin is carried out under a priority based system. An initial estimate of water supply and demands of the basin is required to identify the temporal and spatial distribution of water in the system. The limited data availability, a common feature in many developing world river basins, may not permit a detailed analysis. However, even the outcomes of a less-detailed analysis could be used to understand (1) magnitude of supply (2) storage capacities in the basin (3) water

demand (4) process and non-process depletion from the basin (5) available, committed and non-committed volumes. Based on the availability of data further analysis can be carried out on the frequency and seasonality of river flows, reservoir water balance, feasibility of various demand management strategies etc. This preliminary information can be used to formulate analysis scenarios and management options for a more detailed study.

Improvements to the current water allocations can be proposed as modifications to the   allocation schedules. The effects of a given allocation schedule can be assessed by simulating the allocation process under the given inflows, demands and priorities. This dissertation proposes the use of a network flow based simulation model to estimate the priority based water allocation among water users in the basin. A generalized network flow model that allows allocation prioritization can be used for this purpose. Simulation scenarios can be set up to test the effects of prioritization of water allocation among competing sectors, demonstrate the impacts of various supply and demand management strategies etc.

The information derived from scenario outcomes can be used to formulate water allocation policies. However the sustainability of such policies will depend on the allocation systems ability to withstand the changes in supply and demand. Climate change can affect both. According to the global circulation model (GCM) predictions significant changes are expected in the water supply and demands in the developing world river basins (Arnell 1999). We propose to analyze the future water allocation options using the predicted supplies and demands. Such analysis would demonstrate if a priority based allocation would be able to achieve the national and regional goals of water

resources development under future conditions. It would also enable to identify the

adaptive management strategies for water allocation in the rural river basins.

References

Arnell NW (1999) Climate change and global water resources. Global Environ Change 9: S32-S49

Dinar A, Rosegrant M, Meinzen-Dick R (1997) Water allocation mechanisms-principals and examples. World Bank Working Paper 1779, The World Bank, Washington DC

Howe CW, Schurmeier DR, Shaw WD (1986) Innovative approaches to water allocation: the potential for water markets. Water Resour Res 22:439-445

Meinzen-Dick R, Mendoza M (1996) Alternative water allocation mechanisms: Indian and international experiences. Econ Polit Wkly 31(13): A25-A30

Rees J (1996). Interpreting and applying the Dublin principles. Paper for the Technical Advisory Committee, Global Water Partnership, Agadir, Morocco

Rosegrant MW, Gazmuri RS (1994) Reforming water allocation policy through markets in tradable water rights: lessons from Chile, Mexico and California. EPTD Discussion Paper No. 6. International Food Policy Research Institute (IFPRI),Washington DC

Tang SY (1992) Institutions and collective action: self-governance in irrigation. San Francisco: Institute for Contemporary Studies Press, CA

United Nations (2000) Principles and practices of water allocation among water-user sectors. Water Resources Series No. 80. United Nations, New York

van Koppen B, Geordano M, Butterworth J, Mapedza E (2007). Community-based water law and water resource management reform in developing countries: rationale, contents and key messages. CAB International, Wallingford, UK

World Bank Water Demand Research Team (1993) The demand for water in rural areas: Determinants and policy implications. The World Bank Research Observer 8:47 -70

Young RA (1986) Why are there so few transactions among water users? Am J Agric Econ 68 (5):1143–1151

CHAPTER 2

WATER RESOURCES MANAGEMENT IN RURAL RIVER BASINS OF

DEVELOPING COUNTRIES UNDER COMPETING DEMANDS [1]

Abstract Irrigated agriculture plays an important role in achieving food security in developing countries. Along with suitable land and favorable climate, availability of fresh water is a major requirement for agriculture. While irrigated agriculture consumes more than 80% of the water resources in these countries, there are other emerging water users. The population growth, urbanization, and industrialization increase the demand for freshwater in a river basin. In many cases the temporal and spatial variation of natural water availability does not match with the demands. The water resources development projects are undertaken to build the physical and institutional infrastructure that address this mismatch. However the management of basin water resources is complicated by the growing demand from traditional and new water users. There are many examples from river basins in the developing world, where water resources management has failed to cope with this situation, causing economic loses and degradation of water resources. It is therefore important to identify the possibilities of improvement to current water resources management practices. This study analyses some water resources management issues under competing demands using a test case from a rural river basin in Sri Lanka. Irrigation, hydropower generation, urban use, industry and the environment sectors compete for water in this basin. The study assesses the water availability of the basin, its temporal and special distribution, and compares with the demands. The reasons for

[1] Coauthored by Neelanga Weragala, Jagath J. Kaluarachchi, and Vladimir U. Smakhtin

current water shortages in the basin are discussed. Some possible management changes

that could improve water availability for irrigation, hydropower generation, and other

emerging users are also highlighted.

Introduction

Providing the food security for the population is a problem faced by the

governments of both developed and developing countries. This problem is aggravated by

the increasing population and limited increase in food production. Between 1980 and

2000, global population rose from 4.4 billion to 6.1 billion (World Population Prospects

2000), while the per capita cereal production has been declining since 1984 (Dyson 1999;

FAO 2005). Provision of adequate water for food production comes in to focus in this

context.

The Role of Population Growth in Food Security

The rate of world population growth has almost halved since its peak in 1960's.

However, the global population is expected to reach over 9 billion by the year 2050

(Cohen 2003). The rate of growth differs from region to region. At present Asia accounts

for 60% of the world population and Africa follows with a 12% share (FAO 2005).

Although birth rates are declining slightly on average, there are great differences between

developed countries and developing countries. Of over 90 million people who engross the

human population every year, about 90% is expected to live in developing countries

(World Population Prospects, 2000). The consequences are reflected in IFPRI's IMPACT

WATER model runs for 1995 to 2025 (IFPRI 1995). These results show that an 80%

demand increase for cereal and 90% demand increase for meat will arise from developing

countries during the 30-year period (Rosegrant and Cai 2000). It is evident that

population growth alone can pose a threat to the food security in these countries in the

coming years.

The Role of Grain Production in Food Security

Grain production plays an important role in achieving food security. The majority

of people around the world still primarily eat food made from grain. Grain-based food

supply about 48% of the calories in their meals. Animal products provide 27% of the

food calories in the developed countries and 13% in the developing countries (FAOSTAT

2001). Production of meat also depends on feed grain availability. Livestock consume

about 35% of the world's grain production (Vitousek et al. 1986). Urbanization, rising

incomes and globalization of trade amounts to a considerable change of diets in

developing countries, which has placed an additional demand for grain in these countries

(Pinstrup-Andersen et al. 1997). In 1999/2000 the developing countries imported 231

million tons of grain to bridge the gap between production and consumption. This

consisted of 71% of the worldwide grain imports for that period (FAO 2003b). This

exemplifies the dependence of food security in these countries on world agricultural

market. For the poorest countries with limited economic capabilities, increase of

domestic agricultural production remains the key option for achieving food security.

The Role of Water Resources in the
World Grain Production

About 60% of the world's food crops are grown using rainwater in the humid

regions of the earth. The remaining 40% is produced by irrigated agriculture. About 68%

of irrigated area is located in Asia, 5% in Africa and the remaining in America and Europe (IFPRI 2002). Large contiguous areas of highly irrigated lands are located in North India, Pakistan, China, Egypt and USA. Along with suitable land, availability of fresh water plays an equally important role in crop production. Agriculture accounts for about 70% all water withdrawals globally, and as much as 80% in many developing countries (UNDP 2006).

The production of world's three major cereals (wheat, corn and rice) has declined during the past 15 years (Dyson 1999). As a result, the world grain reserves have fallen to about a fifth of its annual consumption. This is a major reduction when compared to the 1960s, when the world's grain reserve equaled the annual consumption. A commonly agreed reason for this decline in crop production is the record and near record droughts experienced by the major crop growing regions across the world during the recent past (FAO 2003a; Kogan 1997). Limitations in the availability of fresh water due climate change and other factors have exerted pressure on water supply for agriculture worldwide. The situation is further exacerbated by the growing demand for water in the sectors of energy, industry, urban, recreation and environment.

Emergence of New Water Users

The population growth entails the processes of urbanization and industrialization of countries. In the 1960's two thirds of the world population lived in rural areas. Projections of current trends show that by 2025, the scenario will be reversed and two thirds of world population will live in urban areas (Pinstrup-Andersen et al. 1997). As urban population generally depends on the livelihoods related to industry, the water

requirements for industry and cities have come to play a major role. Currently about 22% of the world water use is consumed by the industries and 8% is consumed by the domestic use. These global averages vary greatly within geographic regions (WWDR 2001).

Urban and industrial growth along with improved living standards creates more demand for energy. While many developed countries have reached the saturation of energy demand, the industrialization of developing countries, with their development of primary-industries place an increasing demand for energy. Fossil fuel supplies about 90% of the world energy demand (IEA 2007a). However, after the oil shocks of the 1970s, there has been a shift away from oil. Coal, hydropower and nuclear became the fuels of choice for electricity generation in most industrial nations (Sims et al. 2003). Hydropower provides a renewable energy source with high capital costs but with very low operation costs. At present, most of the economically feasible hydro power potential has been harnessed in the developed countries – most prominently in Europe (Kaygusuz 2004). Moreover, due to concerns of entailed environmental degradation, hydropower is no longer considered as a possible future power source in these countries.

The situation is different in the developing countries. On one hand, more than 90% of the economically viable hydropower potential is located in the developing world (Bartle 2002; Kaygusuz 2004). On the other hand, hydropower provides a cheap natural energy resource affordable to these countries with limited economic potential. In the face of dire economic stresses faced by these countries the related environmental issues are often overlooked.

Usually the high capital costs of the hydropower projects in developing countries are covered by the funding provided by the international institutes (Briscoe 1999). As donor (developed) countries become more concerned about environmental issues, it has become increasingly difficult for these countries to secure funding for major hydropower projects. As an alternative many countries have adopted mini hydropower generation which generally does not contribute to either greenhouse gas (GHG) emissions or other environmental problems. In either of these forms, the share of hydropower generation in the developing countries is rapidly increasing. In 2004, the share of hydropower in total renewable energy supply was 3.1 %, 21.0 %, and 6.8 % in Africa, Latin America, and non OECD (Organization for economic Cooperation and Development) Asia, respectively (IEA 2007b).

In developing countries water resources related environmental problems frequently neglected. Mainly because high priority is given to the problems related to access of safe drinking water, food production and sanitation (UNDP 2006). However the availability of fresh water for these services is inherently related to the environmental well being of the water resource. Therefore the role of environmental flow allocation is receiving more attention in the developing world as well (Barbier 1993).

Competition for Limited Water Resources
in River Basins

The above discussion highlights the role of worlds freshwater in food production, power generation, human consumption, industry, recreation and environment protection. These users obtain their freshwater needs from both the surface and groundwater sources. When the available water in a river basin is not adequate to supply all the demands from

its water users the basin is considered as closed. The increasing uncertainty in supply and the growing demand creates competition among water users in a closed river basin. This in turn calls for supply augmentation, demand control, conserving and water reallocation (Molle 2004). If the river basin supply and demands are not managed in a sustainable manner, it could lead to over exploitation of the resource and water supply system degradation.

More than half of the world's large river systems are either moderately or severely affected by dams. Most of the large rivers in the world, like the Colorado river in US, the Ganges in India and the Yellow river in China are fragmented due to excessive water extraction upstream (Johnson et al. 2001; Revenga et al. 2000). The environmental damage caused to these river basins is mostly irreversible and the consequences are damaging. While the developed countries resolve these issues with improved river basin management techniques and expensive technology, the developing world countries struggle to cope with these issues due to lack of such amenities. Therefore the losses to agriculture, energy production, industry, urban/municipal water use, and recreation are more profound in the developing countries.

The demands for fresh water from basin water users cannot be fully satisfied beyond the capacity of a river basin. However it is possible to manage the supplies and demands in manner to minimize the losses to each user. Unfortunately, most of the river basins in the developing countries are poorly managed, causing social and economic losses to basin water users. Examples of such situations are abundant throughout the developing world.

A typical case is found in the Gediz basin in Turkey. The operation of Demirkopru reservoir, which was used for hydropower generation throughout the year, is now limited to power generation only during the periods of irrigation and flood control releases. The Gediz river delta (a Ramsar site) receives only 26% of water needed to maintain a freshwater bird habitat during the summer months (Svendsen et al. 2001).

The Ombilin river basin in West Sumathra province, Indonesia offers another example. Releases from Singkarak reservoir to the Ombilin river are dramatically reduced due to a trans-basin diversion for hydropower generation. Half of the waterwheels used for traditional irrigation are inoperable now due to the shallow water levels (Peranginangin et al. 2004).

In the Lerma-Chapala basin in Mexico, the main water users are agriculture and urban water supply. Water transfers from agricultural sector are required to supply for municipal demands of a 15 million population dependant on the basin (Wester et al. 2001).

In the Pangani river basin in Tanzania, large scale plantations versus small scale farming and upstream farming versus downstream farming compete for water. Conflicts regarding the allocations for irrigation and power generation also exist in this river basin (IUCN 2003).

Water Resources Management in
Developing Countries

It is true that all these and similar basins have already established water management programs. However the present conflicts indicate that these programs have failed to fully achieve their objectives. While it is impossible to satisfy all users in a river

basin when their demands exceed the supply, it is possible to workout a system of tradeoffs between demands that maximizes the benefits to all users and also adheres to the overarching goals of basin development. This has been proved possible in many river basins, mostly in the developed countries. However, the successful management strategies employed in the developed world, have taken decades or centuries of gradual change to evolve. The limitations to use these solutions in the context of developing countries are attributed to the vast differences in hydrologic, demographic and socio-economic aspects (Shah et al. 2001). Therefore, it is important to undertake studies that explore the water management issues in river basins of the developing countries.

There are many similarities in the socio-economic conditions of the developing countries. This allows one to identify a common set of questions to be answered in finding solutions to the water resources problems. A possible list of such questions would be: What are the goals of basin water resources development? Who are the major users of water in the basin? How much water do they use? What are the conflicting water use demands? What are the possible tradeoffs that match the basin water resources development goals? Is there scope for further water resources development in the basin? Is there scope for better utilization or conservation of water? What is the institutional framework needed to develop & manage the basin water resources?

This study demonstrates how answers to such questions can help in formulating the water resources management methods. A rural river basin in a developing country is selected as a test case. The study tries to identify the reasons for current water shortages in this basin by evaluating the patterns of water availability and demands. It analyses the scope for water conservation and reallocation among different water use sectors. The

economic implications of such measures are also analyzed. Finally, a few possible

changes to the water management practices in the basin and their implications are

investigated.

Study Area

The study area of the test case covers the Walawe River basin in southern Sri

Lanka, and its water resources and users. Basin physiographic features and the spatial

distribution of water resources and users are shown in Fig. 2.1.

Physical Description of Walawe River Basin

The Walawe River basin extends from the southern ridge of central mountains of

Sri Lanka at an altitude of over 2000 m and extends to the sea. It drains about 2440 Km^2.

The basin contains high mountain regions as well as intermediate mountainous

association of ridges and valleys and a low land plain, which accounts for about 70% of

the area (Fig. 2.1).

Majority of these plains are located in the Dry Zone, which is one of the three main

climatic zones identified in Sri Lanka (Baghirathan and Shaw 1978). The dry zone

receives less than 1500 mm of rainfall annually compared to 1500 - 2000 mm rainfall

received in the in the intermediate zone. The wet zone receives more than 2000 mm. The

average annual reference evapotranspiration in the dry zone is about 1700 mm, which

makes this area considered as dry despite having about 1500 mm of annual rainfall

(Droogers and Jayatillake 2003).
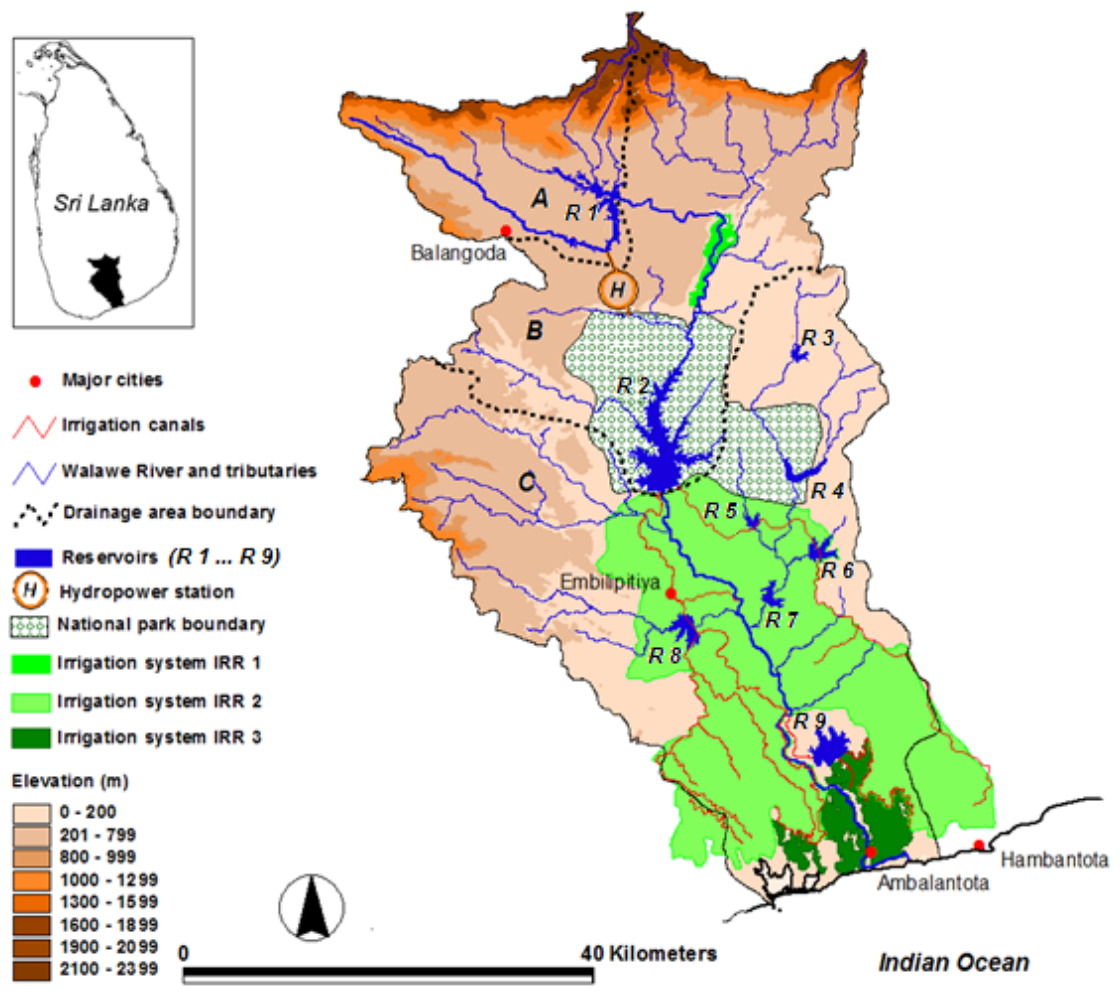
Fig. 2.1 Physical layout of the Walawe River basin, its water resources and demand sites

An important characteristic of the dry zone of Sri Lanka is the well defined distribution of annual rainfall into two monsoon periods (Dharmasena and Keerthiratna 1988). The major rainy season, referred to as *North-Eastern monsoon* (NEM) extends from December to February. The lesser rainfall period called *South-Western monsoon* (SWM) occurs from May to September. The rainfall that occurs between these two periods is due to the mountain effects and is less significant. Walawe river basin is one of

the few basins in Sri Lanka that receive rainfall during both monsoon seasons (Zubair et al. 2008).

The temperatures in the area are constant throughout the year ranging 25-28^0 C in the low land plains and 23-25^0 C in the higher elevations. The relative humidity, wind speed and the sunshine hours are almost constant during the year with minor variations related to the monsoon seasons (Droogers and Jayatillake 2003; Hunting 1968). About half of the average annual rainfall reaches the Walawe river network as runoff while the rest is used by the plants or evaporated (Molle and Renwick 2005). Shallow ground water in the basin is recharged by the natural rivers, irrigation canals, reservoirs and rice fields located throughout the basin. The occurrence of deep ground water is concentrated in the fractured and weathered aquifers in hard rock areas and in the alluvial aquifers. Groundwater recharge in the basin is about 7-12 % of the average annual rainfall and shows a high spatial variability (Seneviratne 2007). On average the Walawe basin discharges about bout 1.1 billion m^3 of water to the sea annually (Molle and Renwick 2005).

Water Users

Historically the major water user in Walawe river basin has been agriculture. Both rain fed and irrigated agriculture are practiced in the basin. In the mountainous regions of the basin located in the wet zone, diversion structures were used to irrigate crop fields. More than 500 ancient diversion structures are located in the upper Walawe basin. Historical evidence indicates that these structures were built around the 1st century BC (Molle and Renwick 2005). In the lowland plains that fall within the dry zone, small

reservoirs were built to store water. The density of ancient irrigation reservoirs in the Walawe basin is one of the highest in Sri Lanka, with approximately 1 small reservoir per 2 km^2 area (Mendis 1967). The remains of more than 600 ancient irrigation reservoirs can be found in the basin.

Over the years the agricultural practice in the Walawe basin has transformed from an individual plot based farming to large scale crop production under public funded irrigation systems. At present Walawe river basin is one of the major crop productions areas in Sri Lanka. This was the result of an irrigation expansion campaign carried out by the government to attain food security in the 1950's. Under this program large areas of forest were converted to lands for crop production. It also re-settled landless farmer families from other regions of the country in the basin (ADB 1979). The second largest irrigation reservoir in Sri Lanka was built on the Walawe River (reservoir R 2 in Fig. 2.1) to irrigate the lands under the project. This irrigation system is referred to as IRR 2 in this text. In addition, there are two relatively smaller irrigation systems (IRR1 and IRR 3) supplied by the Walawe River (Fig. 2.1).

Due to the expansion of agriculture and population, new water users have emerged in the basin. At present only a small fraction of more than 600 000 population, receive pipe borne water from Walawe (Senaratna 2002). However with rapid urbanization it could be expected that municipal water supply will demand a major share of Walawe water. The industrial and environmental water users are also increasing their demands. A brief description of each of the major water users in the basin is given below in the order of their location along the Walawe River.

Walawe Hydropower System (HYDRO)

This system is a relatively new water user in Walawe and started its operations in late 1990's. The purpose of the system is hydropower generation and flood protection. It consists of a reservoir (R 1 in Fig. 2.1) with a capacity of 278 MCM and a power station with an installed capacity of 120MW. The annual average power generation of this system is around 300 GWh (Molle et al. 2005).

Reservoir R 1 is located on the Walawe River just upstream of the diversion point to irrigation system IRR 1. Construction of this reservoir has reduced the catchment area above the IRR 1 diversion point from 410 Km^2 to 56 Km^2 (Bellaaubi 2004). As the power station HYDRO is located near a right bank tributary of Walawe its tail-water is released into this tributary (Fig. 2.1). According to this arrangement irrigation of IRR 1 is possible only when the reservoir spills or when the releases are negotiated from the reservoir.

Due to weak subsurface soil formation, there is a continuous leak from reservoir R1 (Somatilake 2002). This leak has been minimized with structural measures. The discharge from this year-round leak varies with reservoir water levels and currently amounts to an annual average of 55 MCM (Molle et al. 2005). The leaked flows are utilized by the system IRR 1 during the cropping season.

Irrigation System IRR 1

This irrigation system is located in the upper reaches of Walawe, where the river flows from mountainous region to the plains (Fig. 2.1). Two diversion structures on either

bank of the river provide water for this irrigation system. This is a rehabilitated ancient irrigation system and the farmers of this system have the most senior water rights.

At present this irrigation system distributes water through two unlined main irrigation canals that run along the banks of Walawe River. The right bank main canal runs about 12.7 KM and irrigates about 565 Ha of land. The left bank main canal runs about 3.6 KM and irrigates about 300 Ha of land (Molle et al. 2005).

This irrigation system is managed by a government agency. The water issues as well as the operation and maintenance of the irrigation infrastructure is entrusted to this agency. Farmer organizations are entrusted with the operation and maintenance of lower order canals and structures (distributor canals, field canals and farm water inlets).

The major crop in IRR 1 is paddy (threshed un-milled rice). It is cultivated during two cropping seasons (low and high rainfall seasons) each year. The crop water requirement is jointly supplied by the rainfall and irrigation releases. The main irrigation canal issues water to a number of distributor canals on a rotational basis. In each rotation a selected set of distributor canals receive water. This enables to stagger the water issues to canals as well as to efficiently utilize the limited carrying capacity of the main canals. Each season, a cropping calendar (indicating the crop types, the extent to be cultivated and cultivation schedule) is prepared by the system management in consultation with farmers. A pre-season meeting is held with the participation of all the stakeholders (representatives of farmer organizations, relevant line agencies, regional administrators etc.) to agree upon the required water volumes and their release schedules. During the cropping season minor changes to this water allocation scheme is required. This is primarily due to the variability of rainfall. These changes are negotiated between

representatives of farmer organizations and the controlling agencies throughout the cropping season. The approximate annual water requirement of this system at present equals 50 MCM (Molle et al. 2005).

Irrigation System IRR 2

This is the largest irrigation system in Walawe basin located near the middle reaches of river (Fig. 2.1). Reservoir R 2 with a storage capacity of 268 MCM supplies this system. The main purpose of the reservoir is irrigation water supply. At present system IRR 2 irrigates about 25,000 Ha of land (JICA 1993).

Two single banked earthen canals deliver the water to right and left bank irrigated areas (RB and LB). The right bank main canal runs about 40 KM and irrigates more than 12,000 Ha of land. The left bank canal has a length of about 31 KM and irrigates about 13,000 Ha (Molle and Renwick 2005).

In general the crop cultivation and irrigation operations of this system are similar to the above described system IRR 1. However the croplands in this system contain a mix of crops, which include low land crops (paddy, banana), less water intensive high land crops and cash crops (pulses, vegetables, chilly pepper). Much of the paddy cultivated areas are located in the right bank. Majority of the left bank area is cultivated with sugar cane, banana and vegetables. The approximate annual water requirement of the system equals 435 MCM in the right bank and 344 MCM in the left bank (JICA 1993).

Walawe National Park

The Walawe national park is located in the area adjoining two reservoirs: R 2 and the R 4 (Fig. 2.1). This area spreading about 306 Km^2 was established in 1972 to offer a refuge to migratory elephants and to protect the catchment of reservoir R 2. At present more than 400 Asian elephants and numerous other endangered species live in this national park (CEA 1995).

The two reservoirs provide environmental water requirements to this park. The reservoir 4 located on a tributary to Walawe River is required to store a minimum of 7.4 MCM throughout the year to supply wild life water requirements (Irrigation Department of Sri Lanka, personal comm. 2007). At present operators of reservoir R 2 are not legally bound to provide water for environmental requirements. However, the increased water scarcity has necessitated the allocation of environmental flows and their legal enforcement. Dissanayake and Smakhtin (2007) have illustrated a method to estimate the environmental flow requirements under limited data availability for a national park in the adjoining river basin.

Irrigation System IRR 3

This is another renovated ancient irrigation system located in the lowest reaches of the Walawe (Fig. 2.1). A 73 m wide gated structure across the Walawe River creates the water head required to divert irrigation supplies to two main canals on either side of the river. The left bank diversion canal of this system supplies water to reservoir 9 (Fig. 2.1) and runs about 12 Km to irrigate about 3440 Ha (JICA 1993). The right bank main canal runs about 26 KM and irrigates approximately 3300 Ha.

This system is dedicated to paddy cultivation. The cultivation practices and operations of this system are similar to the above described system IRR 1. The crop areas of this system are located immediately downstream of system IRR 2, and therefore receive the return flows. At present there are no major water scarcity issues in the system. The approximate annual water requirement of the system equals 273 MCM (JICA 1993).

Municipal and Industrial Systems

The municipal water supply systems are located in the lower part of the basin near the coastal population centers Hambantota and Ambalantota (Fig. 2.1). Walawe River is the exclusive source of drinking water supply to Hambantota town due to the saline nature of groundwater in this region (Statkraft Groner 2000). Two water withdrawal points for municipal water supply are located below the diversion point for irrigation system IRR 3. In 1999 the municipal water withdrawal by this system approximated 7 MCM annually. The approximate annual water requirement of the industrial systems equals 42 MCM (IWMI 2000).

Walawe Coastal Lagoon Ecosystem

A number of brackish water lagoons are located along the southern coastal boundary of Walawe basin (Fig. 2.1). The return flows of Walawe irrigation systems IRR 2 and IRR 3 drain into these lagoons. It has been established that the water level fluctuations and the opening and closing of lagoon mouths are dependent on these return flows (Smakhtin and Piyankarage 2003). The changes in lagoon salinity levels have severely affected the shrimp population of these lagoons. However the effects of

agricultural run-off on the chemical composition of lagoon waters have not been clearly established (JICA 1993).

In addition to the systems described above, there are other water users in the Walawe basin. The rural population scattered throughout the basin use Walawe water resources for domestic purposes, home gardening and livestock farming. Some small industries (brick production, coir industry etc.) also tap in to these water resources. Another important water user is the inland fisheries that produce more than 600 metric tons of annual harvest (Perera 2003). At present navigation and recreation remain as less important water users in Walawe Basin.

Water Scarcity Issues

The water users in the Walawe river basin experience water shortages during certain periods of the year. These water shortages occur at different scales and at various water use systems. The multitude of factors that contribute to these shortages can be broadly categorized as follows: 1) physical non-availability of water at the resource or allocation to a higher priority user; 2) increased crop areas and cropping intensity; 3) shortcomings in physical infrastructure design, construction, operation and maintenance; 4) absence of a strictly controlled water management practice; 5) emergence of new water users. The following paragraphs describe of each of the above mentioned.

Physical Non-Availability of Water at the Resource
or Allocation to a Higher Priority User

The available inflow and the storage capacity at certain locations of the Walawe river basin are inadequate to supply the demand (Nijman 1991). A typical example is the

situation at hydropower plant HYDRO and irrigation system IRR 1. The combined

demand for power generation and irrigation exceed the supply available at reservoir R 1.

This necessitates prioritizing of allocation and leaves the lower priority user with

shortage. During the past decade a consistent reduction of the crop area has been

observed at IRR 1 due to reallocation of irrigation water to power production (Kumara

and Wijeratne 2004). Similar competition and resulting water shortage is observed

between the left and right bank command areas of the Walawe irrigation system IRR 2.

Increased Crop Areas and Cropping Intensity

The commissioning of new crop areas that rely on already committed water

resources also creates shortages. Due to phase wise development of Walawe irrigation

systems the crop areas were expanded gradually. This process spanned across a number

of years, during which the water supply as well as the demand patterns changed.

The commissioning of the total crop area of system IRR 2 occurred 40 years after

the initial irrigation releases. During the initial years only croplands on the right bank of

the river were irrigated. The improper allocation practices in the system allowed the first

water users (IRR 2 right bank farmers) to exceed their estimated (legal) water allocation

for a number of years. The excess allocation allowed the farmers to save time spent on

the fields (less field manipulations required) and reduce cost (manual land preparation,

low cost weed control). A project completion report in 1972 claimed that 70% of the

irrigated area in the IRR 2 right bank consumed three times the allocation intended for

the entire right bank area (Nijman 1991).

New crop areas on the IRR 2 left bank were commissioned in 2005, demanding the estimated allocation for the left bank. This challenged the right bank farmers to cultivate strictly with their legal water allocation. However, the high water intensive farming methods practiced by them create water shortages with this new reduced allocation. Simulation model results indicate that the entire left bank command area cannot be supplied with its planned allocations (without affecting the right bank) under present conditions (IWMI 2000).

Shortcomings in Physical Infrastructure

As typical to irrigation systems in many developing countries, the Walawe systems also experience water shortages due to infrastructural deficiencies. Lapses in the planning stages have caused limited storage capacity of reservoirs and limited carrying capacities in major irrigation canals. The ad-hoc changes made to the infrastructure, during the initial construction phase (as well as in the subsequent rehabilitation phases) have badly affected the efficiency of the system. Some of these changes include: the construction of single banked canals as main distributaries, low excavation depths in the secondary canals, reduced number of cross regulators in main distributaries etc. These measures have helped reduce the project cost and meet the construction deadlines in the short term. However the long term operation of the system has proved that, the increased seepage and spillage losses resulting from these measures create significant water shortages and economic losses. Moreover the degradation of irrigation infrastructure due to poor operation and maintenance has contributed to the lack of physical control over

water flows (Nijman 1991). High water losses due to infrastructure deficiency are common to all three Walawe irrigation systems.

Absence of an Organized Water
Management Practice

The establishment of suitable water use and allocation practices (and their implementation) is generally entrusted to the management agency of the water resource. As the water supply and demand evolve with time, these practices should be modified accordingly. However the agencies responsible for Walawe irrigation systems management have not been able to incorporate such changes (IWMI 2000; Nijman 1991).

The water shortages in Walawe irrigation systems are often attributed to: Mismatch of crops and soil leading to excess water use at the farm plots, upstream farmers using the allocation of tail-enders, waste of water due to poor operation, corruption among officials leading to un-equal allocation, badly maintained of infrastructure, impractical allocation schedules, unauthorized water use to cultivate lands outside the system, ineffective farmer organizations etc. All the above mentioned indicate the absence of a strictly controlled water management practice in Walawe irrigation sector (Molle and Renwick 2005). A similar situation can be observed at other water use sectors as well.

There are a number of independent agencies involved in the management of Walawe water user systems. This is mainly due to a "sector-based development strategy" adopted in the country up to recent times (Jinapala et al. 2003). The poor coordination among managing agencies at present leads to water shortages that could be avoided otherwise. As common to many rural river basins of the developing world the current

institutional and legal set up in Walawe basin is inadequate to achieve the goals of integrated water resource management (IWRM).

Emergence of New Water Users

With the rapid growth of coastal cities in the Walawe basin new water users have emerged. The ongoing construction of an international sea port, oil refinery and distribution facility, an international airport, industrial zone and the expansion of existing urban water supply invariably exert more demands for water. The upstream irrigation systems have experienced water shortages due to the emergence of high priority users in the lower reaches. The rapid development of rural basins entails increased concern over environmental degradation. The environmental flow requirement in the Walawe basin has emerged as an important water user.

The above mentioned factors that affect the water situation in Walawe can be broadly categorized in to two areas. The physical infrastructural deficiencies and management related issues. While some of the infrastructural deficiencies mentioned above are easy to overcome others (e.g. increase of reservoir capacity, canal lining etc.) may require high capital investments and long term planning. In the case of a developing county, the low cost management improvements that create equally effective water savings are more attractive, compared to high cost infrastructure improvements. The following section of this paper analyses the impacts of some typically proposed changes to water management practices in the example of Walawe water user systems.

Analysis of Water Scarcity
Issues and Solutions

   The situation described above calls for urgent solutions to water shortages faced

by the Walawe water users. Changes to the current water management may be required to

achieve such objectives. In this section the reasons for the above water shortages are

analyzed in order to identify possible solutions.

Estimation of Water Availability
in the Walawe River Basin

   To estimate the water availability in Walawe river basin a water balance study

was conducted on an annual basis. A six year period from 1994 to 1999 was selected for

this analysis based on data availability. This period contains a comparable mix of high

and low water years. For the analysis the Walawe river basin is partitioned in to 3

drainage areas: A) catchment area of reservoir R 1, B) catchment area of reservoir R 2,

and C) the remaining catchment area, as shown in Fig. 2.1.

   Total rainfall incident on each catchment was calculated based on monthly

rainfall data from 11 rainfall stations located within the basin. Theissen polygon method

was used to estimate the aerial-rainfall for each of the drainage areas. Inflows from

drainage area, rainfall and evaporation from the reservoir surface along with the releases

and spills were considered in the reservoir water balance. The net inflows to each

drainage area were calculated as the difference between gross inflow and reservoir

storage change.

   Water depletion from the Walawe basin occurs due to crop and non-crop

evapotranspiration, domestic & municipal use, industrial water use, evaporation from soil

and recharge to ground water. Four major land use categories in the basin were identified from the land use maps: croplands (17 %), forest (21%), grasslands (46 %) and bare soil (16%). Four major types of crops: paddy, banana, sugarcane and other field crops (OFC) were used to estimate the evapotranspiration from croplands.

In the sparsely populated upper drainage areas A and B, the water use for domestic and industrial purposes is not significant. The groundwater recharge in Walawe river basin has been estimated between 7% - 12% of the average annual rainfall (Handawela 2002; Seneviratne 2007). An average value of 10% of the annual rainfall was assumed in this study.

To estimate the water availability for future developments, the above calculated net inflows and depletions were compared. The results of water balance for the three drainage areas are shown in each column of Table 2.1. These results indicate that on an average annual basis about 44 % of the surface water is available for use in the two rural upper drainage areas A and B. The highly populated lower drainage area C discharges about 27 % of its inflows to sea.

Seasonality of Inflows and Water Requirements

Despite having surplus water on an annual basis, the basin water users experience water shortages periodically. This can be due to the seasonal changes in inflows and demand. As mentioned earlier the rainfall pattern in Sri Lanka is highly seasonal. A frequency analyses, carried out using 40 years of annual inflow data of reservoir R 2, demonstrated this seasonal variation. Two of the three lowest annual flows to this reservoir occur within the dry period (June-September) in 77% of the years analyzed. The

Table 2.1 Water balance of the Walawe River basin (using average annual values from 1994 to 1999)

Description	Drainage area A	Drainage area B	Drainage area C
Catchment Area (km^3)	290	730	1,420
Inflows			
From upstream catchment (MCM)	-[a]	399	861
From rainfall (MCM)	902	1,578	2,071
Total Inflow	902	1,977	2,932
Reservoir storage change (MCM)	-8	0	-[a]
Water Use			
Crop evapotranspiration (MCM)	159	179	417
Industrial use (MCM)	< 1	< 1	21
Domestic & Municipal use (MCM)	< 1	< 1	9
Forest evapotranspiration (MCM)	121	243	454
Evaporation from water bodies (MCM)	5	45	10
Bare soil and grassland evaporation (MCM)	118	490	1,011
Percolation to subsurface (MCM)	90	157	207
Total depletion	495	1,116	2,129
Available Water			
Flows to downstream (MCM)	399	861	803
Flows to downstream (% net inflow)	44	44	27

[a] Not applicable

total flow during these dry months is less than 15% of the mean annual flow in 67% of the years analyzed. The peak inflows to reservoir R 2 occur during two periods: March to May and October to December. More than half of the total annual flow occurs in this wet period in 84% of the years analyzed. The bi-modal inflow distribution is seen from the long term monthly inflows plot in Fig. 2.2.

The croplands in Walawe utilize rainwater as well as irrigation water to satisfy the crop water requirement. Hence two distinct cropping seasons are identified. The first
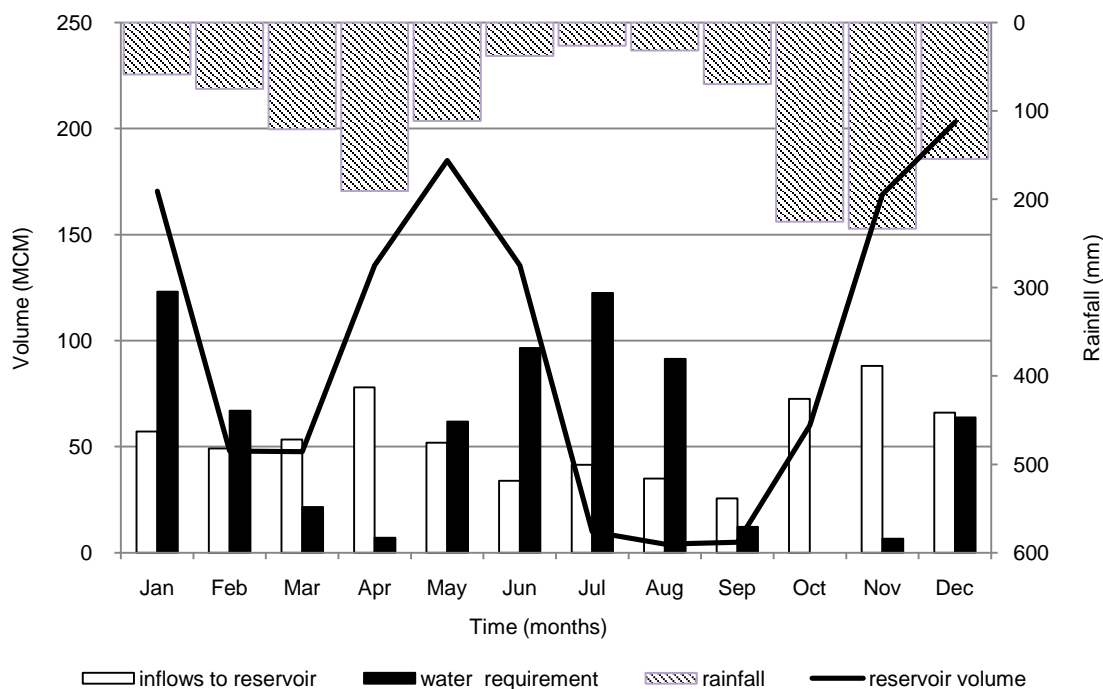
Fig. 2.2 Average monthly inflows, irrigation water requirements, storage volume and the average rainfall at reservoir R 2

cropping season starts in mid April and the second starts in late October, each with the onset of corresponding monsoon rains. As the cropping season continues, the monsoon reaches its peak and eventually diminishes. Therefore the latter parts of the growing season is dependent on the supply of irrigation water.

According to the current agricultural practice a rice crop with 3 to 3.5 month growth period is cultivated in the all Walawe crop areas. During the first cropping season the mid and the later-season growth period of the rice crop extends well in to the dry months of June, July and August. Moreover the frequent delays in the land preparation make this extension of cropping season inevitable (Nijman 1991).

The recurring incidences of crop failure (due to water shortage) in this season (JICA 1993) indicate the inability of reservoir R 2 to provide the total irrigation demand of system IRR 2. As seen from Fig. 2.2, the long term observations of reservoir R 2 water levels indicate a rapid drawdown in these dry months. In July and August when the reservoir storage reaches its lowest values, the irrigation demand is still at its peak. Therefore it is evident that the irrigation demand of the first cropping season cannot be supplied by the reservoir. Due to the high rainfall volume of the second monsoon season the water levels in the reservoir are adequate to supply the peak water requirement during the latter part of second cropping season.

In a complex irrigation system like Walawe, the availability of water at the reservoir alone does not guarantee that water is readily available to the crop fields. The irrigation water applied to the head end of main canals of the irrigation system flow through a complex path before it reaches the fields. This is due to the existence of storage reservoirs, supply rotations, return flow re-use and supply augmentation from local tributaries, etc. in the system. These infrastructure and their management manipulations affect the volume and the frequency of water that reaches the fields. The sum of these actions on the demand-supply situation of the system can be visualized only by modeling the overall water allocation system.

In one such attempt, a water balance model was developed for the Special Assistance for Project Implementation (SAPI) study under the Walawe Left Bank Irrigation Upgrading and Extension project (IWMI 2000). It estimates the weekly water demands of the irrigation system IRR 2 and compares it with available storage at reservoir R 2. The water demands for both left and right banks of the system are

estimated in a weekly time step. The modeling parameters include inflow sequences to reservoirs, cropping patterns, irrigation efficiencies, crop calendar, return flow re-use etc. The variations in supply are incorporated by utilizing the 40-year historical rainfall patterns.

The model results indicate that under the current irrigation performances, it is not feasible to irrigate the planned command area in both left and right banks of the system IRR 2. At the present water supply efficiencies, the planned cropping area (with annual double cropping) can be irrigated with a three-year return period of failure, which is unacceptable. The model results further indicates that a reduction of left bank command area (25 % decrease) or a reduction in the cropping intensity (20% decrease) is required to achieve a failure rate of one in five years (IWMI 2000).

Analysis of historical reservoir operations shows that inter-annual storage of the reservoir R 2 is very low. This is because the annual demand is greater than the annual storage. The average annual flow in Walawe River is 1027 MCM at the location of reservoir R 2. However the storage capacity of the reservoir is only 268 MCM. Increasing the reservoir capacity (by increasing the dam height) would enable the increase of the intra annual storage. However proposals for capacity increase have not been given due consideration (Nijman 1991), due to the low water use efficiencies in this system. Increasing the water use efficiency in the Walawe systems through managerial and simple infrastructure improvements have been on the focus of the controlling agencies.

The irrigation systems IRR 1 and IRR 3 in Walawe exhibit similar seasonal water requirement patterns. The supplies to these systems are further affected by the seasonal

hydropower water requirements (system IRR 1) and return flows from upstream

irrigation systems (system IRR 3).

Low Water Use Efficiency in
Paddy Cultivation

The water use efficiencies of all three Walawe irrigation systems are low.

Moreover, the irrigation system IRR 1 has recorded the lowest water use efficiency in the

country during dry cropping season (WWAP 2006). The high water use in this system is

attributed to the following reasons.

The system IRR 1 is located at the boundary where the mountainous part of the

basin turns to flat terrain (Fig. 2.1). It is therefore largely located in lands with high

slopes. In addition, majority of the lands contain soil consisting of sandy loam to sandy

clay loam surface horizon. This is underlain by a sandy clay loam to sandy clay sub-

surface soil horizon (JICA 1993). The seepage and percolation rates of this soil are about

7-10 mm/day. However some studies in IRR 1 paddy fields have reported seepage and

percolation rates ranging from 1 mm/day to 5 cm /day (Molle et al. 2005).

The major crop cultivated in this system is rice. Compared to other crops rice has

a high water requirement. In addition, rice requires prior preparation of land. This

process consists of initial land soaking (3-7 days) and two times of plowing, bund repair,

puddling and leveling.

According to the current agronomic practices in Walawe the process of land

preparation also incorporates the weed control. Weeds uprooted during tillage are

allowed to decompose in standing water. This method has preference over the labor

intensive manual uprooting or the costly use of agro-chemicals in the rural irrigation systems of the developing world.

The initial soil moisture content, surface condition of land, soil type, level of weed infestation, losses during operations and maintaining standing water, all contribute to the overall water requirement in land preparation process. Moreover, to maintain the standing water, the evaporation and seepage and percolation requirements must be met continuously. Therefore the water requirement increases with the increase of the duration of land preparation. The conventional land preparation method requires minimum of two weeks. However due to various reasons (lack of machinery, lack of adequate irrigation supply, farmer's negligence etc.) this period extends up to 35 days of cultivation season in system IRR 1 consuming about 1/3 of the total water requirement of the cropping season (IIMI 1990). According to Kikuchi (1990) approximate annual water saving of 9% could be achieved by shortening the land preparation period.

By observing the water supplied to the system IRR 1, Molle et al. (2005) estimate an 800 mm of water use during the land preparation period. This is almost twice the amount of water that could be used by seepage, percolation and evaporation taken together. Therefore it is evident that not only the physical composition (permeable soil, high slopes etc) of the area is responsible for such high water use. Much of the water is lost due to poor control over the management of water supply during land preparation for paddy.

Mismatch of Crops with Soil Type

The command area of Walawe system IRR 2 consists of two major soil types: the low permeable Low Humic Glay (LHG) soils and the moderate to high permeable Reddish Brown Earth (RBE) soils. One of the assumptions at project planning stage was, that in the low lands (consisting 30% of the command area) paddy will be grown. Other field crops (vegetables, chilies, pluses, etc.) with less water demand were selected to be cultivated in the rest of the areas of this system. However due to various reasons this was not practiced. The cultivation of paddy in the moderate to high permeable RBE soils has resulted in extremely high water requirements in Walawe (Nijman 1991). At present the management agencies of Walawe irrigation systems are unable to rectify this issue due to their lack of control over the crop types cultivated by farmers.

Growing less water intensive crops on highly permeable soils is beneficial in two ways. First, the high-water intensive land preparation requirement as in the case of paddy will not arise. Moreover due to less frequent water demands the water loss during supply manipulations is minimized. Second, it reduces the high management control needed as in the case of frequent water supply. A possible alternative crop for paddy is banana. As mentioned before this crop has been used to replace paddy in part of the Walawe system IRR 2 successfully (ADB 1999).

A comparison of the water demands for paddy and banana under the present irrigation efficiencies was carried out for system IRR 1. This calculation considers the irrigation water requirement by rice cultivated in highly drained RBE soils. It also takes in to account the conveyance and application efficiencies of irrigation. Table 2.2 shows the results of this estimation. It is evident that major water savings can be achieved due to

Table 2.2 Estimation of annual water requirement at Walawe irrigation system IRR1 for rice and banana crops

RICE			
Description	High rainfall (Maha season)	Low rainfall (Yala season)	Total
Crop evapotranspiration (mm)	538	732	1,270
Percolation from fields (mm)	700	700	1,400
Irrigation requirement (MCM)	10.7	12.4	23.1
Land preparation requirement (MCM)			11.8
Total requirement considering efficiencies (MCM)			**44.3**
BANANA			
Description	High rainfall (Maha season)	Low rainfall (Yala season)	Total
Crop evapotranspiration (mm)	694	1,005	1,699
Irrigation requirement (MCM)	6.0	8.7	14.7
Total requirement considering efficiencies (MCM)			**21.6**

the absence of land preparation and requirement of standing water for banana. According to this estimation, a full replacement of paddy by banana crop in the entire area of IRR 1 will enable a 50% reduction in annual water requirements.

As per this estimation the annual irrigation requirement at IRR 1 for banana crop is 21.6 MCM. According to Molle et al. (2005) the average annual leak from reservoir R 1 is equal to 55 MCM. Therefore, the current reservoir leak amounts to more than twice the irrigation requirement at IRR 1 on an annual basis. However, it remains to be shown that the continuous reservoir leak (which is mainly dependant on the water level of the reservoir) is adequate to supply the water demand of the banana throughout the cropping season.

Moreover, it is unlikely that all the farmers in this ancient irrigation system will embrace such a crop change. The social and cultural setting in this rural region resists such abrupt and full scale changes. It also requires a major commitment from the farmers (as well as irrigation management agencies) to adopt new water management and agricultural practices. However, it should be noted that with correct market conditions in place the enhanced economic benefits of crop change could influence a majority of farmers to switch the crops over time. This has been the case in the irrigation system IRR 2, where 36% of the paddy grown areas were successfully converted to banana and other cash crops during a crop diversification program in the 1990's (ADB 1999).

Another factor that affects the scope for crop diversification is the increase of demand for rice in the country. Sri Lanka has been importing more than 130 000 metric tons of rice on average for the past 15 years to supply the national demand (Dept. of Census and Statistics 2008). This costs about 32 million US dollars annually to the national economy (Central Bank of Sri Lanka 2008). Therefore, the goal of achieving self sufficiency in rice has a high importance in the national economic agenda. As a result, any proposal for crop diversification needs to be supported by evidence of substantial economic benefits both to the individual farmers and to the national economy.

Hydropower Generation and Irrigation

In Sri Lanka the national electric power demand is supplied by many power stations connected to a single grid. At present about one third of these are hydropower stations located in various river basins. Due to their location some of the river basins receive rainfall during both monsoons while others receive rain only in a single monsoon

season. Therefore the share of power added to the national grid by each hydropower station varies from season to season according to the rainfall availability.

Most of the reservoirs built in the country are multi-purpose. They supply water for irrigation as well as for hydropower generation. During the crop growing season most of the multi-purpose reservoirs give priority to irrigation. This increases the share of demand from reservoirs dedicated to hydropower generation. Throughout the year the national power demand is shared among various power stations, depending both on the rainfall availability and priority settings of the reservoirs.

As mentioned before, Walawe river basin receives rainfall during both monsoons. The power station HYDRO is designed to generate power throughout the year. At present this station generates the difference between national energy demand and the energy generated by rest of the power stations in the country (CECB 1985). This is a variable demand that changes on a daily basis. Consequently the reservoir R 1 operates under a *variable power generation mode*.

Reservoir R 1 was built for the purpose of hydropower generation and flood control. However it was built on the Walawe River just upstream of irrigation system IRR 1 depriving the water it diverted from Walawe River. The controlling agency of this reservoir has agreed to release the irrigation requirements of IRR 1 (Molle et al. 2005). These irrigation releases are issued from a low level outlet in the reservoir and cannot be used for hydropower generation. The actual volumes to be released are not defined and are negotiated between the farmers and the agency on a case by case basis. Any irrigation release from the reservoir can be considered as a loss to the national economy due to the forgone benefits of power generation.

A comparison of economic gain to the national economy from water use for

irrigation and hydropower was carried out for the years 1999 and 2003. These two years

were selected due to the data availability. The volume of water released as irrigation

allocations to the system IRR 1 in each year equaled 91 MCM and 87 MCM,

respectively. Table 2.3 shows the results of this analysis. All the monetary values are

indicated in year 2007 Rupee equivalents.

Table 2.3 Comparison of economic gains from water use for rice irrigation and hydropower generation at Walawe (systems IRR1 and HYDRO)

Description	1999	2003
Water use for rice irrigation		
Total cultivated land area (ha)	864	865.5
Total yield (MT/year)	8,300	8,310
Average selling price (Rs./kg)	19.0	17.0
Average production cost (Thousand Rs./ha-season)	40.4	25.2
Net value of crop yield (Thousand Rs.)	87,889	97,649
Water used from dam release and leak (MCM)	91	87
Unit value of irrigation water (Rs./m^3)	0.97	1.12
Water use for hydropower generation		
Volume of water used (MCM)	91	87
Hydropower generated (GWh)	68.25	65.25
Unit value of hydropower (Rs./KWh)	6.82	8.02
Net value of hydropower (Thousand Rs.)	465,465	523,305
Unit value of hydropower water (Rs./m^3)	5.12	6.02
Comparison		
Average import price of 1 kg of paddy (Rs.)	16.8	25.9
Number of energy units forgone to produce 1 kg of paddy (KWh)	8.22	7.85
Cost of fuel imports to produce 1 KWh (Rs.)	3.79	6.10
Cost of fuel imports to produce forgone hydropower (Rs.)	31.15	47.86

Note: All monetary values are indicated in year 2007 Rupee equivalents

It can be seen that for one cubic meter of water used, the net economic value of hydropower is five times greater than net the value of irrigation. When compared with the import prices, the cost of replacement is twice as high for foregone electricity production. The overall implication is that production of hydropower is much beneficial to the national economy when compared with paddy production.

The previous sections discussed the possibility of major water savings at Walawe system IRR 1. The economic gains of allocating water for hydropower production over irrigation were also highlighted. However, one cubic meter of water reallocated from irrigation does not simply translate into one cubic meter of water that that could be used for power generation. The reservoir water for hydropower generation can only be used if stored above the minimum operation level (MOL) of the turbines. Therefore, it would be appropriate to estimate the actual increase in power production that could be achieved due to such reallocation.

A daily water balance of the reservoir R 1 was carried out for 5 years from 1999 to 2003. Starting from a known initial value, the reservoir water levels were estimated for each day, after accounting for releases for hydropower and irrigation as well as reservoir losses including the dam leak. Two water allocation scenarios were simulated. The baseline scenario followed the actual water allocation to both irrigation and hydropower generation according to the demands during 1999 to 2003. In the second scenario all the irrigation water was re-allocated to hydropower generation. Flows through hydro turbines were increased until an operation with no spills and shortages was achieved. In both scenarios the power station was operated under the *variable power generation* mode. The results of this water balance analysis are shown in Fig. 2.3.

Fig. 2.3 Hydro power generation and the corresponding water levels at reservoir R 1, under observed (with irrigation releases to system IRR 1) and simulated (irrigation releases re- allocated to power generation) scenarios. Reservoir is operated under variable power generation mode

The *observed* scenario water levels in Fig. 2.3 show the actual operation of reservoir (with irrigation water issues) during the 5 year period. The full supply level (FSL) and the minimum operation level (MOL) of the reservoir are also shown. It can be

seen that, the reservoir has been operated without spilling and without drawing down below the minimum operation level. The operators have tried to meet the obligatory irrigation requirement and the variable power generation demand (to the possible extent) while maintaining the reservoirs levels within the given range.

The *simulated* scenario water levels show the results from proposed omission of water allocation for irrigation. In this scenario the power generation outflow has been increased as much as possible while maintaining the water levels between MOL and FSL. Analysis indicates that only about 10% increase in flows to power generation can be achieved while operating the power station under the *variable power generation* mode. This corresponds to an increase between 19 – 34 GWh in each of the five years analyzed. The amount of power generated under both scenarios is also shown in the figure in giga-watt hours (GWh).

Conjunctive Use of Reservoirs

The reservoirs R 1 and R 2 are located on the Walawe river about 25 Km apart from each other (Fig. 2.1). It may be possible to operate these reservoirs conjunctively to maximize their beneficial use. This is especially important considering the fact that downstream reservoir (R 2) experiences water shortages at certain times of the year. Moreover there are no major water users between the two reservoirs except the aforementioned irrigation system IRR 1. Therefore an attempt was made to explore the possibility of releasing flows to supplement the storage in downstream reservoir. The period of concern is the months of July, August, and September, when the monsoonal storage fails to fully supply agricultural water requirements of system IRR 2 (Fig. 2.2).

The average monthly inflows to reservoir R 1 and its outflows to power generation are compared in Fig. 2.4. It also shows the average variation of reservoir water levels during the year. It can be seen that during the aforesaid months the power generation outflow exceeds the inflows and the reservoir is releasing water. Figure 2.5 compares the average inflows and low flows to reservoir R 1. The average inflows to the reservoir are at its low flow levels during July to September. This indicates the inability of this reservoir to release water to enhance the downstream reservoir R 2 during these months.

It was mentioned that national hydropower demand is supplied by a pool of power plants that are located in a number of river basins. Figure 2.5 shows the average monthly variation of low flows in other hydropower reservoirs. It can be seen that lowest of their flows occur in the same period as in reservoir R 1. This increases the hydropower demand from the system HYDRO and further reduces the possibility of irrigation releases from reservoir R 1. The estimates carried out by Walawe Irrigation Improvement Project (WIIP 1998) also confirm these conclusions.

Another possibility would be to change the pattern of turbine releases and have enhanced storage at reservoir R 2 for the dry months. More water can be released from reservoir R 1 through the turbines (before the dry months) to accumulate water storage at reservoir R 2. However the generation of hydropower at reservoir R 1 during the dry months is also critical. This is because the cropping season (for paddy) throughout the country occurs at the same time of the year. The hydropower stations that have priority for irrigation are unable to meet their power generation share during this period. As

shown before, the lowest inflows to their reservoirs also occur at this time (Fig. 2.5).

This necessitates reservoir R 1 to generate more hydropower during this period.
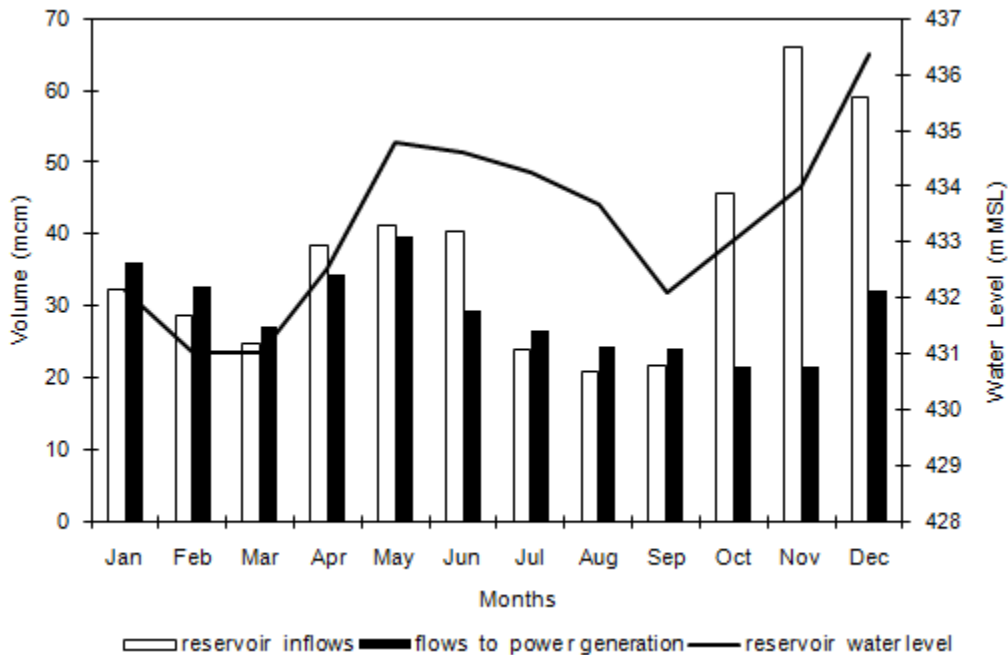
Fig. 2.4 Average monthly inflows, power generation outflows and the water levels of reservoir R 1
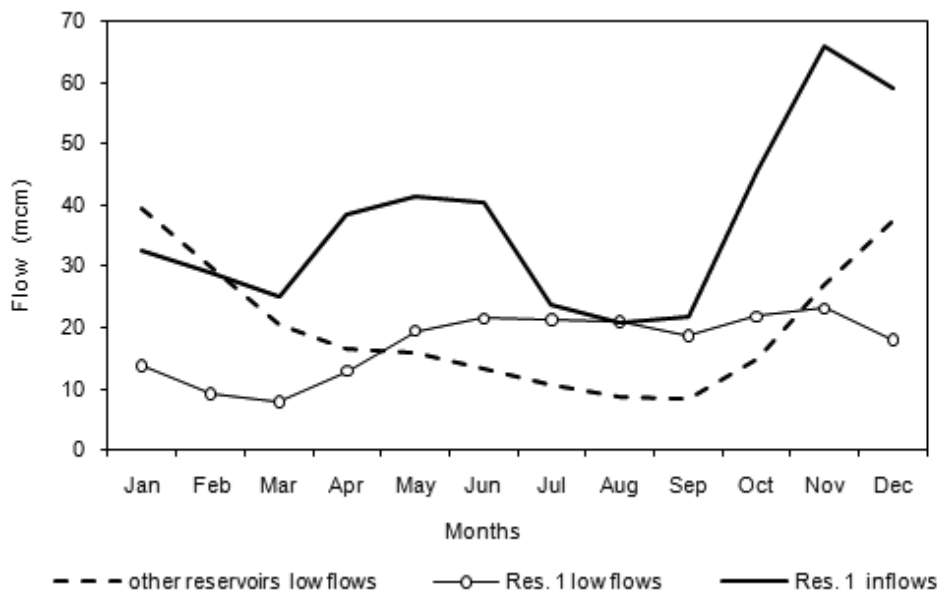
Fig. 2.5 Average inflows and low flows at reservoir R 1 compared with average low flows at other hydropower reservoirs

At the same time, it should be noted that there is a sharp decrease in the share of hydropower as a national power generation resource. During the last few years the thermal power plants and other alternative power generation sources play a dominating role in the national power generation (Somatilake 2002). Therefore a change of power generation from *variable power generation* to a *firm power generation* mode can be considered.   The possibility of generating the similar amount of power (on an annual basis) while making favorable releases to reservoir R 2 is investigated.

As in the previous occasion reservoir R 1 inflow data for 5 years (from 1999 to 2003) were used in this analysis. Two scenarios were compared. The baseline scenario represents the current *variable power generation* mode with irrigation allocations to IRR 1. In the second scenario, a firm power generation target of 285 GWh (annual) considered with no releases for irrigation. This power target corresponds to the reservoir operation without spills or drawdown bellow minimum operating levels during the 5 year period of analysis. In addition it represent s a 5 % increase in annual power generation.

 The results show that under *fixed power generation* mode there is an increase of 9% in the power generation outflows on average. From Fig. 2.6 it can be seen that power output is increased 70% of the time during analysis period. Moreover the power generation during the dry moths (3rd quarter in Fig. 2.6 bottom) is above the *variable mode* power output in three out of five years in the analysis.

Figure 2.6 shows reservoir R 1 water levels under the two operation modes. Under the fixed power mode the reservoir water levels are significantly higher when compared with the baseline scenario. It is estimated that during the months of July,
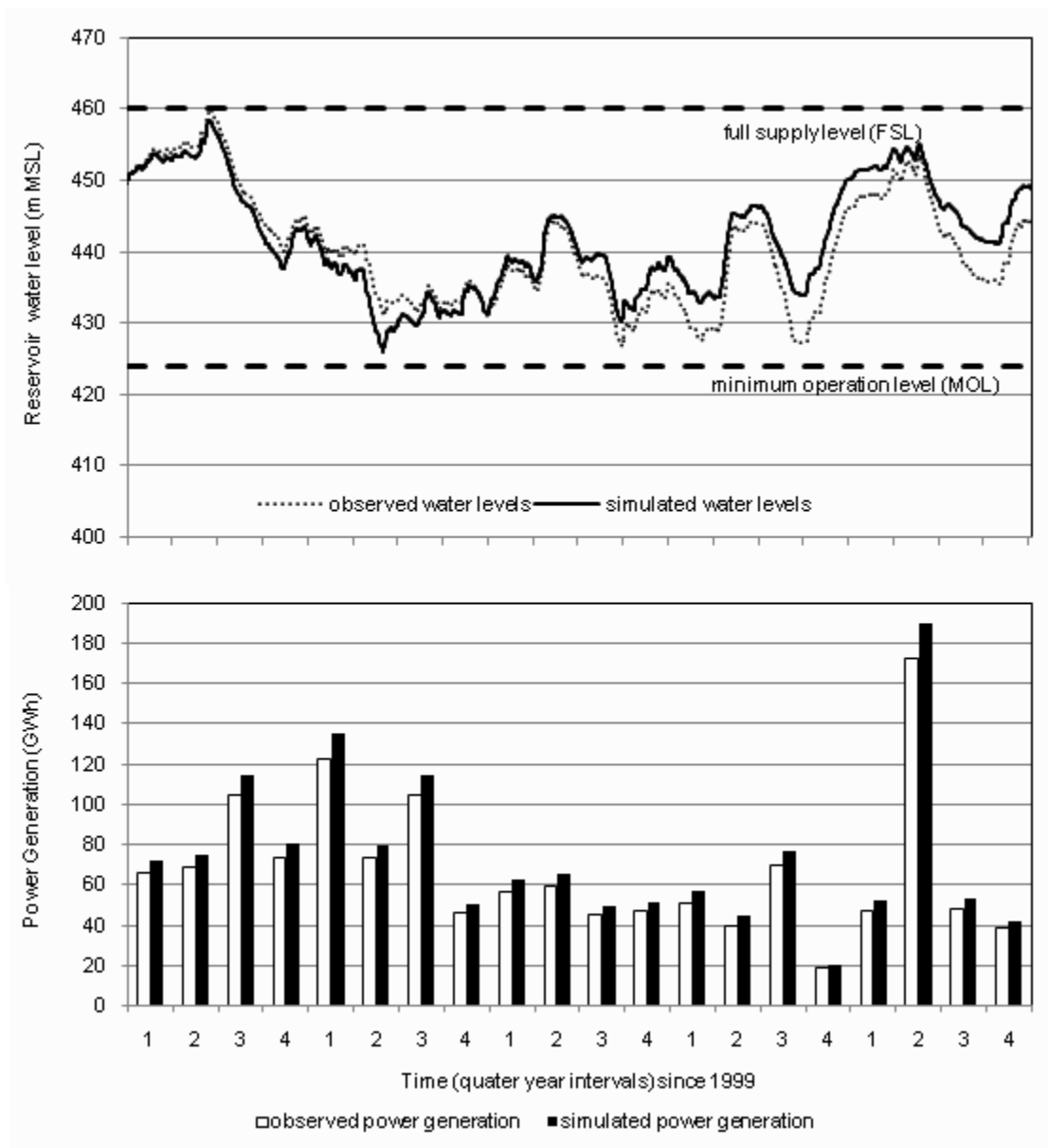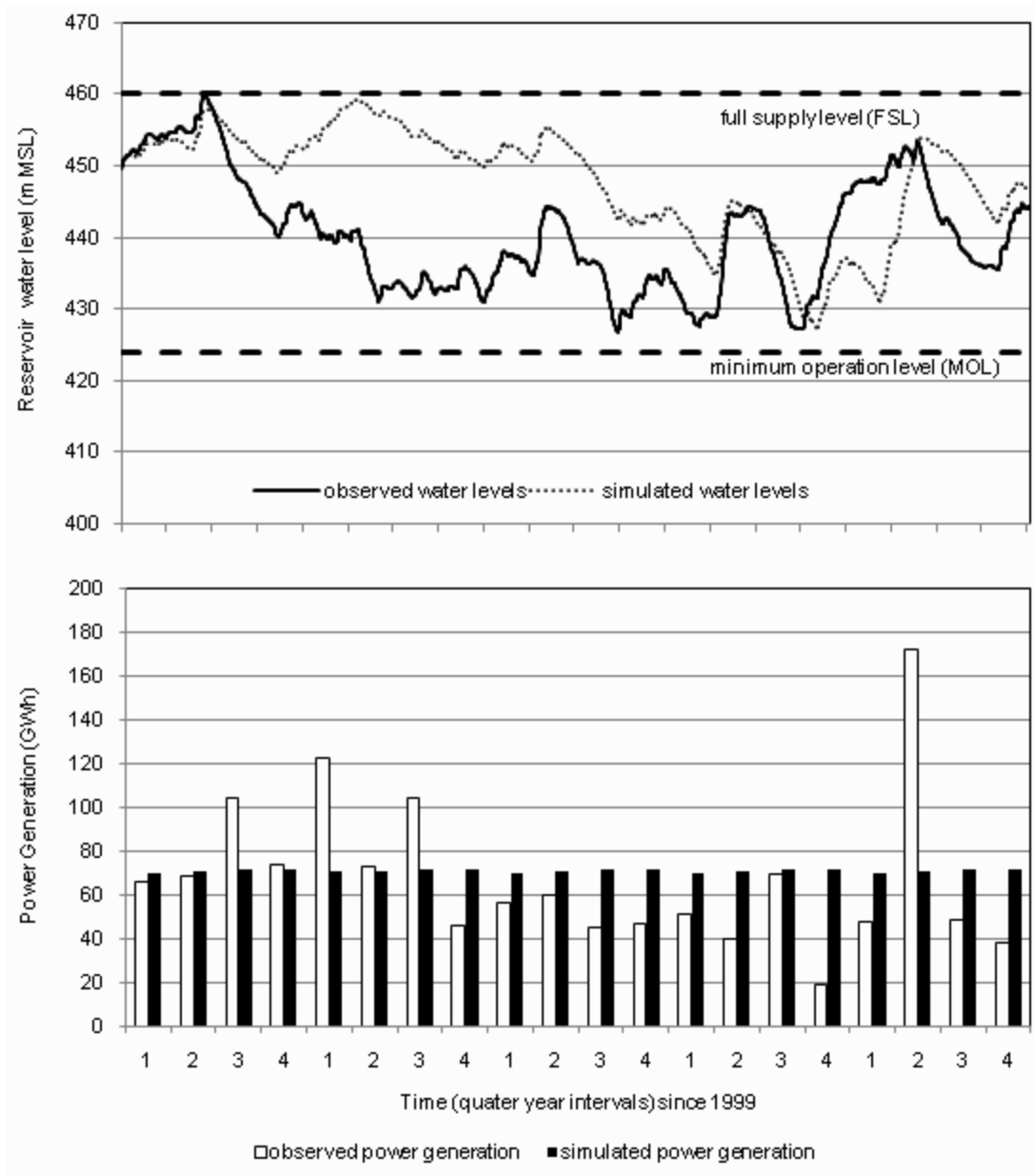
Fig. 2.6 Hydro power generation and the corresponding water levels at reservoir R 1, under observed (with irrigation releases to system IRR 1) and simulated (no irrigation releases but with fixed power generation outflows) scenarios

August, and September the water levels are increased between 2 to 20 m in each of the

five years considered. The increased water levels in the reservoir significantly enhanced

the leak providing more water for irrigation at Walawe system IRR 1. The average annual

increase in leak flow volume equals 10 %. It should be noted that the reservoir leak is a continuous flow throughout the year. The average monthly leak discharge (~ 5 MCM) observed under the increased water levels is more than twice the irrigation requirement for banana crop at system IRR 1.

The elevated water levels under the firm power scenario, indicates the possibility of releases to downstream reservoir R 2 in the months of July, August and September. The increased power generation outflows under this scenario are able to cover 3%, 6%, and 29% of IRR 2 irrigation demands during these months. Further flow enhancements could be expected due to increased return flows from irrigation system IRR 1.

Moreover, it may also be possible to make systematic releases (step wise power demand) throughout the year which could be stored in the reservoir R 2 for irrigation use during the period concerned. These and other possibilities of conjunctive reservoir use could be investigated under a detailed analysis of the Walawe water use systems.

Summary and Conclusions

In the face of rapid urbanization, industrialization and population growth, developing countries face the problem of utilizing their water resources effectively. The development and management of water resources become complicated due to diminishing supplies and growing demand. The aim of this study was to analyze the problems faced by such rural river basins and investigate the possible changes to current management practices that would help solve these issues.

The Walawe river basin in Sri Lanka was selected as a test case. This rural river basin is in the process of rapid development. There are multiple water users in the basin

who compete for the limited water resources. The social and economic stresses due to water shortage are already felt by the basin water users. Therefore basin water managers are compelled to investigate possible improvements to current management practices.

Initially, the study assessed the water availability and demands of the basin. The spatial and temporal variations of the supplies and demands were compared to identify the reasons for shortages. The water shortages experienced by the users at different scales were reviewed. The results of the above activities were used to propose some possible changes to management practices. Finally the implication of these changes was evaluated using actual field data. The findings and conclusions from the study can be summarized as follows:

(1) The water use in the upper and middle parts is much less than in the lower part of the basin. On the annual basis, about two thirds of the water available in the basin is used. The water shortages experienced by the users are due to the seasonality of inflows. The existing reservoirs do not have the capacity to carry over annual storage. It is not possible to increase the irrigated areas in the basin, under the current water use efficiencies and management practices. (2) Up to 50% of water saving can be achieved by switching to less water intensive crops. The change of farming methods (Eg. from flood irrigation to furrow irrigation) gives high water savings in the areas with high slopes and sandy soil. (3) The re-allocation of water from irrigation to hydro power generation is beneficial. However, individual farmers and the national economy could both benefit when the power station operates in the *firm power generation* mode. (4) This mode of operation also enables to supplement flows to downstream reservoir to be used for irrigation during the water short months.

The above results indicate that changes to current water management practices in the Walawe river basin could yield positive results. However, some of the limitations of the analysis are as follows. (1) The analysis was carried under limited data availability; (2) The management changes proposed by the study might not be feasible under certain socio-economic situations; (3) The analysis does not consider water quality aspects; (4) The environment flow requirements of the basin were not considered in this initial analysis.

The analysis uses a range of data sets available from the basin water management agencies. Some of these data sets are not comprehensive enough to represent all the possibilities. It should be noted that limited data availability has been a common challenge to the water resources analyses in developing countries (ADB 2007; Stephenson and Peterson 1991).

 The management changes suggested in the study are results of a preliminary analysis. The "changes to crop type in an irrigation system" or "changes to operation mode of a reservoir" are decisions that are taken based on detailed analysis. Moreover these changes can be implemented fully or partially. A crop type conversion in part of the irrigated area or operation of power station in firm power mode for certain months of the year could yield more socially and economically acceptable results. A detailed study would enlighten such possibilities.

The water users in a basin inherently impose certain water quality demands on its resources. The increased exploitation of the resource leads to its degradation and consequent inability to satisfy these quality demands. This in turn will affect the basin

water allocation decisions. Therefore it is important to incorporate the water quality demands in a detailed study.

At present the environmental flow requirements of the basin are not fully assessed. In future these requirements will be enforced and will affect the water allocation in the basin. It is necessary to properly assess and include environmental flow requirements in a detailed study.

Overall the current study highlights how changes to current management practices could yield positive social and economic impacts. Knowledge gained through such studies is useful to initiate the much needed changes to the river basins management in developing countries.

References

Asian Development Bank (ADB) (1979) Project completion report for the Walawe development. Project Report. Colombo, Sri Lanka

Asian Development Bank (ADB) (1999) Project performance audit report on the Walawe irrigation improvement. Colombo, Sri Lanka

Asian Development Bank (ADB) (2007) Recent advances in water resources development and management in developing countries in Asia: Asian water development outlook 2007. Discussion Paper, Colombo, Sri Lanka

Baghirathan VR, Shaw EM (1978) Rainfall–depth–frequency studies for Sri Lanka. J Hydrol 37:223–239

Barbier EB (1993) Sustainable use of wetlands, valuing tropical wetland benefits: economic methodologies and applications. Geogr J Part-1 59:22-32

Bartle A (2002) Hydropower potential and development activities. Energy Policy 30:1231–1239

Bellaubi F (2004) Water efficiency and equity in an irrigation system: multi-level modeling for the understanding of water allocation in Walawe river basin, Sri Lanka. M Sc thesis, International Centre for Advanced Mediterranean Agronomic

Studies, Montpellier, France

Briscoe J (1999) The changing face of water infrastructure financing in developing countries. Water Resour Dev 15(3):301-308

Central Bank of Sri Lanka (2008) Annual report 2008, Government of Sri Lanka. http://www.cbsl.gov.lk/info/08_statistics/s_3.htm. Accessed on 13 October 2008

Central Environmental Authority (CEA) (1995) Wetland site report: Udawalawe reservoir. Colombo, Sri Lanka

Central Engineering Consultancy Bureau (CECB) (1985) Samanalawewa power project. Technical Report. Ceylon Electricity Board , Colombo, Sri Lanka

Cohen JE (2003) Human population: the next half century. Science 302:1172-1175

Department of Census and Statistics (2008) Government of Sri Lanka. http://www.statistics.gov.lk/agriculture/index.htm. Accessed 13 October 2008

Dharmasena PB, Keerthiratna GB (1988) Agro-climatic analysis of selected locations in the dry zone of Sri Lanka. ICRISAT (informal publication), Andhra Pradesh, India

Dissanayake P, Smakhtin V (2007) Environmental and social values of river water: Examples from the Menik ganga, Sri Lanka. Working Paper 121. International Water Management Institute (IWMI), Colombo, Sri Lanka

Droogers P, Jayatillake PC (2003) Water, climate, food, and environment in the Walawe basin. Contribution to the project ADAPT: adaptation strategies to changing environments. http://www.geo.vu.nl/users/ivmadapt/papers.htm. Accessed 5 May 2007

Dyson T (1999) World food trends and prospects to 2025. Proceedings of the National Academy of Sciences, USA 96:5929-5936

Food and Agricultural Organization statistics database (FAOSTAT) (2001) http://www.fao.org. Accessed May 5 2007

Food and Agriculture Organization of the United Nations (FAO) (2003a) The State of Food Insecurity in the World. Economic and Social Department, Rome

Food and Agriculture Organisation of the United Nations (FAO) (2003b) Unlocking the water potential of agriculture. Land Natural Resources Management and Environment Department, Rome

Food and Agricultural Organization(FAO) (2005) Statistical year book 2005. http://www.fao.org. Accessed 5 May 2007

Handawela J (2002) Use of water for protecting ecosystems. In : Imbulana KAUS, Makin IW, Droogers P (ed) Proceedings of workshop on Ruhuna Basins. IWMI, Sri Lanka.

Hunting Technical Services Ltd. (1968) The Uda Walawe report, Volumes I and II. Transactions 1983. Institute of Engineers, Colombo, Sri Lanka

International Energy Agency (IEA) (2007a) Key world energy statistics. http://www.iea.org. Accessed 12 May 2007

International Energy Agency(IEA) (2007b) Renewables in global energy supply. http://www.iea.org. Accessed 5 May 2007

International Food Policy Research Institute (IFPRI) (1995) Global food projections to 2020: Implications for investment. Discussion Paper 5. Washington, DC

International Food Policy Research Institute (IFPRI) (2002) The role of rain-fed agriculture in the future of global food production. Environment and Production Technology Division, Discussion Paper 90. Washington, DC

International Irrigation Management Institute (IIMI) (1990) Irrigation management and crop diversification in Sri Lanka, Final Report, Volume III. Colombo, Sri Lanka

International Water Management Institute (IWMI) (2000) Special assistance for project implementation (SAPI) for Walawe left bank irrigation upgrading and extension project, Mahaweli Authority of Sri Lanka, Sri Lanka

IUCN (2003) The Pangani river basin: a situation analysis. IUCN eastern Africa regional office, Nairobi

Japan International Cooperation Agency (JICA) (1993) Feasibility study on Walawe irrigation upgrading and extension project. Main Report-Volume 1. Sri Lanka.

Jinapala K, Somaratne PG, Perera LR, Makin IW, Bandaragoda DJ (2003) Multi-level participatory consultative approach for institutional change in river basins: lessons from the Deduru Oya case study in Sri Lanka. IWMI Working Paper 59. International Water Management Institute (IWMI), Colombo, Sri Lanka

Johnson N, Revenga C, Echeverria J (2001) Managing water for people and nature. Science 292(5519):1071-1073

Kaygusuz K (2004) Hydropower and the world's energy future. Energy Sources

26:215-224

Kikuchi M (1990) How to evaluate economic returns from management innovations in which no cost is involved: call for comments. IIMI Inter-Office Memorandum. Colombo, Sri Lanka

Kogan FN (1997) Global drought watch from space. B Am Meteorol Soc 78 (4): 621-636

Kumara UE, Wijeratne AW (2004) Estimation of economic loss due to reduction of paddy land areas: Construction of Samanalawewa reservoir. In: Proceedings of Water Professionals' Day 2004, Geo Informatics Society of Sri Lanka (GISSL), Sri Lanka

Mendis DLO (1967) Planning by network for construction of Uda Walawe headworks. Transactions 1967. Institute of Engineers, Sri Lanka

Molle F (2004) Technical and institutional responses to basin closure in the Chao Phraya river basin, Thailand. Water Int 29(1):70–80

Molle F, Jayakody P, Ariyaratne BR, Somatilake HS (2005) Balancing irrigation and hydropower: A case study from southern Sri Lanka. Research Report 94. International Water Management Institute (IWMI), Sri Lanka

Molle F, Renwick M (2005) Economics and politics and of water resources development: Uda Walawe irrigation project, Sri Lanka. Research Report 87. International Water Management Institute (IWMI), Sri Lanka

Nijman C (1991) Irrigation management processes and conditions: A case study of Sri Lanka's Walawe irrigation improvement project. International Irrigation Management Institute (IWMI), Sri Lanka

Peranginangin N, Shakthivadivel R, Scott NR, Kenedy E, Steenhuis TS (2004) Water accounting for conjunctive groundwater/surface water management: case of Singkarak-Ombilin river basin, Indonesia, J Hydrol 292(1):1-22

Perera LR (2003) Assessment of multiple use of water resources: Inland fisheries in the Walawe basin. International Water management Institute (IWMI), Sri Lanka

Pinstrup-Andersen P, Lorch PR, Rosegrant MW (1997) The world food situation: Recent developments, emerging issues, and long term prospects. Food Policy Report. International Food Policy Research Institute (IFPRI), Washington, DC

Revenga C, Brunner J, Henninger N, Kassem K, Payne R (2000) Pilot analysis of global ecosystems: Freshwater ecosystems. World Resources Institute, Washington, DC

Rosegrant MW, Cai X (2000) Modeling water availability and food security: a global perspective: the IMPACT-WATER model. Working Paper. International Food Policy Research Institute (IFPRI), Washington, DC

Senaratne S (2002) Water for basic needs, water supply and water quality. In: Imbulana KAUS, Makin IW, Droogers P(ed). Proceedings of Workshop on Ruhuna Basins, International Water management Institute (IWMI), Sri Lanka

Seneviratne AAAKK (2007) Development of steady state groundwater flow model in lower Walawe basin-Sri Lanka. In: Proceedings of the Water Professionals' Day 2007, Geo-Informatics Society of Sri Lanka (GISSL), Sri Lanka

Shah T, Makin IW, Sakthivadivel R (2001) Limits to leapfrogging: Issues in transposing successful River basin management institutes in the developing world. In: Inter-sectoral management of river basins. Proceedings of International Workshop on Integrated Water Management in Water-Stressed River Basins in Developing Countries, International Water management Institute (IWMI), Sri Lanka

Sims REM, Rogner H, Gregory K (2003) Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation, Energy Policy, 31:1315-1326

Smakhtin VS, Piyankarage S (2003) Simulating hydrologic reference condition of coastal lagoons affected by irrigation flows in southern Sri Lanka. Wetl 23(4):827 – 834

Somatilake HS (2002) Water for energy. In: Imbulana KAUS, Makin IW, Droogers P(ed). Proceedings of Workshop on Ruhuna Basins, International Water Management Institute (IWMI), Sri Lanka

Stephenson D, Peterson MS (1991) Water resources in developing countries. Elsevier Science Publishers, Amsterdam, The Netherlands

Svendsen M, Murray-Rust H, Alpaslan N (2001) Governing closing basins: the case of the Gediz River in Turkey. In: Inter-sectoral management of river basins. Proceedings of International Workshop on Integrated Water Management in Water-Stressed River Basins in Developing Countries, International Water Management Institute (IWMI), Sri Lanka

Statkraft Groner, BLOM, HALCROW and CEYWATER (2000) Sociology and water allocation. Draft Final Report -Annex I. pp 13-22

The World Conservation Union (IUCN) (2003) The Pangani river basin: a situation

analysis. Report. IUCN Eastern Africa Programme, Nairobi, Kenya

United Nations Development Programme (UNDP) (2006) Human development report 2006. United Nations Development Programme, New York

Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA (1986) Human appropriation of products of photosynthesis. Biosci 36(6):368-373

Walawe Irrigation Improvement Project Report (1998) Effects of Samanalawewa on the Walawe irrigation project. Sir Mott MacDonald & Partners Limited, Consulting Engineers, WIIP, International Irrigation Management Institute (IWMI), Sri Lanka

Wester P, Burton M, Mestre-Rodriguez E (2001) Managing the water transition in the Lerma –Chapala Basin, Mexico. In: Inter-sectoral management of river basins. Proceedings of International Workshop on Integrated Water Management, International Water Management Institute (IWMI), Sri Lanka

World Water Assessment Program (WWAP) (2006) Sri Lanka national water development report. Imbulana KAUS, Wijesekera NTS, Neupane BR (ed), Sri Lanka

World Water Development Report (2001) World Bank, Washington, DC

World Population Prospects (2000) Revision, Population Division Department of Economic and Social Affairs. United Nations, New York

Zubair L, Siriwardhana M, Chandimala J, Zeenas Yahiya (2008) Predictability of Sri Lankan rainfall based on ENSO. Int J Climatol 28: 91–101

CHAPTER 3

SIMULATION MODELING OF PRIORITY-BASED WATER RESOURCES

ALLOCATION IN RURAL RIVER BASINS OF THE DEVELOPING WORLD[1]

Abstract The processes of population increase, urbanization and industrialization has resulted in a rapid demand increase for water resources in the developing world. Water managers in the river basins of the developing world face the increasingly difficult task of allocating the limited water resources among competing users. In addition climate change is causing supply variation that increases the uncertainty of water allocations. As a result, the difference between available water resources and water demands is ever increasing. Different approaches to increase water use efficiency as well as water management efficiency have been tried out in various parts of the world with mixed results. Successful water allocation policies and institutions of the developed countries have not produced the expected results in the developing world. Therefore it is important to investigate the social, economical and political aspects of water management issues in the developing world to arrive at sustainable solutions. In the face of growing competition the water allocation has evolved to be a complex process that involves a number of actors, techniques and legislations. Simulation and optimization modeling techniques can help the water managers to analyze this complex process and develop sustainable water allocation solutions. Over the years a number of computer based tools that employ simulation and optimization techniques have been developed. The first part of this paper reviews some major actors, techniques and legislature that are involved in the water

---

[1] Coauthored by Neelanga Weragala, Jagath J. Kaluarachchi, and Vladimir U. Smakhtin

allocation in river basins. In the second part, computer based water allocation modeling techniques are reviewed. A priority based water allocation simulation model is selected for the analysis of water allocation issues of a rural river basin in the developing world. Several water use and water management efficiency increase methods are also evaluated.

Introduction

The rural river basins in developing countries face the problem of increasing demand for freshwater resources due to urbanization, population growth and industrialization. The supply is dependent on the rainfall variability. The climate change effects add further to supply uncertainty. In some river basins of the developing world the demands already exceed supply. Many others are yet to reach *closure*. However conflicts among competing water users have been observed in many river basins in the developing world. Generally, the demand for water includes both quantity and quality criteria. As the abstraction of water is increased, many water bodies are over exploited and polluted. Some have reached their assimilation capacity of human and industrial waste. In this context, it has been increasingly difficult for the water managers to design allocation schedules that satisfy the sustainability of water resources, economic efficiency and equity among water users and environmental flow requirements at the same time. There are a number of examples from the developing world river basins, where increased competition among water users and ensuing conflicts have lead to socio-economic as well as environmental losses. The East Rapti river basin in Nepal provides an example of conflicts between user sectors due lack of appropriate techniques and institutes to mange multi-sectoral water use (Adhikari 2001). The hotels industry in the lower reaches of this

river suffers water shortages for recreation activities due to extensive irrigation

abstractions in the upstream. The Ombilin river basin in West Sumatra, Indonesia

provides a classic example of competition for water between hydropower generation and

irrigation. The reduced flow in the Ombilin River due to the construction of a

hydropower reservoir, has limited the use of water wheels lifting water for irrigation

(Helmi 2002). A major environmental concern (regarding the salinity intrusion in dry

season) due to extensive abstractions for irrigation, urban and industrial use is observed

in the Dong Nai river basin in Vietnam (Ringler et al. 2002). These and many other

examples indicate that current water management (and allocation) practices in the river

basins of developing world need improvements.

Development of Water Allocation Policies

A widely accepted criterion for evaluating water allocation policy is the economic

efficiency (Dinar et al. 1997). This criterion enables re-allocation of water from low

efficient uses to highly efficient uses. When all the water in a river basin is efficiently

allocated, the marginal benefit should be equal across all water use sectors. There are

examples from the developed world where water allocation based on the principals of

economic efficiency has worked out successfully. In addition to economic efficiency

there are other criteria that need to be considered in a multiple user environment (Carraro

et al. 2005). Equity, predictability, strategic considerations, flexibility, technical

feasibility, political and public acceptability are all considered as acceptable criterion for

evaluating water allocation (Carraro et al. 2005; Dinar et al. 1997). In the developing

world, some of these criteria may play a dominant role in selecting water allocation

policies and mechanisms, at times transcending the role of economic efficiency.

Methods of Water Allocation

The water allocation policies are implemented through water allocation

mechanisms. The currently observed water allocation mechanisms can be broadly

categorized in to three groups: 1) Public (administrative) allocation 2) User based (user

managed) allocation and 3) Water markets (Dinar et al. 1997; Meinzen-Dick and

Mendoza 1996). It is common to find combinations of these mechanisms as well. These

mechanisms are briefly discussed below.

Under public allocation mechanism water allocation is managed by the state. The

allocation volumes are defined based on quantity (quota-oriented) or based on a marginal

cost pricing method (Dinar et al. 1997). This allocation method has been applied at river

basin level, water user systems levels or at individual water user level. Public water

allocation is commonly practiced in the large scale water projects managed by the state

sector. The state usually enforces public allocation using a system of regulations and

sanctions.

Practice of public water allocation in developing world has run into a number of

difficulties. Lack of a comprehensive legal framework, unclear institutional

responsibilities, inadequate staffing of allocation agencies, lack of proper systems of

water rights and inadequate monitoring are some of the common reasons (UN 2000). In

general, the water allocations from public systems are heavily subsidized and do not

reflect the actual supply cost. Therefore the water users are inclined to receive water

exceeding their allocation. This leads to a range of management irregularities including the practice of rent-seeking by agency staff responsible for irrigation operations, seriously disrupting the official allocation schedules (Johansson 2000; Meinzen-Dick and Mendoza 1996; Repetto 1986; Wade 1982).

User based/managed water allocation has been promoted in the developing world to address some of the shortcomings in public allocation (Van Koppen et al. 2007). This method allows users to participate in water allocation decisions. The major advantage of this method is the ability to incorporate knowledge of local conditions and adaptability. Performance data from a number of irrigation systems in the developing world have shown that, user based allocation performs better when compared to public allocation (Merry 1996). Many public irrigation systems have adopted a user based allocation approach by establishing water user associations (WUA) at secondary and tertiary levels.

The above two methods have long being criticized for locking the water resources in to uses that have diminishing value to the economy. Water markets introduce flexibility in water allocation by allowing trade of water rights across sectors, across locations and time. A market approach allows the water users to seek the highest value application of scarce water through voluntary exchange and generation of information about scarcity and demand. It also creates an incentive to conserve water and invest in water saving technology. Despite these positive characteristics, formal water markets have not evolved in many of the developing world river basins (Rosegrant and Binswanger 1994).

For a water market to function in a river basin, its user water rights must be well defined, enforceable and transferable (Koundouri et al. 2003; UN 2000). Moreover

markets require third-party effects such as return flows, pollution, water logging, and overdraft of groundwater, environmental impacts etc. to be fully quantified and associated costs to be incorporated in the exchange. Transaction costs (information gathering, conveyance losses, monitoring, enforcements etc.) should be lesser than the benefits earned from the trade of water rights. Many developing countries do not possess the capital, technology or the institutional structure that is needed to establish these conditions. The absence of water laws, clear jurisdiction over water and water markets has impeded the reallocation of water to efficient uses in the developing world (Howe 1978; Thobani 1998). However in some developing world irrigation systems, emergence of formal and informal water markets have been observed due to significant efficiency gains from water right transfers (Rosegrant et al. 1995).

Water Rights

In public as well as in market allocation, clear definitions of user water rights play an important role (Rosegrant and Binswanger 1994; UN 2000). However due to the specific nature of water resources, a simple straightforward definition of rights is not always possible. One reason being the existence of users holding overlapping rights to water. Another is the existence of multiple legal frameworks for defining water rights (Bruns and Meinzen-Dick 2005). The existence of non documented implicit water rights that are backed by social norms also complicates the issue of water rights. With the increase of water scarcity, the priorities in water use change and to maintain efficiency reallocation of water rights is required (Freebairn 2003). Consequently water rights too need to change, evolve and adapt over time (Bruns and Meinzen-Dick 2005).

Allocation Priority

Another important concept in both public and market methods, is the allocation priority. Allocation priority becomes important when the full water rights of all water users cannot be supplied. In such a situation water could be allocated under 1) Natural priority (allocation from upstream to downstream order) 2) Assigned priority 3) Same priority (proportional allocation) (Wurbs 2003). The assigned priority system allows the water managers to take control over the water use in a river basin by allocating water in a preferential order. Priority based allocation could be used to address some specific issues faced by the water users in the developing world as described below.

Traditionally, water resources projects in the developing world have one major goal, and all other uses of water take a secondary nature (Schramm 1978). Water development projects that aim to achieve food security, employment generation, hydropower generation, flood control, drought mitigation are abundant in the developing world. In a water scarce situation, the water allocation for this high important water use can be guaranteed by prioritizing its water rights.

In public allocation systems, prioritization is often used to attain social objectives such as redistribution of income, protect environment and ecology, provide self sufficiency in food, power generation, protect cultural and religious values, ensure employment opportunities etc. It has been used to prevent extreme loss to sensitive users under drought conditions. It allows recovery of capital costs of public investments. Prioritization can be used to mitigate the *return flow* effects as well. It is also used as an instrument to protect the poor against development of market power (UN 2000).

In a water market, water rights are transferable among users and they will be reallocated from low to high added value uses. Theoretically the final equilibrium allocation of water rights will not be affected by their initial distribution. However this holds true only when ideal market conditions (zero transaction costs, full information, many buyers and seller etc) are exists. In practice the initial allocation of water rights significantly affects the final outcome of market allocation (Lee 1999). While proportional allocation gives an equal starting ground for all users in a subsequent water market, prioritization places preferred users on a privileged position. This inequality may prevent from achieving economic efficiency in water allocation, but at the same time it may be used to safeguard public interests.

The above discussion highlights some of the important factors that affect the water allocation of river basins in the developing world. The limitations in capital, technology and legal frameworks as well as social and environmental specifics in these countries pose problems to establishing fully market-based allocations. Priority based allocation provides a method to achieve basin water development objectives while adjusting to the basin specific socio-economic conditions. The performance of such allocation method can be evaluated by simulating the allocation process and estimating the social, economic and environment effects of the resulting allocation schedules (Jain and Singh 2003). Computer based simulation and optimization models have long been used to estimate the best allocation schedules under competing water demands.

Modeling of Water Allocation

Simulation models available for river/reservoir system analysis can be categorized in to two main groups: 1) models that use ad hoc algorithms (heuristic procedures, search algorithms etc.) 2) models that use mathematical programs (network linear programs). The simulation models that use linear programming (LP) algorithms can be further categorized in to two groups, based on how the algorithm solves the allocation problem. Models in the first group step through the simulation time periods sequentially. In this case the optimization process is based on the current and past river flows only. Therefore the reservoir operation policies derived do not reflect the future river flows. However in this case, long term optimization over the simulation period can be achieved by incorporating the user defined *target reservoir operation rules* to the model (Perera and James 2003). The second group of models uses an LP algorithm that solves the network flow problem for the entire simulation period simultaneously.

The simulation models can be further divided in to three categories based on the sequence of calculating the decision variables (stream flows, diversions, reservoir storages and releases etc.). In pure simulation models these variables are generally calculated in upstream to downstream progression starting at the upstream locations of the river network. The models with LP algorithms calculate these variables either on a user defined priority order or simultaneously (same priority).

Network flow programming is widely used in the above described simulation models that use LP optimization. First, the steady-state operation of a surface water system can be easily described as a network flow problem. Second, the network flow programming is a computationally efficient form of linear programming (Durbin and

Kroenke 1967). The solution algorithm used to solve the problem may vary based on the model.

In a network flow model, the water courses connecting the water users and reservoirs are represented in a network consisting of arcs and nodes. The nodes are connected with arcs representing the possible flow paths. Each arc has a user defined lower and upper bound and a unit cost factor for flows through that arc. The criteria for evaluating the performance of water allocation are related to variables corresponding to the flows in the network. Determining the minimum cost flow in this network is equivalent to determining the optimal values for the variables (Jain and Singh 2003).

The network flow models use the unit costs in the arcs to assign relative priorities for water allocation among nodes and maintaining target storage levels in reservoirs. This prioritization method allows simulating the priority based allocation discussed above. In addition, some network flow based models allow accumulating the incremental local flows (Wurbs 2005). This enables the downstream users to utilize the local tributary inflows that are added to the network below the upstream diversion points.

This study uses a network flow simulation model to estimate the priority based allocation schedules for water users in a rural river basin in Sri Lanka. The WEAP (Water Evaluation And Planning) model (Stockholm Environment Institute, US Center) is a network simulation model that allows to evaluate priority based water allocation policies (Yates et al. 2005).

Study Area

Water Resources and Water Users

The study area consists of Walawe river basin in Southern Sri Lanka (Fig. 3.1). The basin area is about 2471 sq. Km. It receives rainfall from two monsoon seasons a year. The southwest monsoon occurs from May to June and the northeast monsoon occurs from October to January. The average annual rainfall over the basin varies between 2000 mm and 1000 mm from mountainous upper reaches to the coastal plain. The average annual reference evapotranspiration in the basin is about 1700 mm. Under natural conditions the average annual discharge to sea is about 1 billion cubic meters.

The major water user in the basin is irrigated agriculture. At present three irrigation systems with a total area of about 32,000 ha are located in the basin (Fig. 3.1). The major crop cultivated is rice, which also is the staple food in Sri Lanka. In IRR2 along with rice other field crops (banana, vegetable, chili, pulses, and sugarcane) are grown. Crops are cultivated in two cropping seasons that coincide with the two monsoon seasons.

The irrigation systems IRR 1 & IRR 3 are supplied by diversion structures across the river. An irrigation reservoir (R 1) with a capacity of 268 MCM is located in the middle reaches of the basin. This reservoir supplies the main irrigation system IRR 2 that spreads from the middle reaches to the southern end of the basin. The study area consists of numerous other smaller reservoirs that either augments the major irrigation system or capture local runoff for individual farming plots that are located outside the above mentioned irrigation systems.
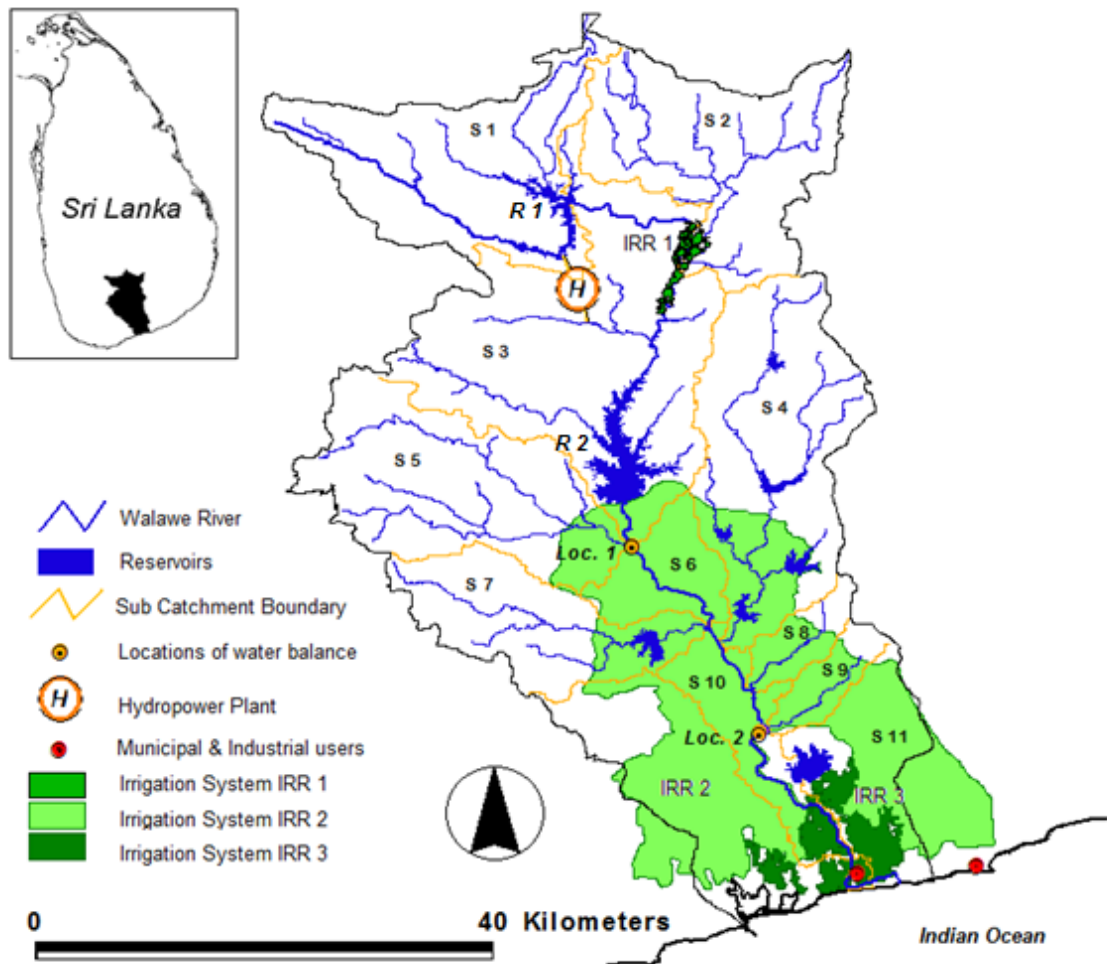
Fig. 3.1 Physical layout of the Walawe River basin, its sub catchments, water resources, and water users

Hydropower production is another major water use in the Walawe basin. The hydropower reservoir R 1 is located in the upper most reaches of Walawe and has a storage capacity of 278 MCM. Power station HYDRO is capable of generating around 300 GWh annually.

Other water uses in the basin are industrial water use, municipal water use and environmental water use. The industrial water use is mainly for paper production, sugar refinery, brick and tile production and rice mills. The municipal water use in the basin is

located in the coastal cities. The water for these demands is abstracted from the lower

reaches of the Walawe River. Environmental water use is mainly from the wild-life-

conservation park located directly upstream of reservoir R 2 (Fig. 3.1).

The groundwater usage is mainly for domestic consumption and watering home

gardens which are scattered throughout the basin. The groundwater recharge in the basin

is estimated to be about 10% of the annual rainfall. The groundwater levels near the

irrigation systems are usually elevated due to continuous seepage and leaks from the

irrigation canals.

Water Supply Network and User Demands

The Walawe River and its tributaries supply the water demands of users in the

basin. The uppermost water user is irrigation system IRR 1 which has a cultivation area

of 860 ha. The estimated annual irrigation demand is around 55 MCM. This system has

the most senior water rights in the basin. Irrigation releases from reservoir R 1 to

downstream through Walawe River are diverted to this system. In addition the leak

discharges from reservoir R 1 are also utilized for irrigation diversions (Fig. 3.2).

The system IRR 2 has an area of 12,000 ha on each of the left and right banks.

The estimated annual crop water requirement is around 435 MCM and 344 MCM on the

right bank and the left bank, respectively. Both banks have the same seniority in water

rights. Irrigation releases from reservoir R 2 are supplied through main irrigation canals.

In addition, the tributary inflows to Walawe River captured in reservoirs R 8 and R 7 are

used to supplement the water demands of left and the right banks respectively (Fig. 3.2).

A hierarchical system of branch, distributory and field canals carry the supplies to

Fig. 3.2 Network diagram showing tributaries, distributory canals, return flow paths, reservoirs, and water user nodes in the Walawe basin

the farm plots. Operation of these canals is carried out in a rotational schedule.

The system IRR 3 has a crop area of about 3300 ha on each bank. The estimated crop water requirement is around 273 MCM for each. The irrigation requirement of this system is jointly supplied by the return flows from IRR 2 and the irrigation releases from the diversion on Walawe River (Fig. 3.2). Command areas on both left and the right bank have equal water rights.

The return flows from HYDRO flows back to Walawe River below the diversion point of IRR 1. Therefore the outflows from power generation are available to all downstream users except system IRR 1 (Fig. 3.2). As is a continuous demand for additional power production, the flow requirement for power generation is limited by the capacity of the plant and the availability of inflows. The rated discharge of the turbines installed equals 42 m^3/sec. The hydropower reservoir has a minimum operation level of 424 m MSL.

The municipal water requirements in the coastal cities are estimated to be 5.72 MCM in 1990 and 7 MCM in 1999. The industrial water requirement increased from 32 MCM to 42 MCM during the same period. Municipal and industrial water requirements are pumped directly from Walawe River.

A comprehensive assessment of the environmental flow requirements have not been carried out in the basin to date. However, the water requirements of the wild-life conservation park are assumed to be satisfied as long as water levels in the reservoir R 2 remain above its minimum operation level of 75 m MSL. In addition, a continuous outflow to the sea from the Walawe River is identified as an environmental flow requirement. However the minimum requirement of flow has not been quantified.

Methods

This study uses priority based simulation model WEAP to evaluate selected scenarios of basin water resources management and development. The selected methodology consists of four main steps: 1) estimate inflows to the Walawe river; 2) develop demand scenarios under various water resource development goals and management practices; 3) simulate water allocation schedules for demand scenarios; 4) analyze the socioeconomic and environmental impacts of simulated allocation schedules. The study is carried out for a period of 10 years from 1990 to 1999. The rainfall records indicate an equal distribution of wet and dry years within this period. Moreover this period corresponds to the full utilization of land resources for agriculture, emergence of hydropower generation and rapid expansion of industry and municipal water use in the basin.

Estimation of System Inflows

The inflows to Walawe River were calculated by sub dividing the catchment area into 11 sub-catchments (Fig. 3.1) and estimating the run-off from each. Weekly rainfall data from 11 rain gauges located across the basin, supplied by the Meteorological Department of Sri Lanka were used to estimate the areal rainfall. Theissen polygon method was used to average the point rainfall records. Rainfall over the catchment area is converted to runoff using runoff coefficients derived for each sub-catchment in previous studies by the Mahaweli Authority of Sri Lanka (MASL 1995).

To evaluate the accuracy of runoff estimation, a water balance was carried out at two locations on Walawe River (Fig. 3.1). The locations were selected based on the

availability of measured stream flow data. Location 1 is on the Walawe River at reservoir R 1. A record of weekly inflows to the reservoir, (estimated by reservoir water balance) is compared to the flows from rainfall-runoff conversion for the three upstream sub-catchments S1, S2 and S3 (Fig. 3.1). Location 2 is on the Walawe River at the irrigation diversion structure for system IRR3. The sub-catchment run-off from S4 through S9, spills from reservoir R 2, and the irrigation return flows from IRR 2 contribute to the flow at this location. Since the irrigation return flows, the reservoir spills and the flow at Location 2 are known, a water balance was carried to estimate the flows from upstream sub-catchments. This estimated flow is compared to the flows derived by the rainfall – runoff conversion for sub-catchments S4 through S9.

Water Demands Scenarios

The Walawe water demands are modeled in this study based on the following assumptions. Irrigation water demands correspond to the water demand for maximum cultivable area and yield in all three irrigation systems. The irrigated land consists of three hydrologic soil types: high, low and moderately permeable soils. In system IRR 2 a mix of six crop types are grown: two lowland crops (rice and banana) and four highland crops (chili, pulses, vegetables, sugarcane). The crop areas under each crop vary slightly from year to year depending on the farmer's preference. For the current study the observed cropping pattern of 1996 was used.

Rice is preferably grown on low permeable soil. As the cropping technique used for rice in Walawe basin is highly water intensive, the water demand tends to increase if majority of rice crop is grown in moderate to highly permeable soils. In addition, the

preferred soil for banana is low to moderately permeable soil. An optimization model was setup to maximize the crop areas of rice and banana on low permeable soil. This enables an efficient irrigation water use.

A continues deficit for hydropower generation is observed in the basin. To simulate this, a maximum water demand for hydropower generation (corresponding to the rated capacity of power station) was used. The municipal & industrial demands based on observed values for 1990 and 1999 with a fixed rate of increase were used in the estimation. The environmental flow demands were not included in the model. These baseline water demands are further modified as needed in the *demand management strategies* scenarios.

Computer Based Water Allocation Software
(WEAP Model)

The WEAP model is based on the principle of water balance accounting (Yates et al. 2005). This model contains a hydrologic modeling component as well as a water management component (allocation module). This study only uses the allocation module of the WEAP model. The objective of allocation module is to minimize the water deficits at each user node under the given priority order and equity constraints.

The water users and water resources in the basin are represented with a node-arc network (Fig. 3.2). The main inputs to the model are the inflows to the network, reservoir storage capacities, user demands and capacity of flow paths at a selected time scale: daily, monthly weekly or annual. Water allocation to demand sites occur under a user defined priority order. Each user (or group of users) is assigned a priority number between 1 and 99 such that high priority users getting lower order numbers. Additionally,

a single water user supplied by several resources can assign a preference order for its suppliers.

Allocation calculations are carried out sequentially at each times step. At runtime the users with same priority are assigned to an *equity group*. The water allocation is carried out by a linear program (LP) algorithm that iterates from one equity group to another. The first iteration of the LP algorithm occurs at the equity group consisting of the top priority users. The objective of the LP algorithm is to maximize the coverage of all user demands in that group.

In addition to the physical constraints on supply limitations and arc capacity limitations, an *equity constraint* is included in the algorithm. This constraint ensures that, in case of a shortage in supply, all users in the group are supplied with the same percentage of their demands. When multiple suppliers are present the LP algorithm engages in an additional iteration through each suppler (in their preference order).This enables to maximize the coverage at each demand site utilizing all suppliers.

Once the optimal allocations for all the users in the equity group are defined, the model simulates the reservoir storage, flows to downstream reaches, return flows etc, corresponding to optimal allocations. Next, the LP algorithm iterates to the equity group with the second most priority. This procedure continues through all equity groups according to their priority order. Once all the users in all equity groups are optimally allocated and the corresponding system storages and flows are simulated the model proceeds to the next time step. At the end of simulation, water allocation schedules are output for each user node. In addition the allocation deficits (unmet demands) are also calculated by WEAP.

The selection of model time step is dependent on data availability and the required level of detail in results. The available data allows selecting a weekly or a monthly time step for the analysis. However the major water user in the basin – the irrigation sector shows significant variation of water use within the months at the beginning and end of cropping seasons. Therefore a weekly time step is selected for this analysis.

Formulation of Allocation Scenarios

The water allocation scenarios were designed under two main categories in line with the objectives of the study. Scenarios under category A evaluate the effects of prioritization of water allocation between sectors and within a single water use sector. Scenarios under category B demonstrate the impacts of various *demand management strategies* that could be adopted by basin water managers. Table 3.1 contains the detailed description sub scenarios under each of the main categories.

Table 3.1 Description of water allocation scenarios

Scenario Category	Analysis Type	ID	Description
A	Prioritization between sectors	A1	Hydropower > Irrigation
		A2	Irrigation > Hydropower
A	Prioritization between Left Bank (LB) and Right Bank (RB) of IRR2	A3	LB > RB
		A4	RB > LB
		A5	LB = RB
B	Modification of Hydropower demand	B1	Variable power demand
		B2	Fixed power demand
		B3	Step-wise demand
B	Irrigation efficiency increase	B4	Current efficiencies
		B5	Increased efficiencies
B	Irrigation systems upgrade	B6	Current system
		B7	Upgraded system

Evaluation of Allocation Scenarios

Scenarios were compared based on their social, economic and environmental outcomes. The scenarios involving agriculture and hydropower sectors were compared based on their production levels as well. The environmental impacts were evaluated based on the flows available for environmental use at sensitive locations. Comparison across all sectors was achieved by estimating net economic benefits generated by each sector. The social impacts were considered in evaluating the scenarios involving agricultural sector, where majority of employment are generated in this basin.

In addition to the above mentioned allocation volume based criteria, the performance of the water allocation system was also evaluated. A *Shortage Index* (SI) was calculated to evaluate the impact of water deficits. This index also implies the socio-economic effects of deficits (Hsu et al. 2008). The reliability of allocation and the resilience and vulnerability of the system to shortages in supply are compared for alternative scenarios. The formulae used in these estimations are given in the appendix.

Results and Discussion

Estimation of Inflows

The results of the water balance for Location 1 and Location 2 are shown in Fig. 3.3. The annual volumes match above 80% in all years except in the two drought years 1992 and 1996. It is possible that runoff-coefficients derived by previous studies under average conditions are not applicable to the dry years. Moreover the river flow measurements obtained under low flow conditions in dry years may contain inaccuracies.
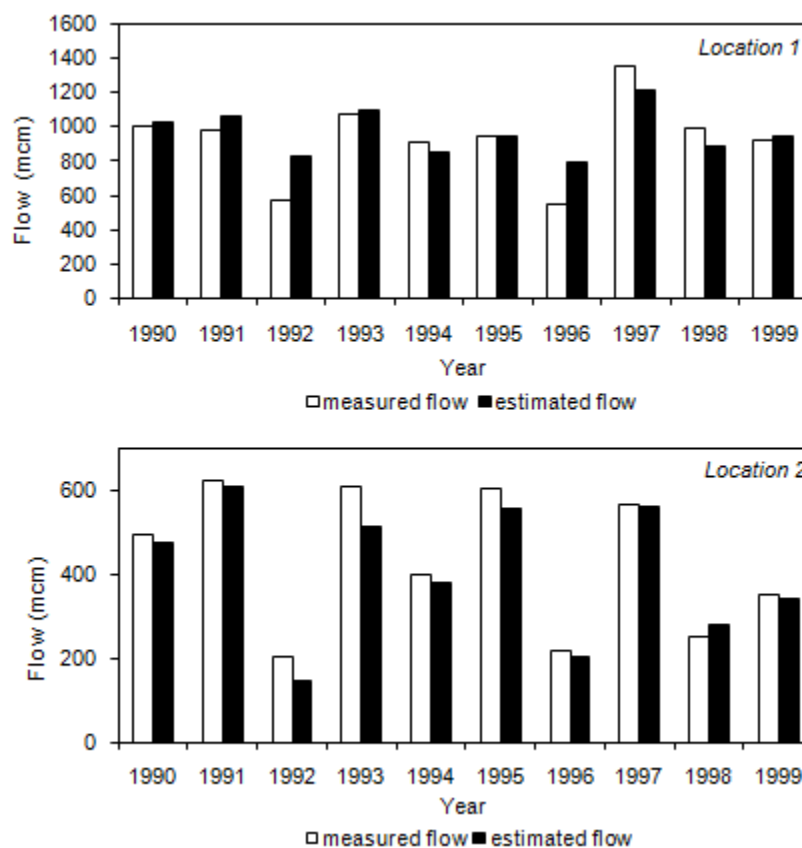
Fig. 3.3 Comparison of measured and estimated flows at Location 1 (top) and Location 2 (bottom) on Walawe River

Since the water balance results are satisfactory for 8 out of 10 years, the estimated sub-catchment run-off volumes are considered as adequately accurate for this study.

Effects of Priority Based Water Allocation

Prioritization of water allocation may occur among several competing water use sectors as well as among users within a single sector. The first case considered is allocation prioritization between two sectors: Irrigation and Hydropower generation. The second case considered is prioritization of allocation between the left bank (LB) and the right bank (RB) command areas of irrigation system IRR 2.

The main water uses of reservoir R 1 are power generation at HYDRO and irrigation at system IRR 1. The volume of water used by the system IRR 1 is significantly low when compared to power generation. However analysis of data indicates that, the temporal distribution of water demands within a year is such that the two users reach their peak demands at the same time. Moreover the low inflow period and the demand peak coincide, creating water deficits for both users. The allocation priority assigned to each user plays an important role in this context.

The two users use their allocations to achieve different objectives that have national and regional importance. On the one hand power station HYDRO has the capacity to use all the water available at reservoir R 1 for power generation. Generating more hydropower at HYDRO reduces the portion of coal and fuel based power generation currently used to meet the national demand. This is highly economical and has positive environmental effects as well. On the other hand, water use for power generation at HYDRO is a relatively new water use compared with the traditional irrigated paddy cultivation at IRR 1. In addition, system IRR 1 provides employment to more than 1500 families living in a mountainous and difficult–to-access rural area, where employment opportunities are few. Therefore securing irrigation water at IRR 1 has a regional importance.

To assess the effects of prioritization, two simulation scenarios were developed. In scenario A1 the hydropower production at HYDRO has priority over irrigation at IRR 1. Scenario A2 prioritizes irrigation at IRR 1 over power generation. Fig. 3.4 shows the annual water deficits at irrigation system IRR 1 under the two scenarios.
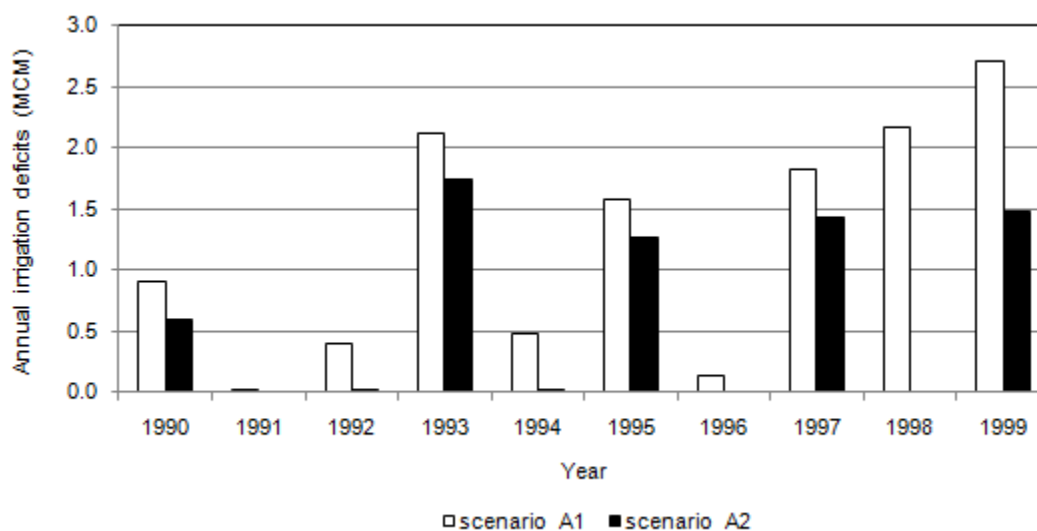
Fig. 3.4 Annual irrigation deficits at IRR 1 under two priority settings:
Scenario A1 and A 2

In each of the 10 years of simulation the irrigation deficits are lower under

scenario A2. Compared with A1, the average annual deficit reduction is about 38 %.

Moreover, the annual reduction of hydropower generation under A2 is less than 0.5 % in

each of the simulation years (Table 3.2). These results indicate that prioritization of

irrigation is beneficial while the consequent losses in power generation are not overly

significant. The system performance criteria at IRR 1 are also assessed to verify the

feasibility of such a prioritization.

Figure 3.5 shows the weekly water shortages at IRR 1 under A1 (bottom) and A2

(top) scenarios. When compared with A1, the short concentrated deficits in irrigation are

eliminated under A2. Table 3.3 shows four performance indices estimated for the

irrigation water supply to IRR 1 under scenarios A1 and A2. Compared with A1 the

Table 3.2 Annual power generation at HYDRO under A1 and A2 scenarios

Year	Scenario A1 (GWh)	Scenario A2 (GWh)	Percentage of decrease (%)
1990	277.8	277.2	0.20
1991	296.5	296.0	0.20
1992	173.4	173.2	0.10
1993	305.9	305.7	0.10
1994	214.2	213.5	0.30
1995	255.6	255.5	0.03
1996	158.3	158.2	0.01
1997	318.7	318.5	0.10
1998	202.2	201.5	0.40
1999	268.7	268.1	0.20
Total	**2471.3**	**2467.5**	**0.20**
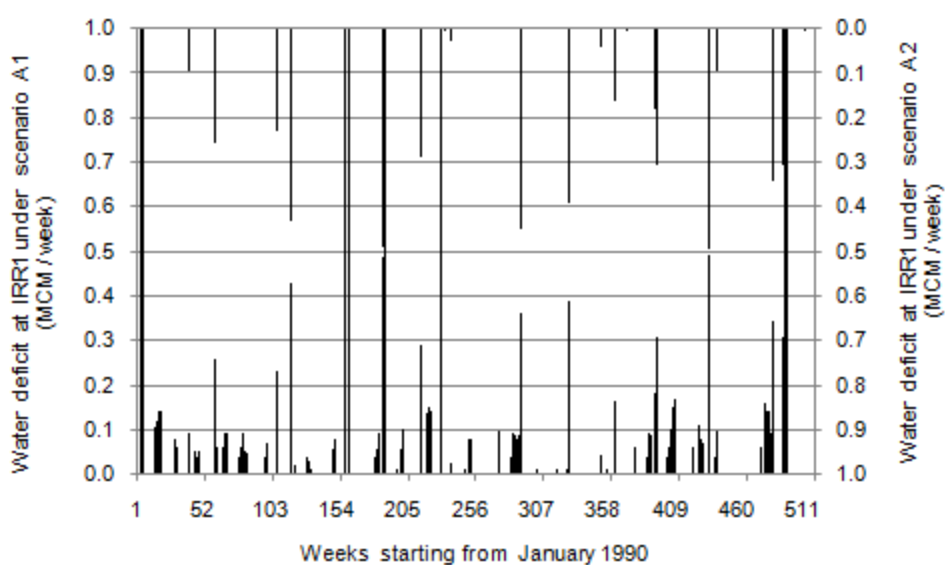
Fig. 3.5 Weekly water shortages at IRR 1 under A1 (bottom) and A2 (top) scenarios

shortage index in A2 has reduced by 51 %. This is due to the reduction of concentrated periods of deficit. The reliability and the resilience of the water supply have increased.

While the volume vulnerability is not affected, the time vulnerability has reduced. Rare large shortages contribute to the volume vulnerability. These shortages (occurring due to supply inadequacy) remain in both scenarios (Fig. 3.5). However small but

Table 3.3 Performance indices of irrigation supply at IRR 1 under A1 and A2 scenarios

Performance Index	Scenario A1	Scenario A2
Shortage Index (SI)	0.35	0.17
Reliability (REL)	0.78	0.94
Resilience (RES)	0.47	0.87
Volume vulnerability (Vv) [MCM]	0.89	0.89
Time vulnerability (Vt) [weeks]	7	4

frequent shortages (occurring due to flow allocation to higher priority user) are eliminated in A2 and the time vulnerability is reduced accordingly.

The second case considers prioritization between users in the irrigation system IRR 2. Figure 3.6 (top-left) shows the average fraction of water used by each crop in this system. The fraction of economic gain from each crop is shown in the Fig. 3.6 (top–right). The crop area distribution between the left and the right banks of the system are also shown in Fig. 3.6 (bottom).

Analysis of this data indicates that high value crops use less water but they are cultivated in smaller quantities. The high water consumptive paddy crop returns lower economic gains. However rice is grown on more than 45% of the area on both left and the right banks of the system. Prevailing socio economic conditions influence the demands for crops and the extent of areas allocated to each crop by the farmers.

Analysis of inflows to reservoir R 2 for the past 40 years shows, that the reservoir does not always receive adequate flows to supply the full irrigation demand of system IRR 2. This results in an irrigation deficit, which could affect the farm plots on one or both banks of the river. Since the cropping patterns and the resulting economic gain from each bank are different, prioritization between demands from left bank (LB) and the right bank (RB) command areas could be investigated to identify possible allocation

improvements. Three allocation scenarios are designed for this purpose. 1) Scenario A3

prioritizes left bank demands over right bank. 2) Scenario A4 prioritizes right bank

demands over left bank. 3) Scenario A5 gives same priority to both left and the right

banks (equal percentage of irrigation deficits shared).
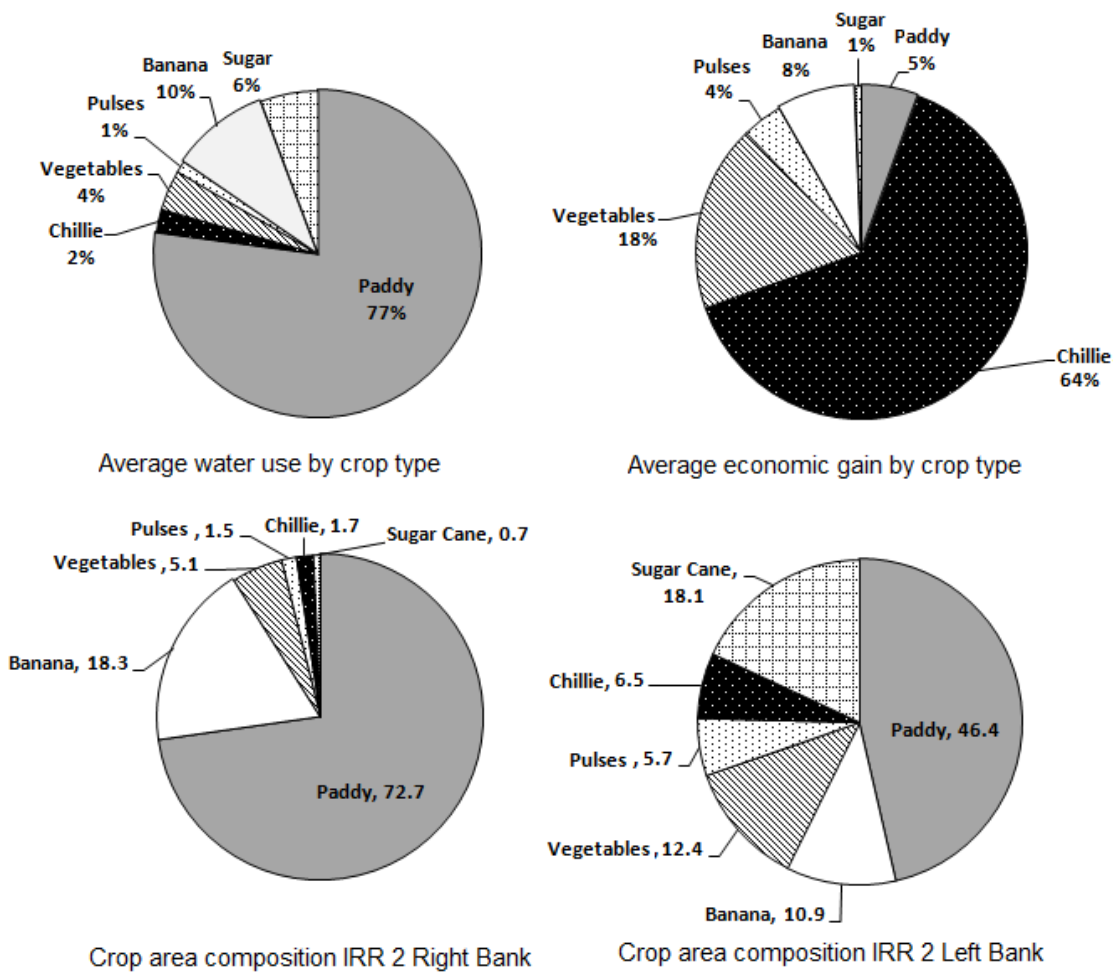
Fig. 3.6 Average water use and economic gain by crop type in system IRR2 (top). Crop area composition in the Right bank and the Left bank of IRR2 (bottom).

Analysis of results is carried out based on the socio-economic consequences of each scenario. Figure 3.7 compares a) annual paddy yields, b) annual number of farmer families affected by deficits, and c) annual economic gains under each scenario. The
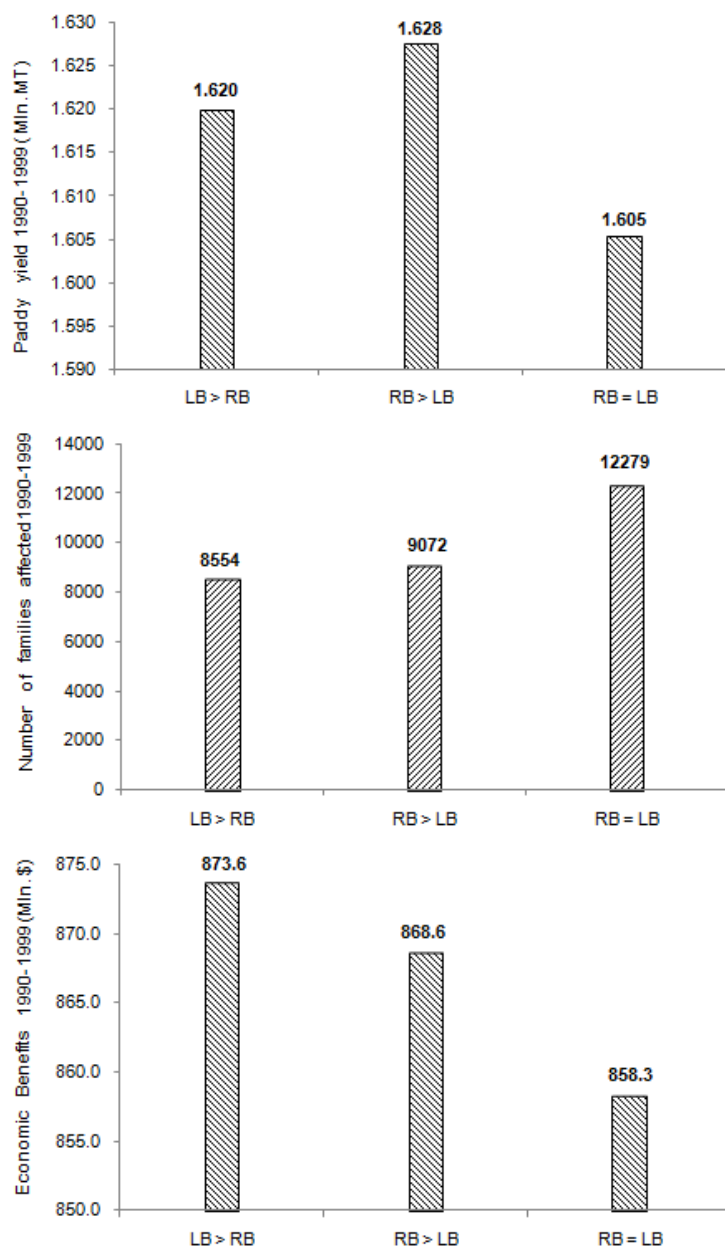
Fig. 3.7 Comparison of A) annual paddy yield B) number of farmer families affected and C) annual economic benefits under scenarios A3, A4, and A5 at system IRR2.

paddy yields and the number of farmer families affected by deficits are estimated based on the irrigable paddy area under each scenario. The overall economic gains from crop cultivation is estimated based on the information of average yield per unit area of crop and the average economic gain from unit crop yield based on the available data.

The results indicate that giving equal priority to LB and RB (scenario A5) produces lowest paddy yield, lowest economic gains and the highest number of affected farmer families. This is due to the distribution of deficits on both banks. Under this scenario 3207 and 3725 more farmer families are affected when compared with A4 and A3 scenarios, respectively. Figure 3.6 (bottom) shows that RB command area has more paddy areas. Therefore by prioritizing RB (scenario A4), it could be expected that rice production could be increased. However analysis indicates that the increase is marginal and amounts to less than 2% on average for the period of 1990 to 1999. Scenario A3 represents the prioritization of LB over RB. Due to the presence of cash crops in the LB the economic gain in this scenario is increased by 15.3 million dollars when compared to A5 and 5.0 million dollars when compared to A4 during the course of 10 years.

Analysis of these results indicate that prioritization of allocation between the left and the right banks is required to reduce the number of farmer families affected by irrigation deficits. Prioritizing one command area over the other could be decided based on the preference for increasing overall economic gains or maximizing rice production. Either choice will not significantly change the number of farmer families affected.

Effects of Demand Management Strategies

Three demand management options were tried out in the test basin: 1) modification of hydropower demand, 2) crop diversification and cultivation technique change, 3) irrigation system upgrade. The impacts of these modifications were evaluated based on the socio-economic and environmental outcomes.

Modification of Hydropower Demand

The national power demand is represented by a variable power demand curve that corresponds to the average demand over the simulation period. Two other power demand curves were developed based on the observed inflows to reservoir R 1. The first is a *fixed power generation flow*, where a fixed flow is channeled through the hydro turbines. The highest possible fixed power generation flow was derived on a trial-and error basis. An initial flow rate was incrementally increased until the annual water deficits were equal or lesser than the deficits under variable curve. The second power demand curve is derived based on the seasonal variation of flows into reservoir R 1. This *step-wise demand curve* is designed to utilize the peak flows into the reservoir for increased power generation. Under this demand curve power generation is carried out at an increased capacity from April to June and from October to December each year. The power generation is reduced to a minimum from mid June to September. The peak turbine flow values were decided on a trial and error basis considering the reservoir R 1 inflows, power plant capacity and the downstream reservoir's (R 2) capacity to store the increased power generation outflows. The three demand curves derived are shown in Fig. 3.8 (top).

Three model scenarios were designed to evaluates the three operation modes: Variable (scenario B1), Fixed (scenario B2), and Step-wise (Scenario B3). The power outputs for the three scenarios are shown in Fig. 3.8 (bottom). The variable and

(A)

(B)
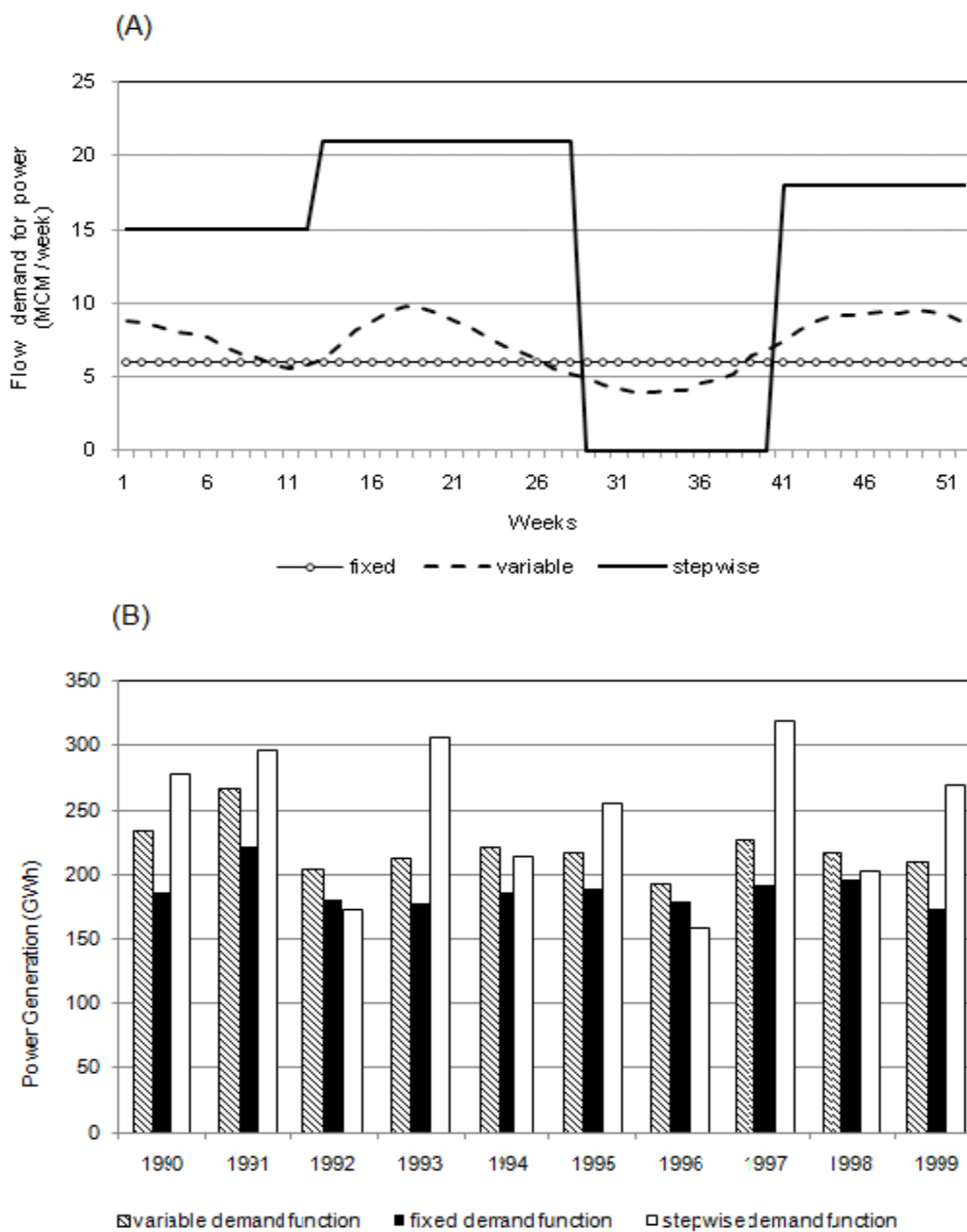
Fig. 3.8 A) Three power demand curves B) Annual power outputs corresponding to scenarios B1, B2, and B3

the step-wise power demand curves generate more power output compared to the operation under fixed demand curve. As expected operation under the step-wise demand curve generates the highest power output, by utilizing the peak inflows to the reservoir.

This operation mode allows up to 20% increase of power output compared to the variable mode of operation and up to 40% increase compared to the fixed mode of operation. Moreover this operation mode does not create additional irrigation deficits at the downstream system IRR 2 during the simulation period, when compared with the fixed mode.

Crop Diversification and Cultivation
Technique Change

Two methods for increasing the farm irrigation water use efficiency are considered. Previous study (Chapter 2) results show that a complete conversion from paddy to banana crop enables a 50% water saving. Other studies (Molle et al. 2005) have indicated cultivation technique change could help increase water use efficiency by 40%. Assuming a 50% water use efficiency increase at system IRR 1, an analysis was carried out to find the effects of crop diversification and cultivation technique change on reservoir R 1 water users. Scenarios B4 and B5 corresponds to the 100% and 50% of current water use at IRR 1, respectively.

The reduced irrigation demands at IRR 1 do not affect the hydropower generation. This is due to the large differences between the volumes of water used. However, efficient water use in IRR 1 has positive impacts on the irrigation water supply to system IRR 1 itself. Scenario B5 indicates reduced shortages and reduced vulnerability (volume and time) in irrigation supplies to IRR1. The system reliability and resilience have

increased (Table 3.4). Consequently the numbers of affected farmer families in IRR1
have reduced (Fig. 3.9).

Irrigation System Upgrade

Seepage losses from earthen canals contribute to a major portion of irrigation
water demand. According to literature canal lining with hard surfaces could reduce up to
60% of the seepage volume (Goldsmith and Making 1989). Studies in the Walawe basin

Table 3.4 Performance indices of irrigation supply at IRR1 under B4 and B5 scenarios

Performance Index	Scenario B4	Scenario B5
Shortage Index (SI)	0.25	0.07
Reliability (REL)	0.72	0.97
Resilience (RES)	0.42	0.83
Volume vulnerability (Vv) [MCM]	0.85	0.43
Time vulnerability (Vt) [weeks]	9	2
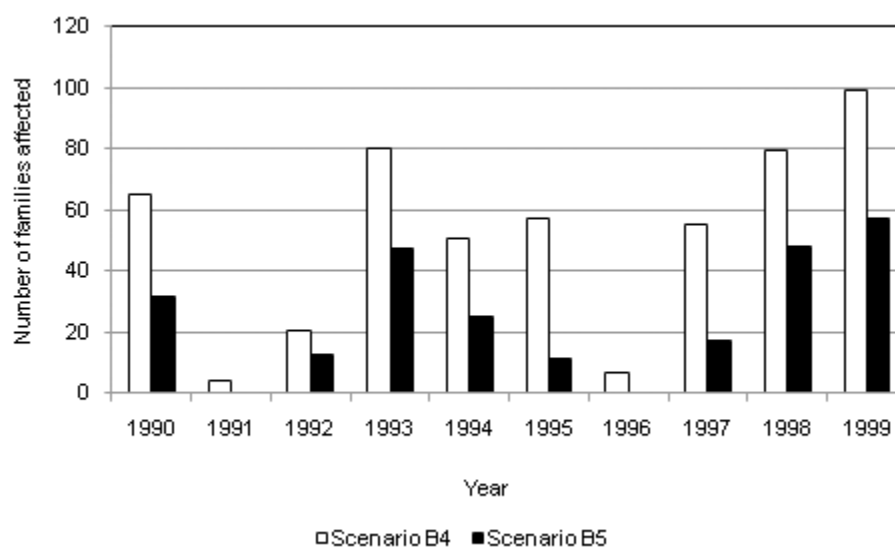
Fig. 3.9 Comparison of number of farmer families affected by irrigation deficits in
system IRR 1 under scenarios B4 and B5.

have indicated seepage up to 75% of supplied volume in dry months (Meijer et al. 2006).

In addition to the conveyance losses, irrigation techniques employed can lead to

significant water losses as well. On farm irrigation efficiency can be improved by

adapting sprinkler or drip irrigation methods for selected crops (Vickers 2002).

Technically advanced and costly methods (micro irrigation, canal lining, etc.) of

efficiency improvement may not be feasible in the conditions of developing world river

basins. However a number of low cost maintenance approaches (clearing of plant growth

inside earthen irrigation canals, reduction of spills and leakage with timely repairs to flow

regulatory structures, etc.) could be applied to achieve significant water savings.

The effects of irrigation system upgrade were analyzed, assuming a 30%

irrigation water use reduction in improved irrigation systems. Scenarios B6 and B7

correspond to 100% and 70% of current irrigation water use in the irrigation systems. The

water demands of all water users below reservoir R 2 are completely satisfied in the

upgraded scenario B7. A two fold increase in annual flows is observed at the lowest

reaches of the river. This enables to fulfill the environmental flow requirements at the sea

outfall. This also implies the availability of water for increased industrial and municipal

demands in future.

Summary and Conclusions

The use of a priority based water allocation method was demonstrated using a

simulation method. The Walawe river basin in Sri Lanka was selected as the test basin.

The findings and conclusions from the study can be summarized as follows:

1) The impact of social and environmental aspects is more profoundly felt in water resources management in the developing world. A number of preconditions required for the functioning of a market based water allocation are absent in the developing countries. In contrast, public managed, priority based allocation could be devised to address a number of social and environmental issues observed in river basins of the developing world.

2) Computer based simulation and optimization models can be successfully used to evaluate the socio-economic impacts of water allocation policies. Generic modeling software based on the network flow algorithms could be easily adopted to represent site specific river basin conditions. Highly efficient computation algorithms are available for solving complex water allocation issues.

3) Priority based water allocation is useful in considering the social and environmental concerns in water allocation. The study demonstrated how traditional water right of farmers could be protected while preserving the benefits of hydropower generation by selecting the priority order. It also demonstrated how the number of farmer families affected by water deficits can be minimized using prioritization of allocation.

4) In the face of dwindling supplies, demand management strategies could be successfully used to reduce water shortages. Results of analysis showed that by modifying the hydropower demands to utilize the peak flows, significant gains in power production can be gained with the currently available generation facilities. The study demonstrated how efficient irrigation techniques and crop diversification can help reduce the irrigation system vulnerability and increase system resilience to shortages.

5) The study highlights the importance of irrigation system upgrade in mitigating the observed water deficits. The current irrigation infrastructure and irrigation techniques contribute to major water losses. Water saved through irrigation system upgrade can improve the water availability for other water use sectors as well.

The results of the study provide a wide range of information on various aspects of basin water management. However some of the limitations of the current study can be summarized as follows: 1) The analysis was carried out under limited data availability. 2) The study does not contain a comparison of economic gains from priority based allocation with a market allocation. 3) The study does not consider the water quality demands.

This study uses a range of data sets available from different data sources. Some of the data sets are not comprehensive. The simulation model requires all the data sets used in the model to be in similar time steps. However in practice this is not always achievable. The simulation time period was limited to 10 years due to limited availability of overlapping periods of measured climatic and hydrologic data. The limited data availability seriously affects the reliability of model outputs. However this is a common feature for most river basins in the developing world (ADB 2007; Stephenson and Peterson 1991).

As discussed in previous sections, the priority based allocation method does not warrant the most economically efficient water allocation among all water users. The intent of priority based allocation is to achieve allocations that are more acceptable in terms of social, economic and environmental aspects. However it would be useful to

compare the economic benefits of a priority based simulation, with an economically efficient optimization approach under the same supply-demand conditions.

Water quality is gaining importance in the water demands of many of the developing countries. As water sources are over exploited and polluted, maintaining the required water quality is becomes increasingly difficult. However due to the costly and elaborate measurement procedures, water quality measurements are much rare in the developing world. Due to extremely limited data availability water quality aspects of allocation were not considered in this study.

Some specifics of water allocation in rural river basins in the developing world were discussed in this paper. The importance of allocation principles that consider social and environmental aspects was highlighted. The use of priority based allocation and the use of demand management strategies were demonstrated.

Although Walawe is a river basin located in a developing country, the knowledge gained through this study can be used to improve water allocation in river basins of the developed world where similar or different socioeconomic conditions may prevail. In the western United States water rights are assigned according to the prior appropriation rule. The initial ownership of water rights may exchange between the users based on market transactions. However at a given point of time each of the water user in the system will have a priority based allocation determined by the seniority of the water right. The methodology described in this work can be employed by the state water managers to evaluate the socio-economic impacts of a given appropriation of water rights. Similar methodology could also be employed by the water users in making decisions on trading of their water rights.

References

Adhikari KR (2001) Diagnosis of the east Rapti River basin of Nepal. In: Integrated Water Resources Management in a River-Basin Context. Proceedings of the Regional Workshop. Malang, Indonesia

Asian Development Bank (ADB) (2007) Recent advances in water resources development and management in developing countries in Asia: Asian water development outlook 2007. Discussion Paper, Colombo, Sri Lanka

Bruns BR, Meinzen-Dick R (2005) Frameworks for water rights: an overview of institutional options. International Food Policy Research Institute (IFPRI), Washington DC

Carraro C, Marchiori C, Sgobbi A (2005) Applications of negotiation theory to water issues. World Bank Policy Research Working Paper, The World Bank, Washington DC

Dinar A, Rosegrant M, Meinzen-Dick R (1997) Water allocation mechanisms-principals and examples. World Bank working paper 1779. The World Bank, Washington DC

Durbin EP, Kroenke DM (1967) The Out-of-Kilter algorithm: A primer, memorandum, RM-5472-PR. The RAND Corporation, Santa Monica, CA

Freebairn J (2003) Principles for the allocation of scarce water. The Australian Econ Rev 36(2)203-212

Goldsmith H, Making IW (1989) Canal lining: from the laboratory to the field and back again. Institute of Irrigation Studies, Southampton University, UK

Helmi M (2002) Water management in the upper sub-basin of the Inderagiri River basin in Indonesia. In: Inter-sectoral management of river basins. Proceedings of International Workshop on Integrated Water Management in Water-Stressed River Basins in Developing Countries, International Water management Institute (IWMI), Sri Lanka

Howe CW (1978) The effects of water resource development on economic growth: The conditions for success. In: Utton AE, Teclaff L (ed) Water in a developing world. Westview Press, Boulder, Colorado

Hsu NS, Cheng WC, Cheng WM, Wei CC, Yeh WWG (2008) Optimization and capacity expansion of a water distribution system. Adv Water Resour 31:776-786

Jain SK, Singh VP (2003) Developments in water science, water resources systems

planning and management. Elsevier Science B.V, The Netherlands

Johansson RC (2000) Pricing irrigation water: a literature survey. Unpublished. The World Bank, Washington DC

Koundouri P, Howe C (2003) Introduction, The economics of water management in developing countries. Edward Elgar publishers, UK

Lee TR (1999) Water management in the 21St century: the allocation imperative. New Horizons in Environmental Economics. Edward Elgar Publishers, Massachusetts

Mahaweli Authority of Sri Lanka (MASL) (1995) Review report on feasibility study for Walawe left bank irrigation upgrading and extension project, Vol. 3. Nippon Koei Co., LTD, Tokyo, Japan

Meijer K, Boelee E, Augustijn D, van der Molen I (2006) Impacts of concrete lining of irrigation canals on availability of water for domestic use in southern Sri Lanka. Agr Water Manage 83:243-251

Meinzen-Dick R, Mendoza M (1996) Alternative water allocation mechanisms-Indian and international experiences. Econ Polit Wkly 31(13):A25-A30

Merry D (1996) Institutional design principles for accountability in large irrigation systems. Research Report 8, International Irrigation Management Institute (IIMI), Sri Lanka

Molle F, Jayakody P, Ariyaratne BR, Somatilake HS (2005) Balancing irrigation and hydropower: a case study from southern Sri Lanka. Research Report 94, International Water Management Institute (IWMI), Sri Lanka

Perera BJC, James B (2003) A generalized water supply simulation computer software Package –REALM, Hydrol J 26(1-2)

Repetto R (1986) Skimming the water: rent-seeking and the performance of public irrigation systems. World Resources Institute, Washington DC

Ringler C, Vu HN, Cai X, Linh HG (2002) Water allocation policies for the Dong Nai river basin in Viet Nam: an integrated perspective. Proceeding of Conference on Irrigation Water policies: Micro and Macro Considerations, 15-17 June, Agrdir Morocco

Rosegrant MW, Binswanger HP (1994) Markets in tradable water rights: potential for efficiency gains in developing country water resources allocation. World Dev 22(11):1613-1625

Rosegrant MW, Schleyer RG, Yadav SN (1995) Water policy for efficient agricultural diversification: market-based approaches. Food Policy 20(3):203-223

Schramm G (1978) Human-institutional factors. In: Water in a developing world, Utton AE, Teclaff L (ed). Westview Press, Boulder, Colorado

Stephenson D, Peterson MS (1991) Water resources in developing countries. Elsevier Science Publishers, Amsterdam, The Netherlands

Thobani M (1998) Meeting water needs in developing countries: resolving issues in establishing tradable water rights. In: Easter KW, Rosegrant MW, Dinar A (ed) Markets for water potential and performance. Springer Publishers, GmbH, Berlin

United Nations (2000) Principals and practices of water allocation among water-use sectors. Water Resources Series No. 80. United Nations, New York

Van Koppen B, Geordano M, Butterworth J, Mapedza E (2007) Community-based water law and water resource management reform in developing countries: Rationale, contents and key messages. CAB International

Vickers A (2002) Agricultural water use and efficiency measures. In: Water use and conservation, WaterPlow Press, Amherst, MA

Wade R (1982) The system of administrative and political corruption: canal irrigation in South India. J Dev Stud 18(3):287-328

Wurbs RA (2003) Water rights analysis package (WRAP) Modeling system reference manual. Texas Water Resources Institute, TR-255

Wurbs RA (2005) Comparative evaluation of generalized river/reservoir system models. Texas Water Resources Institute, TR-282

Yates D, Seiber J, Purkey D, Annette Huber-Lee (2005) WEAP21-A demand-priority and preference driven water planning model part 1: model characteristics. Water Int 30(4):487-500

Appendix

Formulae for assessing the water allocation system performance:

Shortage Index (SI)

$$SI = \frac{100}{M} \sum_{t=1}^{M} \left(\frac{AS_t}{AD_t}\right)^2$$

where   M   – number of years in the planning g horizon

   AD_t - annual water demand in the year t

   AS_t - annual water shortage in the year t

Reliability (REL)   and   Resilience (RES)

$$REL = 1 - \frac{\sum_{j=1}^{K} d(j)}{T} \qquad\qquad RES = \left(\frac{1}{K} \sum_{j=1}^{K} d(j)\right)^{-1}$$

where   K   - number of failure events

   T   - total number of time intervals

   d (j)   - duration of the j [th] failure event

Volume vulnerability (Vv)   and   Time vulnerability (Vt)

$$V_v = max\ (S_j) \qquad\qquad V_t = max\ (d_j)$$

where

   S(j) and d(j) - magnitude and the duration of the j [th] failure event

CHAPTER 4

ANALYSIS OF CLIMATE CHANGE IMPACTS ON BASIN WATER RESOURCES

AND EVALUATION OF MITIGATION MEASURES: A CASE STUDY FROM

WALAWE RIVER BASIN IN SRI LANKA[1]

Abstract Demands for freshwater resources in river basins are ever increasing and the water managers are faced with the problem of allocating limited water among competing users. While usability of available water is reduced by pollution the supply is endangered by impacts of climate change. Due to the complex nature of the interactions between climate and the hydrologic cycle, impacts on the water resources are hard to predict. Moreover the predictions from current generation of climate models are applicable to vast spatial resolutions. However the water resources impact assessments and management decisions are required at the catchment and sub-catchment levels. In addition, decisions related to water resources allocation need to incorporate local hydrologic conditions. While improvements in the general circulation model (GCM) predictions and establishment of their relationships with local hydrologic variables are awaited, impacts of climate change on water resources need to be assessed utilizing the available tools. This work investigates such possibility with available GCM predictions, a statistical downscaling method, and a water allocation simulation model for a rural river basin in the developing world. The water supply and demand situation of the basin is analyzed under baseline and future climatic conditions. Mitigation measures for shortages and methods for utilizing favorable flows are analyzed.

---

[1] Coauthored by Neelanga Weragala, Jagath J. Kaluarachchi, and Vladimir U. Smakhtin

Introduction

Water Resources Management
and Climate Change

Climate change aggravates the stresses imposed on water resources management

by population growth, urbanization, industrialization and environmental degradation. It is

argued that rising water demands due to human development outweigh the impacts of

global warming on the world's water resources (Vorosmarty et al. 2000). However an

increasing number of evidence indicates that global water use will be negatively affected

by the predicted changes in climate and the corresponding impacts on water supply

(IPCC 2008; USGS 2000; WMO 2007).

Globally an increasing number of people are living in water stressed basins,

where the annual per capita water availability for domestic, industrial and agricultural

water needs is bellow 1000 m^3. The growing population in the developing world requires

increased food production. As per the estimates of FAO, a 0.6 % annual expansion of

irrigated area is expected in the developing countries until 2030. Currently about 40 % of

global agricultural output is produced by irrigation (Fischer et al. 2006), which consumes

more than 70 % of global water withdrawals. The amount of water available for

irrigation is declining due to urban, industrial, energy and environmental demands. The

same human development processes that place increased demands on water have

impacted the world climate. Due to the increase in greenhouse gases in the atmosphere

the global mean temperatures are predicted to increase, resulting in significant changes in

the global hydrologic cycle (IPCC 2008).

Climate Impacts on Hydrology
and Water Resources

The global climate and the hydrologic cycle are tightly related. Water in its three phases contributes in different ways to define Earth's climate. The increase of global temperature is expected to increase evaporation from seas. The high temperatures enable the atmosphere to hold additional water vapor which in turn acts as a greenhouse gas (GHG) creating a positive feedback. In addition, the predicted change in the cloud cover is expected to affect earth's radiation budget resulting in a range of effects from cooling to warming. Precipitation is predicted to increase at higher latitudes and over tropical oceans. Different GCMs produce different geographical patterns of precipitation change. The agreement among GCMs is less with regard to precipitation than with temperature. However, many models conclude that intensity and variability of precipitation will increase (Trenberth et al. 2003; WMO/GWP 2009). Predictions on evaporation generally follow the rainfall and also share similar uncertainties (Gautier 2008). The vegetation cover over the land surface further complicates the estimation of evaporation. The melting of the ice on land and sea is also expected to create a global mean sea level rise between 14-44 cm by the end of this century (IPCC 2007). The above discussion exemplifies the complicated nature of interactions between climate change and the hydrologic cycle.

The surface runoff and the groundwater are two important components of the hydrologic cycle that define the availability of water for human use. The magnitude of runoff predictions also contain vast differences among GCMs. However many models agree that, changes in flow seasonality can be expected in the river basins where much of

the winter precipitation falls as snow, whereas in rainfall dominated basins an increase in

seasonality is observed (IPCC 2007). Due to the increased variability in river flows the

occurrence of floods and droughts increase (Wetherald and Manabe 2002). According to

simulations using the HADCM3 GCM the global land surface in extreme drought is

expected to increase between 10-30% under SRES A2 scenario (Burke et al. 2006). The

impacts of climate change on groundwater have shown very site specific results (IPCC

2007). Climate change impacts are felt both on the quality and quantity of groundwater

resources. Generally groundwater levels have shown higher correlation with precipitation

than with temperature. Change in precipitation seasonality affects the aquifer recharge

patterns (Brouyere et al. 2004). The sea level increase can impact the saltwater intrusion

in to coastal aquifers (Hiscock and Tanaka 2006). These impacts on surface and

groundwater resources limit their availability for use in different water use sectors.

Climate Change Impacts on
Water User Sectors

The changes in climate affect both availability and demand for water. Moreover

there exist a number of non-climate related factors that affect the future water demand.

Therefore water management decisions need to be made considering these climate and

non-climate driven impacts on supply and demand.

Agriculture sector, the largest of global consumptive water user, provides a good

example of climate change affected supply and demand. Rainfed agriculture which

consists of about 80% of agriculture globally is directly affected by the change in rainfall

patterns. As a result the global cereal production is expected to reduce between 5 - 40%

by 2100 (Aggrawal 2009; Easterling et al. 2007). In China and India, the countries with

largest irrigated areas worldwide, net irrigation demands are expected to change by +2 to +15% and -6 to +5% in 2020 (IPCC 2007). The water demands from domestic, industrial and other sectors are expected to be less affected by climate driven changes when compared to non-climate driven changes.

The non-climate drivers of water demand change include population growth, urbanization, industrialization, economic policies, lifestyles and society's valuation of environmental requirements. Developing countries with rising populations, income levels and energy use are expected to be increasingly affected by climate change related water scarcity issues (Cosbey 2009). Two thirds of world population is expected to live in the developing countries by 2025 (Pinstrup-Andersen et al. 1997). Consequently the urban and industrial water demand in the developing world is expected to be twice as high when compared to the countries in the developed world (Rosegrant et al. 2002; Vairavamoorthy et al. 2008). Moreover the urban and industrial growth along with improved living standards creates increased demands for energy. The developing countries are projected to account for almost 60 percent of the global increase in commercial energy consumption by 2020 (U.S. Congress 1991). Hydropower generation which remains an attractive option for energy production in the developing world is also affected by the predicted changes in climate. The above mentioned estimations indicate impact of climate change (along with the non-climate driven changes) on the water demands for agriculture, domestic use, industry and energy production.

Assessing the Impacts of Climate Change
 on Water Resources

Assessment of climate change impacts on water resources provides important

information for the efficient allocation of water and sustainable management of the water

resources. A framework for climate change impact assessment prepared under IPCC

suggests seven steps in conducting such assessment (Carter et al. 1994). The "selection of

analysis methodology" and "definition of climate scenarios" are identified as the most

important steps in hydrological and water resources impact studies (Arnell 1996).

Hydrological models can be used to analyze the hydrological implications of changes in

climate inputs. Water allocation and distribution models utilizing these hydrologic

responses can be used to evaluate effects on different water user sectors. The current

study uses the Water Evaluation and Planning (WEAP) model (a network flow simulation

model) to evaluate a priority based water allocation strategy under a baseline and future

climate scenarios.

An impact assessment compares the conditions before and after a change. The

baseline period of assessment should be selected based on the objective of the study as

well as the data availability (Arnell 1996). The selection of a future climate scenario

could be based on the general circulation model (GCM) outputs. The current generation

of GCMs simulates the atmospheric circulation, and also represent the relationships and

fluxes between atmosphere, land surface and oceans. The climate (temperature, rainfall

etc) predictions are available for different levels of GHG concentrations in the

atmosphere. While GCM predictions on climate are available as far as to the end of

current century, the selection of a future assessment period for water allocation can be

constrained by other factors. Evaluating the water management options for future requires predicting not only the changes in supply, but also the changes in demands and objectives of water allocation. Although numerous techniques are available for predicting the future water demands in different water use sectors, their use is limited by the data availability and the results are considered relatively uncertain (Stakhiv 1993).

Mitigating the Impacts of Climate Change

Most water management systems have experience in coping with natural variability in supply and demand as well as maximizing the system reliability. The options for mitigating the impacts of climate change are similar. Enhancement of supply (new reservoirs, dams, pipelines, diversions, treatment plants, etc.) and management of demand (efficiency increase, modifying demand, land use change, etc.) remain important tools in minimizing the climate effects (USGS 2000). Traditionally planning, design and operations of water projects have relied on historic data. Adaptation to climate change requires incorporation of anticipated but at times highly uncertain predictions in to water management process. Improved monitoring of climate induced hydrological impacts (floods, droughts, water quality, etc.) is required to incorporate local conditions to the planning and management of water projects. A greater communication among stakeholders (climatologists, hydrologists, water managers, and users) is also essential. For planning and management purposes the economic valuations of climate change impacts and adaptation options are required. In the case of developing countries, where financial resources for adaptation and mitigation of climate impacts are limited, efficient use of available water supply infrastructure through management improvements play an

important role. Water supply and distribution models are widely used to simulate the consequences of climate change and evaluate mitigation measures (Arnell 1996). The current study demonstrates the use of a water allocation model, to analyze the climate change impacts and evaluate possible mitigation measures in a rural river basin of the developing world.

Study Area

Climate, Topography, and Hydrology

Walawe River basin has a catchment area of 2471 Km^2. It is located in southern Sri Lanka, which is an island in the Indian Ocean located between 5° 55'- 9° 55' N and between 79° 42' - 81° 52' (Fig. 4.1). Topography of the island consists of a central mountainous area surrounded by extensive lowlands. The warm climate of Sri Lanka is moderated by the ocean winds. The rainfall pattern in Sri Lanka is influenced by the vast Asian Monsoon system. Four climate seasons are observed in the country: two monsoon and two inter-monsoon seasons. Monsoon winds from the northeast, carrying moisture from the Bay of Bengal generate the North-Eastern monsoon (NEM) during December to February. First inter monsoon season (FIM) occurs during March and April. Winds originating from the south- west carrying moisture from the Indian Ocean generate the South West monsoon (SWM) rains from May to September. The second inter monsoon (SIM) season occurs from October to November.

The mean temperature in the country ranges from 15.8° C in the central mountains to a high of 29° C in the north east coast. The average annual temperature in
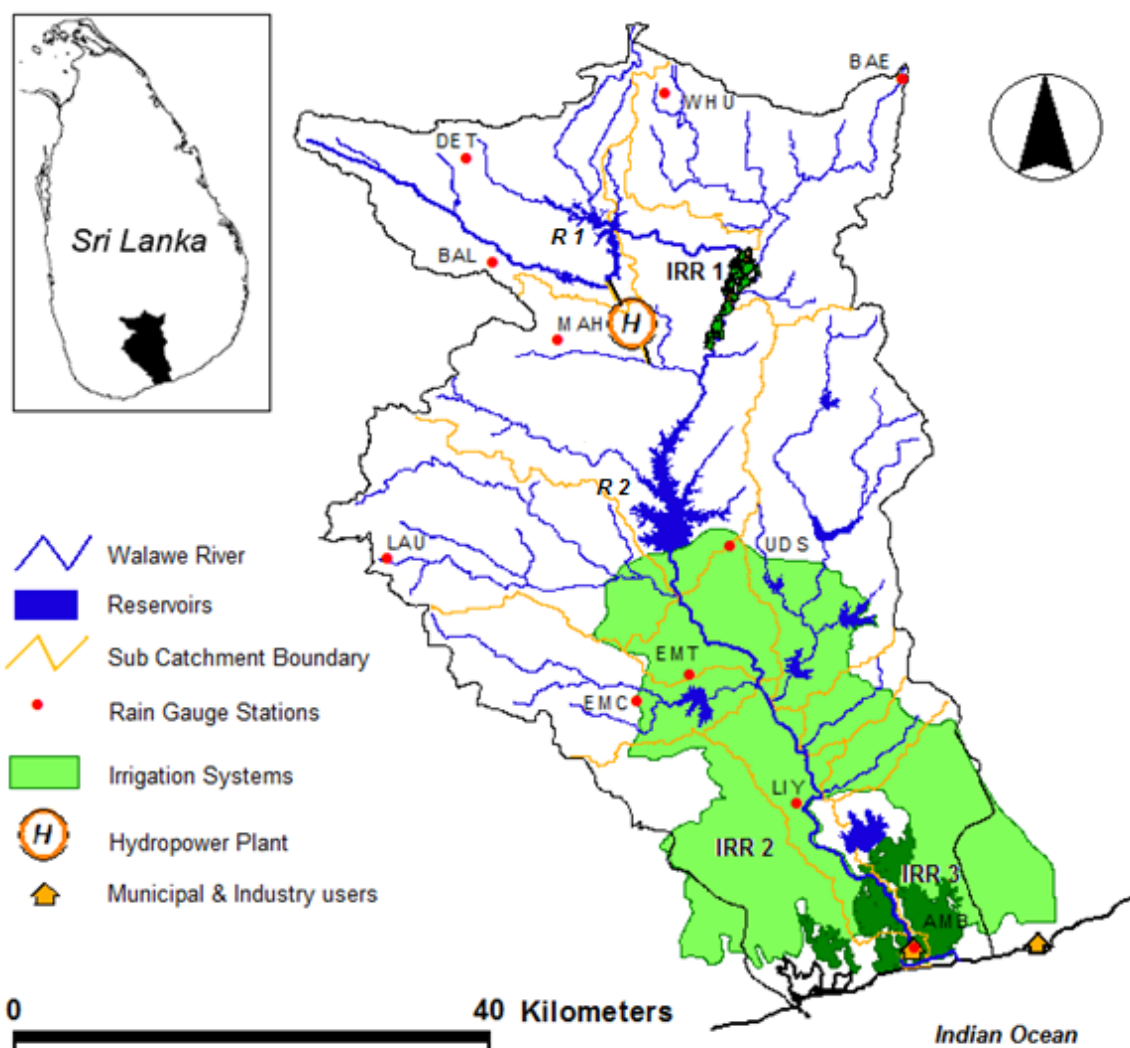
Fig. 4.1 Physical layout of the Walawe river basin, its water resources and demand sites

the country varies between 26°-28° C. The temperature variation between day and night ranges from 4°-7° C. The rainfall and temperature patterns of Sri Lanka are found to be significantly influenced during El-Nino Southern Oscillation (ENSO) episodes (Suppiah 1996; Zubair et al. 2008).

The headwaters of the Walawe River basin are located in the aforementioned central mountainous area of the island, and receive rainfall during both SWM and the

NEM seasons. The average annual rainfall over the basin varies between 2000 mm and 1000 mm from upper reaches to the coastal plain. The average annual reference evapotranspiration in the basin is about 1700 mm. The groundwater recharge in the basin is estimated to be about 10% of the annual rainfall. The major land use types in the basin are: forests (29%), scrubland (26%), shifting cultivation (23%), rice (10%) and home gardens (12 %) (Droogers 2004). The Walawe River runs about 106 Km, mostly along the flat plains before it reaches the Indian Ocean. Under natural conditions the average annual discharge to sea is about 1 billion cubic meters.

Water Users and Demands

The major water use in the basin is irrigated agriculture. One minor and two major irrigation systems IRR 1, IRR 2, IRR 3 (Fig. 4.1) are located in the basin. The main crop grown in these systems is rice. Rice is cultivated during two cropping seasons attuned to the occurrence of monsoon rainfall. The average annual irrigation demand in the basin for the 1990-99 period equaled 790 MCM. The irrigation demands of the two major irrigations systems are supplied by reservoir R 2 (Fig. 4.1). This reservoir has a capacity of 268 MCM.

The main function of the reservoir R 1 at the upper reaches of the basin is hydropower generation. In addition it acts as a flood control reservoir. This reservoir has a capacity of 278 MCM. Power station HYDRO at this reservoir is capable of generating about 400 GWh annually. The average annual flow allocated to hydropower generation equaled 350 MCM during the 1990-99 period.

Other main water users in the basin include municipal and industrial water users. These water uses are concentrated in the urban areas of the basin near the coast. These water use sectors indicate a rapid increase in demand due to urban population growth and industrial development. During the period of 1990-99 the population in the basin exceeded 600,000. However the municipal water demand was represented only by the number of households supplied with pipe borne water. This consisted of a small fraction of the total population. Therefore during the period of 1990-99 the annual municipal water demand increased from 32 MCM to 50 MCM. Majority of urban water demand was supplied by the shallow groundwater wells. The annual industrial demand rose from 5 MCM to 15 MCM during the same period.

Climate Change

Analysis of historical records indicates changes in temperature and rainfall over Sri Lanka. During 1961-1990 the mean air temperature increased at a rate of 0.016° C annually. The Hambantota meteorological station within the Walawe river basin indicated a temperature increase of 0.5° C from 1981-2000 (Droogers 2004). Reduced rainfall has been observed during NEM and SIM seasons, while increased variability in rainfall is reported during NEM season (Basnayake et al. 2002; Jayatillake et al. 2005).Changes in rainfall trends are observed (based on 30 year rainfall records) over the mountainous regions of Sri Lanka, where the headwaters of Walawe River originate (Herath and Ratnayake 2004). Identifying the past trends in climate, a number of attempts have been taken to predict the future rainfall and temperatures using GCM simulation outputs. Outcomes from these studies indicate an approximate 2.5 °C (SWM

season) and a 2.9°C (NEM season) increase (above the 1961-90 average temperatures) by year 2100. Predictions of rainfall vary over a wide range. In addition, Sri Lanka falls in to the IPCC's category of *vulnerable small island nations* which are predicted to face multiple effects of climate change, like sea levels rise, severe droughts and floods (IPCC 2001).

Methods

Selection of Scenario Time Periods

Two simulation periods were selected for comparison of climate change effects on basin water users. The baseline period consisted of 10 year period from 1990 to 1999. The selection of which, is based on the availability of meteorological, hydrological and water demand data. Usually the future time period is selected based on the requirement of the analysis. However the prediction of water demands by different water user sectors is again limited by the data availability. Analyzing the past trends, available development plans and population growth in the basin a ten year period (2041-50), leading to the middle of the next century is selected as the future time period of this analysis.

Selection of GCMs and Future
Climate Scenarios

The effects of future climate on basin water resources are assessed based on the predicted changes in precipitation and temperature. Coupled atmosphere-ocean general circulation models (AOGCM) consider a wide range of physical processes occurring on land, in the atmosphere and in the upper ocean layer, when simulating the response of the global climate system to increasing greenhouse gas (GHG) concentrations. The Fourth

Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate

Change (IPCC) identifies a number of GCMs that simulate global climate, under a range

of GHG emission scenarios. While majority of these models agree on their predictions on

global mean values, significant differences are observed in the predictions at local levels.

This is due to the structural differences in models and individual model biases (IPCC-

AR4 Chapter 10). This study incorporates rainfall and temperature predictions by 5

GCMs: CGCM3 (Boer et al. 2000), HADCM3 (Gordon et al. 2000), ECHAM5

(Roeckner et al. 2003), CSIRO (Gordon et al. 2002) and PCM (Washington et al. 2000).

In general the atmospheric component of these GCMs has a spatial resolution of 2.75°

latitude and 3.75° longitude at the equator. This corresponds to a grid cell of

approximately 275 km by 375 km. From each GCM, precipitation and temperature value

of the grid cell closest to the study area are selected for the analysis.

The observed historical mean annual rainfall over the study area could be

compared with the estimations by the 5 GCM models to identify the GCM model that

best simulates the basin rainfall. However the annual values may not indicate how best

the monthly variation is represented. Therefore an analysis is carried out based on the

model error in estimating historical monthly means of rainfall and temperature for the

period of 1961-90. Weights are assigned to each model based on the correctness in

estimating historical values. Separate model weights are calculated for rainfall and

temperature. Model selection for the analysis is based on these weights.

A GCM predicted value of a climatic variable for a given grid cell, represents the

average value of that variable over that grid cell area. Generally significant scale

differences exist between the GCM grid cell area and the headwater areas of the river

basins for which the river flows are needed to be predicted (Leavesley and Hay 1998).

Effects of meso-scale forcings (topography, coastline, inland water bodies and

vegetation) on the local climate are not reflected in the GCM predictions (Arnell 1996;

Giorgi and Mearns 1991). Generally two basic approaches are used to incorporate the

influence of finer scale topographic and land cover features in to GCM predictions:

dynamic and statistical downscaling (Wilby and Wigley 1997; Xu 1999). Dynamic

downscaling refers to regional climate models (RCM) nested within the GCMs. The

statistical downscaling requires establishing empirical relationships between GCM

variables at grid scales with the surface variables at sub-grid scales (Wilby et al. 1999).

Several attempts to investigate the South Asian monsoon dynamics using RCMs are

available in literature (Ashfaq et al. 2009; Kumar et al. 2006). However due to the

unavailability of RCM simulation data for the specific study area, a conventional

downscaling method was adapted for this study. Details of using this method for

downscaling precipitation and temperature are described in sections below.

The IPCC climate scenarios are based on four qualitative storylines that describe

how the future will develop: A1, economic-global; B1, environmental global; A2,

economic regional; and B2, environmental regional. Six scenario groups are derived from

these four categories (families). One group each in A2, B1, B2, and three groups within

the A1 family, characterizing alternative developments of energy technologies: A1FI

(fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel) (IPCC

2000).While population growth in the study area remains low the land use changes and

energy use are increasing. In the absence of one single scenario that describes the

development conditions within the Walawe river basin, a range of scenarios were

analyzed. Accordingly, Scenarios A1B, A2 and B1 are selected for this analysis.

Characteristics of the selected emission scenarios are given in Table 4.3 in the appendix.

Estimation of Future Water Availability

Water availability in the basin under future climate is assessed by calculating

runoff generated by the predicted rainfall. Each of the five selected GCMs provides 30

year mean monthly rainfall under A1B, A2 and B1 emission scenarios on a global scale.

The rainfall flux through the GCM grid cell that is closest to the Walawe River basin is

selected for this analysis.

A downscaling approach described in Droogers (2004) and Alcamo et al. (1997)

is used in this work. In this approach the future rainfall is estimated by multiplying the

measured historical precipitation by a transformation factor. This transformation factor is

established in the following manner. The GCM estimations of 30 year mean monthly

rainfall values for the historical (1961-1990) and the future (2040-2069) periods are used

to calculate the ratio of precipitation change between the historical and future time

periods. This calculation generates a set of 12 mean monthly ratios (transformation

factors) of GCM estimated rainfall change. Precipitation in each year of the historic time

period (1961-90) multiplied by the relevant monthly transformation factor now

corresponds to the precipitation in future period (2040-69). According to this

correspondence, the observed precipitation of 1962-71 can be used to predict the

precipitation in 2041-50 using the calculated transformation factors. This procedure is

described by Equation 1 in the appendix. This method does not allow incorporating the

change in rainfall variance (Xu 1999). However in the absence of high resolution

predictions of rainfall data for the region, the above approach was selected.

In tropical climate runoff is generated by rainfall infiltrating into and flowing

through soil and the rainfall incident on the saturated areas. The increased temperatures

and rainfall can result in loss of soil organic matter, soil cracking and formation of gleyed

layers within soil (Arnell 1996). This in turn will affect the moisture holding capacity as

well as infiltration of rainfall through soil. However in the absence of information on the

relation of soil properties and climate change, future runoff is calculated using runoff

coefficients estimated for the baseline period. Analysis of available land use maps

indicates that, the forest covered mountainous headwater areas of this basin have

remained mostly unchanged during the past 40 years. Therefore, it is assumed that the

baseline land cover/land use conditions remain unchanged in the basin.

In addition to future inflows, changes to the storage capacity also affect the

surface water availability in the basin. While capacities of the current reservoirs in the

basin may remain largely unchanged, the water losses due to reservoir surface

evaporation may change under future climate. Evaporation from reservoirs is estimated

for current and future temperatures based on the heat-budget method using Penman 1948

formula (Vardavas and Fountoulakis 1996). These evaporation losses are incorporated in

the corresponding simulation scenarios.

Estimation of Future Water Demands

Irrigation Water Demand

A major component of irrigation water demand is the crop water requirement for evapotranspiration. Evapotranspiration from crop fields is influenced by energy supply, vapor pressure gradient and wind. It is also affected by the plant physiology (Allen et al. 1998). While the maximum energy supply for evapotranspiration is not expected to change, net radiation will be affected due to changes in cloud cover, atmospheric vapor content, CO_2 content and surface temperature. The increased CO_2 concentrations affect the plant growth rates and stomatal conductance rates (Arnell 1996; Drake 1992; Kimball et al. 1993). Moreover crop biomass increase under elevated CO_2 concentrations is dependent on a range of factors: crop type, crop water stress, nutrient supply etc. Recent studies have revealed that changes in temperature and precipitation can offset the effects of increased CO_2 concentration on plants (IPPCC 2007). Therefore the overall effects of climate change on crop evapotranspiration remain uncertain.

Detailed crop modeling under a range of models and range of water availability conditions are required clarify this uncertainty. Literature reveals some efforts that have satisfactorily modeled the crop response for CO_2 effects (Asseng et al. 2004; Ewert et al. 2002). However within the scope of this study only two aspects of climate change on irrigation demand is evaluated: 1) the effects of temperature increase on crop evapotranspiration water demand and 2) the change in rainfall over the crop growing areas (change in the rain-fed portion of crop water requirement).

Future changes in average surface temperature over the study basin are estimated based on the predictions of 5 GCMs described above. Downscaling is similar to the

above mentioned procedure for downscaling rainfall (Alcamo et al. 1997; Droogers 2004). The GCM predicted changes in temperatures are estimated as the difference of model predictions for historic and future periods. This offset value should be then applied to the measured historic values to calculate future temperatures. The relevant transformation is shown in Equation 2 in the appendix.

For the purpose of estimation of reference evapotranspiration, it is assumed that minimum and maximum deviations in future mean monthly temperatures remain similar to the current conditions. The FAO Penman-Monteith method is used to estimate reference evapotranspiration. Other climatic parameters required are estimated based on the predicted temperature. Crop evapotranspiration is calculated using the current crop coefficients assuming no change.

The crop growing areas in the study basin are both rain-fed and irrigated. The rainfall on command and surrounding areas plays a major role in defining irrigation requirement. The current cropping seasons are scheduled to coincide with the two monsoon seasons. Consequently the current irrigation demands correspond to the rainfall deficiency during the cropping season. GCM predicted changes in magnitude and seasonality of rainfall will have a significant effect on the irrigation water demand. To estimate this effect, rainfall incident on the largest command area in the basin was calculated under current and future rainfall scenarios.

Hydropower Water Demand

The amount of power generated at reservoir R 1, is based on the national power demand. However, along with hydropower there are a number of other power generation

sources that supply the national power demand. Statistics indicate that the role of

hydropower in supplying the national demand in the country has been declining due to

uncertainty related to rainfall availability (Somatilake 2002).Moreover, the power station

at reservoir R 1 feeds into a national power grid along with other hydropower stations,

and the actual distribution of future demand among these hydropower stations remains

unknown. However the total predicted demand is expected to exceed the supply

generated by the available power generation facilities. Therefore it can be assumed that

power station at reservoir R 1 will operate utilizing the future inflows up to the limit of

storage and generation capacities of current infrastructure. The implications of future

supply and demand pattern changes on hydropower generation were studied in this work.

Three annual water demand patterns for hydropower production were analyzed:

variable, fixed and step wise (2-step). A variable water demand curve represents the

average monthly variation of demand for hydropower within a year. This demand curve

was derived using actual hydropower water demands for the period of 1999-2003 at

reservoir R 1. A fixed demand curve assumes a fixed flow rate through turbines. A range

of flow rate values were evaluated to establish a constant rate that maximizes the power

output under the available inflow patterns and storage. The step wise (2-step) water

demand curve was designed to demonstrate the possibility of using the increased flows to

increase power production in the future. The step wise demand curve utilized in the

simulations of this study represents two levels of demand that correspond to the high and

low inflows periods of the year. The turbine flow rates for the high and low steps were

estimated through a trial and error basis. Derivation of optimal hydropower demand

curves that maximize the power generation falls outside the scope of this paper.

The power generated under each demand curve is a function of the turbine flow discharge, the hydraulic head under which the turbines operate, and the efficiency of the turbine-generator group. Usually the amount of energy generated by a power plant is expressed by the energy rate function (ERF) (Diaz et al. 2000). The ERF calculates the amount of energy (in KWh) generated by the power plant per unit volume of water (in m^3) per unit time (in 1 hour). A simplified ERF is derived by assuming the effective head as a linear function of reservoir storage. An ERF for reservoir R 1 is derived based on a range of water surface elevation and corresponding energy storage data available.

Municipal and Industrial Demands

The future water demand for municipal and industrial sectors in the Walawe basin are estimated based on the proposed developments in each sector. The annual water demand in municipal sector in 1990 was 5.72 MCM. According to the Southern Area Development Master plan (GOSL 1997) this demand will increase up to 9.11 MCM by 2015 under the current development plans. In the absence of a better information, the same annual rate of increase was assumed to predict the water demands for the simulation period from 2041-2050. However these values represent the domestic water requirement of a small fraction of population that is supplied with pipe borne water. Majority of population in Walawe still relies on shallow groundwater wells to satisfy their domestic water demand. A comparison of future groundwater recharge and domestic water demand was carried out based on the ECHAM5 rainfall predictions, population projections and per capita water consumption in the basin. In the industrial sector annual water demands

increased from 32.2 to 42.1 MCM during the baseline period. Water demands for the

future simulation period were estimated assuming the same annual rate of increase.

Estimation of Climate Change-
Related Water Deficits

The water evaluation and planning (WEAP) model (Yates et al. 2005) is used to

simulate the water allocation among water users in the basin under future climate

conditions. This model has been successfully used to analyze the water allocation options

in river basins with competing water users under current and future climate conditions

(McCartney et al. 2009). WEAP is a network flow-based water allocation model. The

water supply, demand locations and the conveyance paths in the basin are modeled as a

network consisting of arcs and nodes. The inflows to the network, its physical features

and water demand at each user node are input to the WEAP model. Each model

configuration is called a scenario and allocation simulations can be carried out on a daily,

weekly, monthly or annual time step. Model runs can be carried out for multiple year

simulation periods in a continuous manner. WEAP allocates water to each user node

based on the priority order, flow and storage availability, equity and other network

constraints. Unmet demand (deficit) at each user node is calculated at each simulation

time step.

Model runs for the future period were carried out under the three SRES

scenarios described above (A1B, A2, B1) for each of the five selected GCMs. A model

time step of one week was selected according to data availability. At each run the WEAP

model simulates 10 consecutive years of water allocation. The model simulated deficits

under baseline and future time periods are compared to assess the effects of climate change on water demands.

Analysis of Climate Change-Related
Water Deficits

Comparison of Rainfall Seasonality

It has been observed that generally GCMs predict a change in the monsoon rainfall pattern for the South Asian region (IPCC 2007; Kripalani et al. 2007). To verify this fact and its effect on the future distribution of monthly rainfall over the study area, the mean monthly rainfall predicted by the 5 models was compared with the baseline (1990-1999) period rainfall. Observations for this analysis were used to explain the simulation outputs and design mitigation measures.

Comparison of Runoff Variability

Increased variability of rainfall and the corresponding shifts in runoff are important in determining the basin water availability. A flow duration curve shows the proportion of time the river flows exceed a given discharge. By examining the slope and the shape of the flow duration curve, the variability of flows can be assessed. The change in flow variability in the baseline and the future period is evaluated using flow duration curves for the Walawe River and one of its major tributaries.

Climate Change Incorporated Future
Water Deficits

Unmet water demands in each water use sector are analyzed to identify climate change incorporated future water deficits. Water deficits are analyzed under monthly and weekly time steps to identify the impacts of seasonal variations in rainfall and

temperature. Feasible management and structural solutions are proposed considering the

site conditions, for mitigating the identified deficits. Additional model scenarios are run

to test the usefulness of proposed mitigation measures.

Results and Discussion

Assignment of Model Weights

Figure 4.2 compares the measured mean annual rainfall over the study area with

model estimations, for the historical period 1961-1990. On an annual basis HADCM3

and ECHAM5 models predict mean rainfall values closer to the basin observations.

Further, an analysis of mean monthly values (rainfall and temperature) is carried out.

Each of the 5 GCMs show different degrees of success in estimating the historical

monthly means of rainfall and temperature in the study basin. Weights are assigned to the

models accordingly. The ECHAM5 and the PCM models that carry weights 0.31 and

0.26 perform better in estimating the mean monthly rainfall for the historical period. For

the purpose of this study, these two models are considered to have a higher confidence in

predicting future rainfall. The CSIRO, CGCM3 and HADCM3 models carry the weights

of 0.17, 0.13, and 0.13, respectively.

The PCM model with a weight of 0.40 performs best in estimating the mean

monthly temperature for historical period. The CSIRO, ECHAM5, CGCM3, and

HADCM3 models carry weights of 0.25, 0.14, 0.13, and 0.08, respectively. The CGCM3

and HADCM3 models do not perform well in estimating both monthly rainfall and
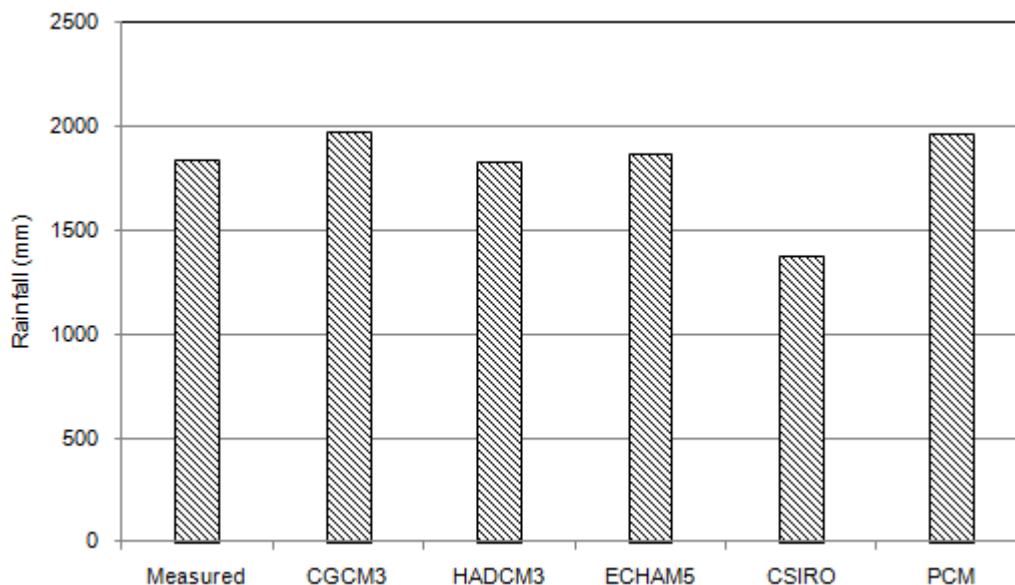
Fig. 4.2 Comparison of measured mean annual rainfall over the Walawe river basin (column 1) with estimates of five GCM models for the historical period 1961-90

temperature. These results indicate the suitability of a multi-model approach when model predictions vary in a wide range.

Assessment of Basin Inflows

The mean annual rainfall (MAR) over the Walawe River basin is analyzed under future rainfall to identify the changes in basin inflows. Figure 4.3 compares the MAR for baseline and future time periods as predicted by the five GCM models.

According to all five models, the MAR in Walawe basin will either increase or remain at the baseline level under all three emission scenarios. The high confidence rainfall models ECHAM5 and PCM predict a MAR of about 2000 mm for A1B and B1 scenarios. This is a 25% increase from the baseline scenario. The ECHAM5 model shows more variability across emission scenarios when compared to the PCM model. Therefore
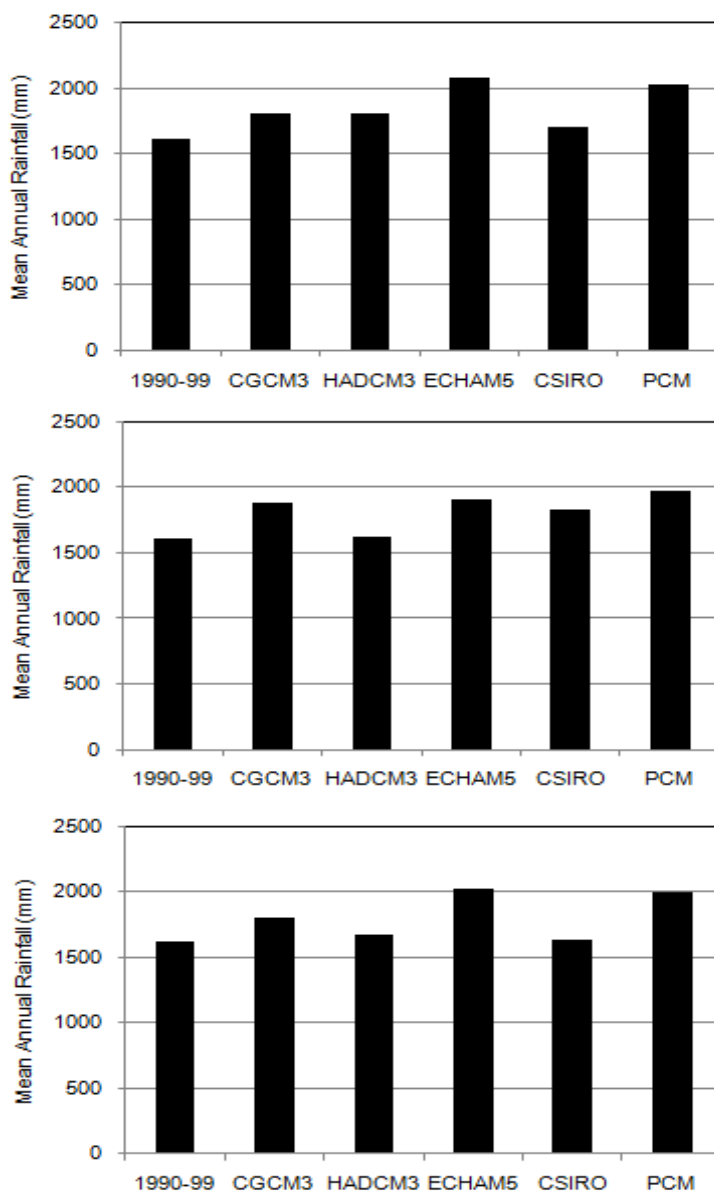
Fig. 4.3 Mean annual rainfall over the Walawe river basin. Values for the baseline period (1990-99) compared with predictions for 2041-50 period under A1B (top), A2 (middle), and B1 (bottom) emission scenarios

ECHAM5 predictions are better suited for identifying a wider range of climate change

impacts on basin water resources.
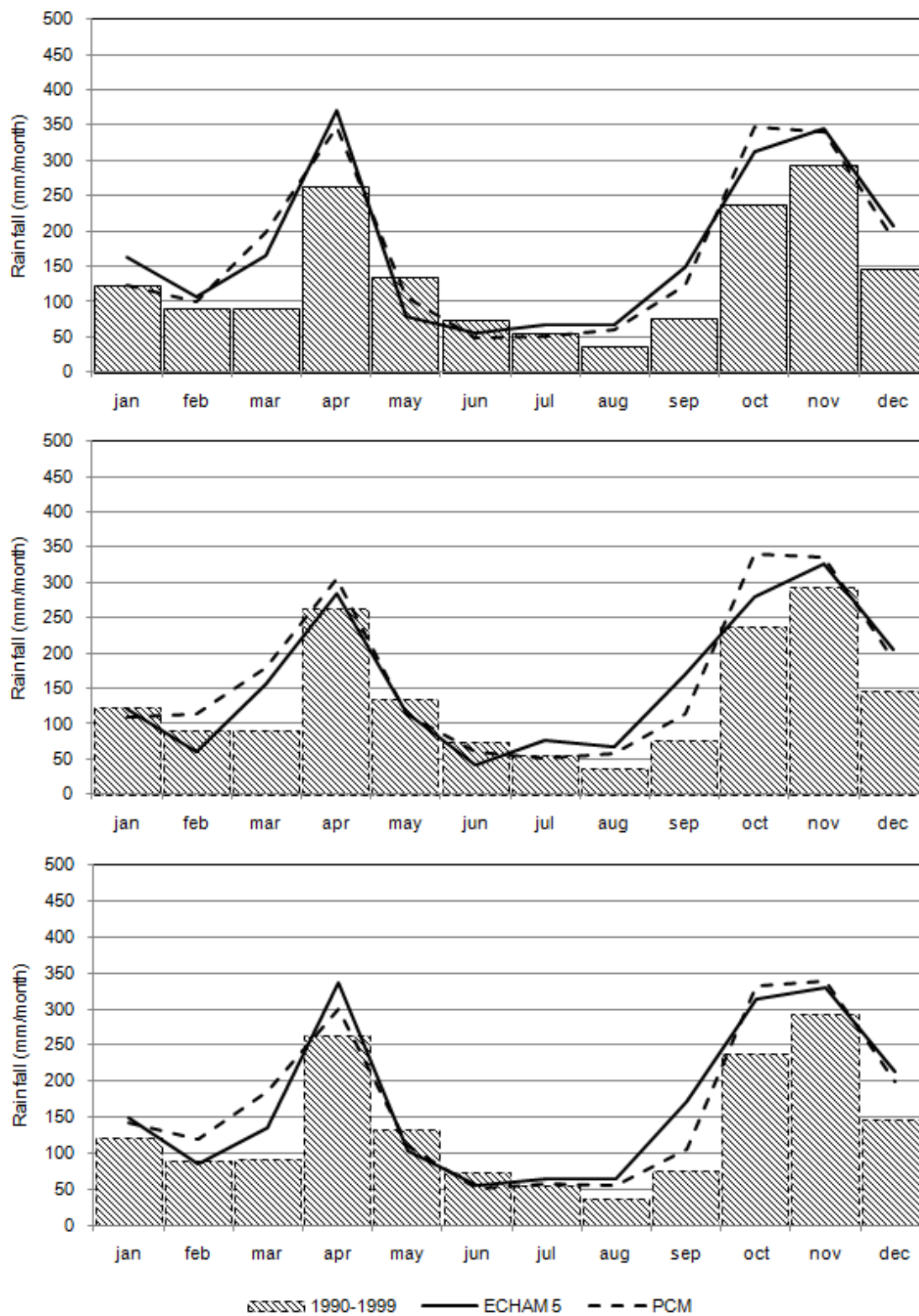
Fig. 4.4 Comparison of mean monthly rainfall over the Walawe basin under baseline and future climate scenarios (A1B-top, A2-middle, B1-bottom): ECHAM5 and PCM

The seasonal variation of rainfall within a year has significant impact on water allocation. To identify this effect, mean monthly rainfall predictions by the ECHAM5 and PCM models are compared to the baseline period. Figure 4.4 shows the mean monthly rainfall over the Walawe river basin. Both models predict an increase in mean monthly rainfall during the last five months of the year under the three emission scenarios. Moreover the rainfall is predicted to increase in the first inter monsoon season during March and April.

The magnitude of runoff variability under the baseline and future (EHCAM5-A1B) scenarios are compared in Fig. 4.5, for the headflows of the Walawe River and for one of its right bank tributaries. In both cases the future flow duration curve lies above the baseline curve, indicating that a given magnitude of flow will be exceeded more frequently in the future. For example, a head flow discharge of 20 m^3/sec (Fig. 4.5-top) that is exceeded 22% of the time in baseline scenario will be exceeded 30% of the time in future. However the presence of similar slopes in the flow duration curves indicates no significant changes in variability between baseline and future flows.

Effects of Climate Change on
Basin Water Users

The effects of climate change are assessed by estimating the water deficits in each water use sector under baseline and future scenarios. Water supply and demand in each water user sector is estimated incorporating the predicted rainfall and temperature changes as well as the projected *demand expansion* of that sector. For the purpose of clarity in the analysis that follows, predictions from ECHAM5 and PCM models are used. These two models show similar rainfall and temperature response for the study area
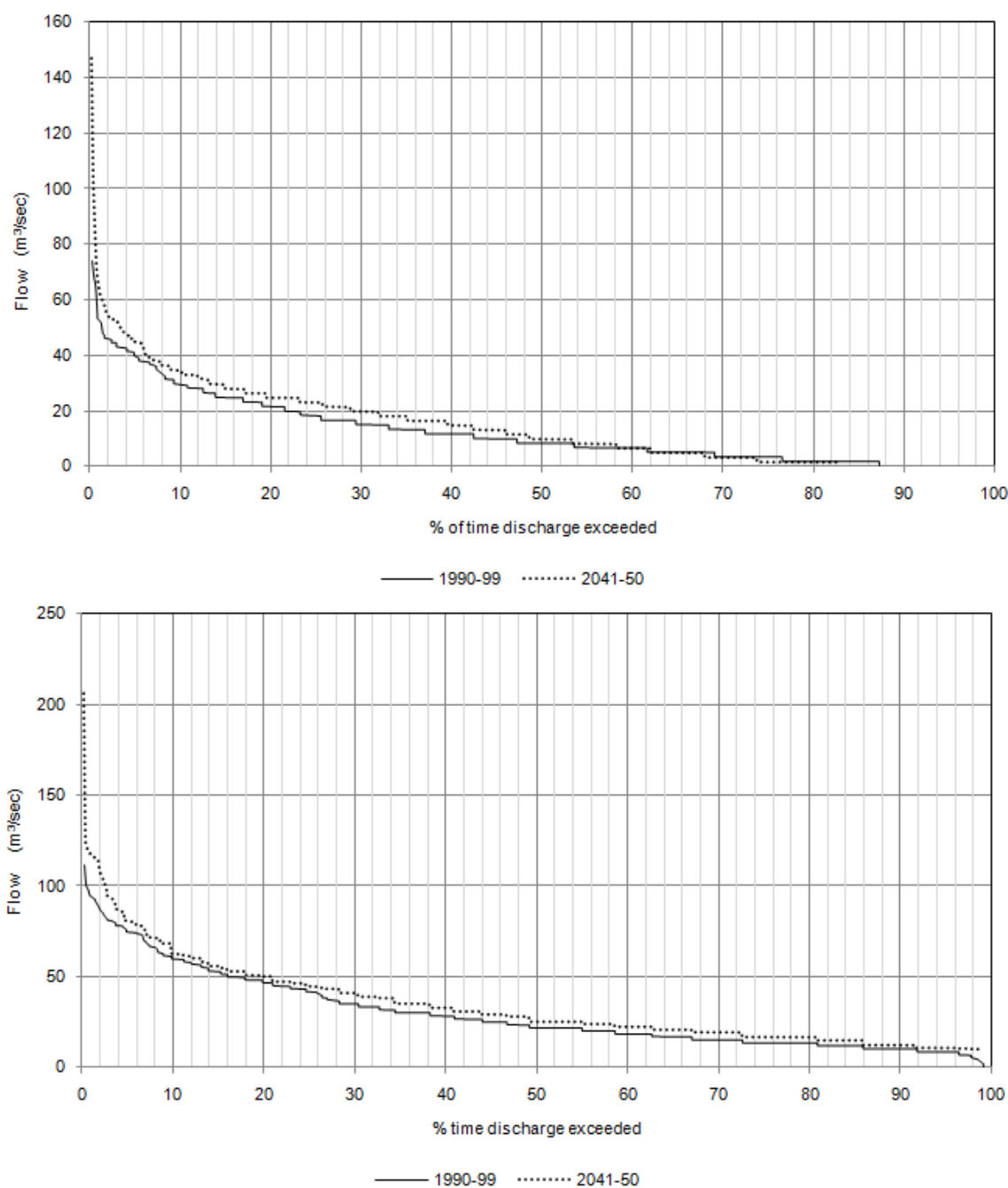
Fig. 4.5 Flow duration curves for Walawe River headflows (top) and right bank major tributary (bottom) : baseline and ECHAM5-A1B scenarios

under emission scenarios A1B and B1. Therefore only predictions for scenarios A1B and A2 are used in this analysis. Results are shown only for the combination of GCM model and emission scenario that has most extreme effects on the water use sector analyzed.

Irrigation Water Demands

In estimating the irrigation water demands for the Walawe River basin, several assumptions are made. First, the total irrigable area in the river basin is assumed to be utilized during the baseline period, and no *expansions of agricultural areas* are anticipated for the future time period. This is based on the available information on land resources of the area. The irrigation infrastructure, the water distribution and water use efficiencies, cropping patterns, irrigation and farming techniques for the future period are assumed to be same as in the baseline period. Therefore any change in the irrigation demand in future is attributed to crop evapotranspiration demand driven by climate change.

The evapotranspiration demand is expected to increase due to temperature effects. The highest temperature increase is observed under the A2 scenario. However according to EHCAM5 predictions this increase is less than 2° C for the study area. Analysis indicates that increase in evapotranspiration requirement for a 2° C increase in temperature in the study area is around 1 %. As described before the mean annual rainfall over the study area is predicted to increase according to most GCMs considered. Therefore the crop ET-related demand increase is expected to be offset by the increased rainfall over the command area.

In ECHAM5, scenario A1B predicts the highest precipitation and temperature

increase. Scenario A2 predicts the lowest precipitation increase along with a lower

temperature increase. To capture the effects of both precipitation and temperature
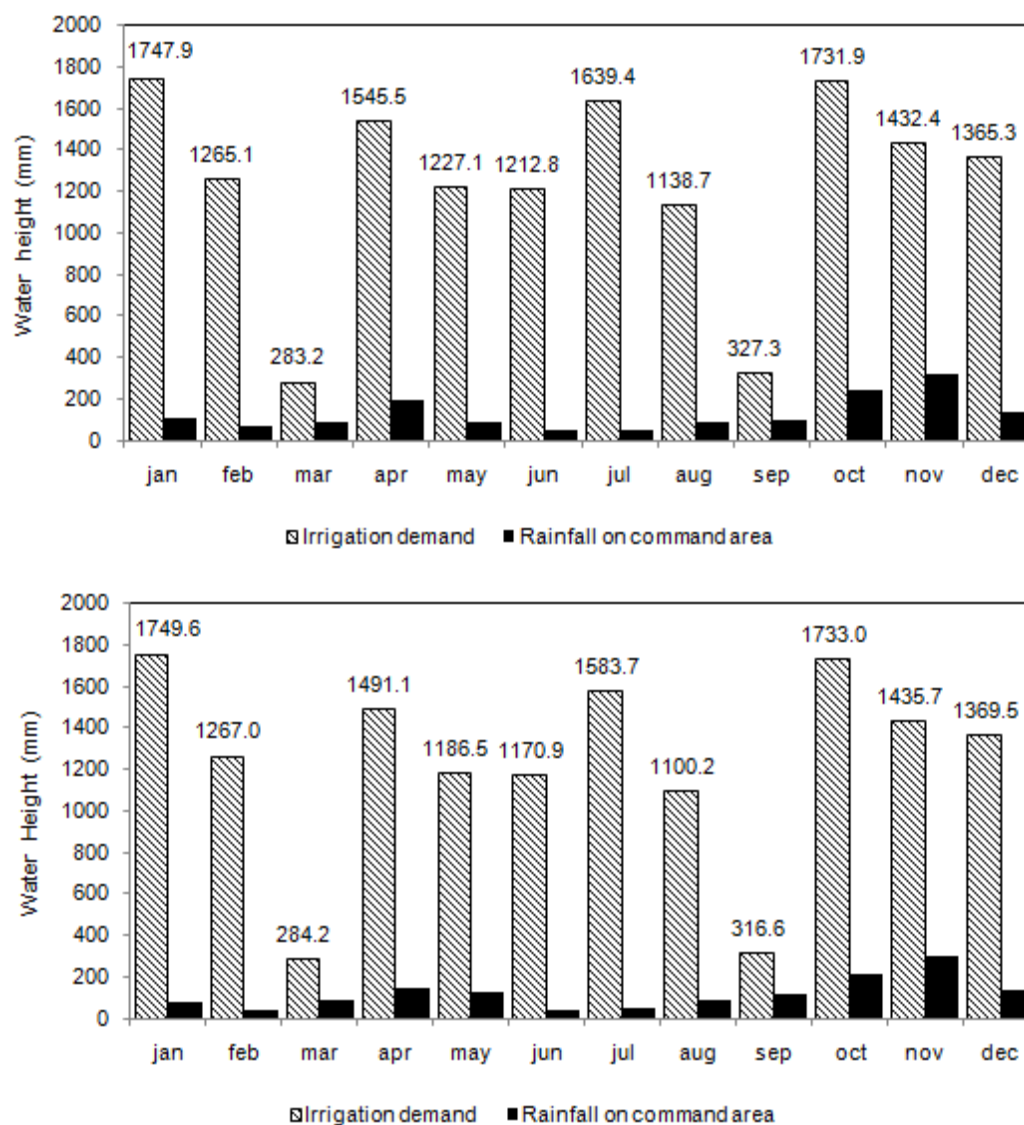
Fig. 4.6 Comparison of mean monthly irrigation demands (incorporating temperature effects) with mean monthly rainfall over the command area in IRR 2 right bank during 2041-2050 under SRES A1B (top) and SRES A2 (bottom) according to model ECHAM5

extremes on overall irrigation demand, two estimations were carried out under the A1B and A2 scenarios. The increased irrigation demand and the rainfall over the command area were calculated for the largest rice irrigation system (IRR 2 right bank) in Walawe Basin. Results are shown in Fig. 4.6.

Figure 4.6 compares the average rainfall and irrigation demand for the period of 2041-2050 as water heights over the command area for A1B (top) and A2 (bottom). Higher rainfall predicted in A1B scenario is evident in the months of March-April and October-November. The increase in ET (and the corresponding irrigation demand) due to elevated temperatures are evident in the period from April to August.

In both A1B and A2 scenarios, the average monthly rainfall incident on command area comprises between 3 – 36 % of the average monthly irrigation demand. Therefore this rainfall increase can easily surpass the 1 % demand increase due to temperature effects. However the overall agricultural water requirement is not significantly reduced by the rainfall increase during the crop growing months (May-August and October-January). Therefore supplemental irrigation is required even under the enhanced rainfall scenarios.

The water allocation options for Walawe irrigation systems are analyzed under baseline and future scenarios with WEAP model. The future scenario incorporates the rainfall and temperature effects as predicted by ECHAM5 model for A1B. The annual irrigation deficit in Walawe irrigation systems in the baseline period is about 1 % of the annual demand. This deficit occurs in the months of April and October, when land preparation of the rice fields occur. According to the simulations, during 2041-50 period
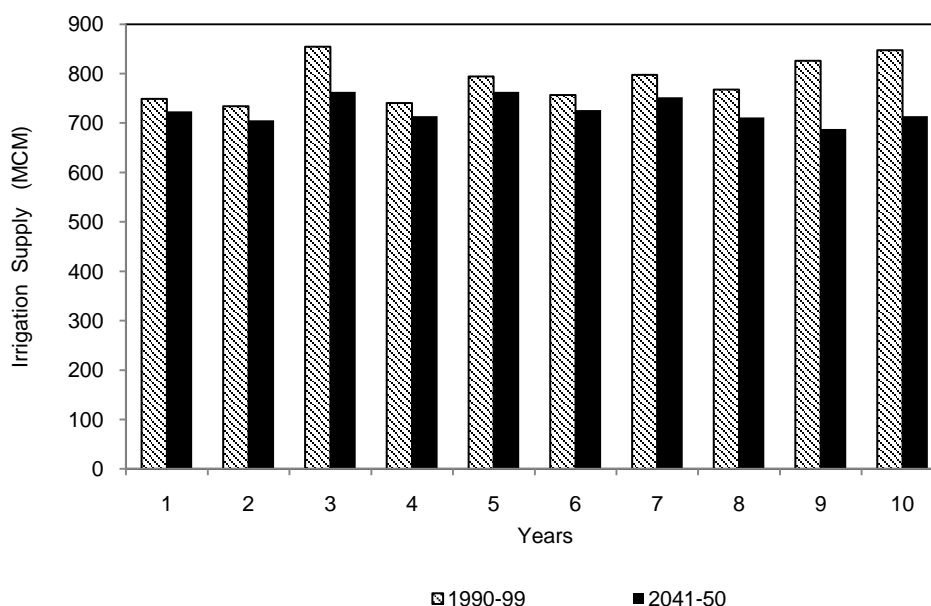
Fig. 4.7 Comparison of annual irrigation allocation in Walawe river basin under baseline and future (ECHAM5-A1B) climate scenarios

irrigation deficits do not exist. Moreover the irrigation allocation is reduced due to the increased rainfall on command area. Figure 4.7 compares the annual irrigation supply during the two periods. The reduction in irrigation requirement varies between 3 – 16 % during the 10 year period analyzed.

Hydropower Generation Water Demands

The annual inflows to reservoir R 1 under baseline and future scenarios are shown in Table 4.1. The A1B scenario shows an increase up to 40% and A2 shows an increase up to 30% compared to the annual inflows for the baseline period. However several years show a reduction of inflows to reservoir R 1. These correspond to the years of baseline period where inflows significantly surpass historical mean values. Hydropower

Table 4.1 Annual inflows to reservoir R 1 under Baseline (1990-99), A1B (2041-50), and A2 (2041-50) scenarios based on ECHAM5 predictions

Year	Baseline MCM	A1B MCM	(%) [a]	A2 MCM	(%) [b]
1	422.9	499.0	(18)	484.0	(14)
2	464.5	648.9	(40)	592.2	(28)
3	362.2	418.3	(16)	383.3	(6)
4	467.1	553.2	(18)	534.4	(14)
5	379.6	500.2	(32)	455.0	(20)
6	410.7	432.0	(5)	388.4	(-5)
7	313.7	387.3	(24)	366.3	(17)
8	514.5	423.1	(-18)	400.8	(-22)
9	371.4	404.3	(9)	360.4	(-3)
10	405.1	569.9	(41)	532.0	(31)

[a, b] Percentage of increase from Baseline scenario

generation at reservoir R 1 is further analyzed based on the A1B and A2 scenarios which show the highest and the lowest inflows in ECHAM5 predictions. The hydropower generation is analyzed under three power generation modes. In the *variable* mode weekly flows through the turbines vary according to the national power demand. A variable mode demand curve (weekly variation of flows through turbines) is developed based on the observed data on national power demands. In the *fixed* power generation mode the weekly flow through turbines is fixed to a given discharge rate. Fixed discharge rates which generate maximum hydropower output were estimated by trial and error method for the baseline and future scenarios. As seen from Fig. 4.4 both ECHAM5 and the PCM models predict an increase in precipitation in the latter part of the year. Therefore a third mode of operation called *2-step* mode was tested to verify the feasibility of increased power generation during the last five months of the year. Table 4.2 shows the total hydroelectric power generated (during the 10 year simulation period) under the three power generation

Table 4.2 Total hydroelectric power generated, unmet turbine flow demand and reservoir spills, under three power generation modes during the 10-year simulation periods

Power Generation Mode	Climate Scenario	Power Generation (GWh)	(%) [a]	Unmet Demand (MCM)	Reservoir Spills (MCM)
	Baseline	2762		0	0
Variable	A1B	3248	(18)	0	233
	A2	2982	(8)	75	78
	Baseline	2678		0	149
Fixed	A1B	3246	(21)	116	62
	A2	2982	(11)	36	132
	Baseline	2217		990	0
2-step	A1B	3173	(43)	399	0
	A2	2743	(24)	626	0

[a] Percentage of increase from Baseline scenario

modes in baseline and two future scenarios. The corresponding turbine flow deficits and reservoir spills are also shown in the table.

Results on Table 4.2 indicate that any of the three power generation modes can be utilized to generate a comparable amount of hydroelectric power. However the reservoir spills and amount of turbine flow deficits will vary. In A1B scenario (with highest inflows) the power generation is increased between 18 - 43 % from the baseline under the three power generation modes. In the A2 scenario (with lowest inflows) this increase is between 8 – 24 % from the baseline. The effects of fixed flow rates through the turbines are shown under the fixed mode of operation. A 6 MCM weekly discharge under the baseline conditions generates a maximum power output while supplying the demand with no shortages. However under A1B scenario, an 8 MCM weekly flow through the turbines generates the maximum total power output. Under A2 scenario, a 7 MCM weekly flow generates the maximum power output. A fixed water allocation for hydropower generation will create reservoir spills in all three scenarios. During the 10-year simulation

133

period, there are several occasions when turbine flow demand is not fully met under A1B

and A2 scenarios. As expected a 2-step power demand curve can utilize the increased

inflows during the latter part of the year to increase power generation. In this study a

simple 2-step demand curve was employed to evaluate the effects. An extensive analysis

with a range of stepwise demand curves is required to reveal the optimum operation.

However these preliminary results indicate that a step wise mode can be designed to

maximize the power generation while minimizing the reservoir spills.

Flood Control Requirements

In future the flood control capacity of reservoir R 1 will play an important role

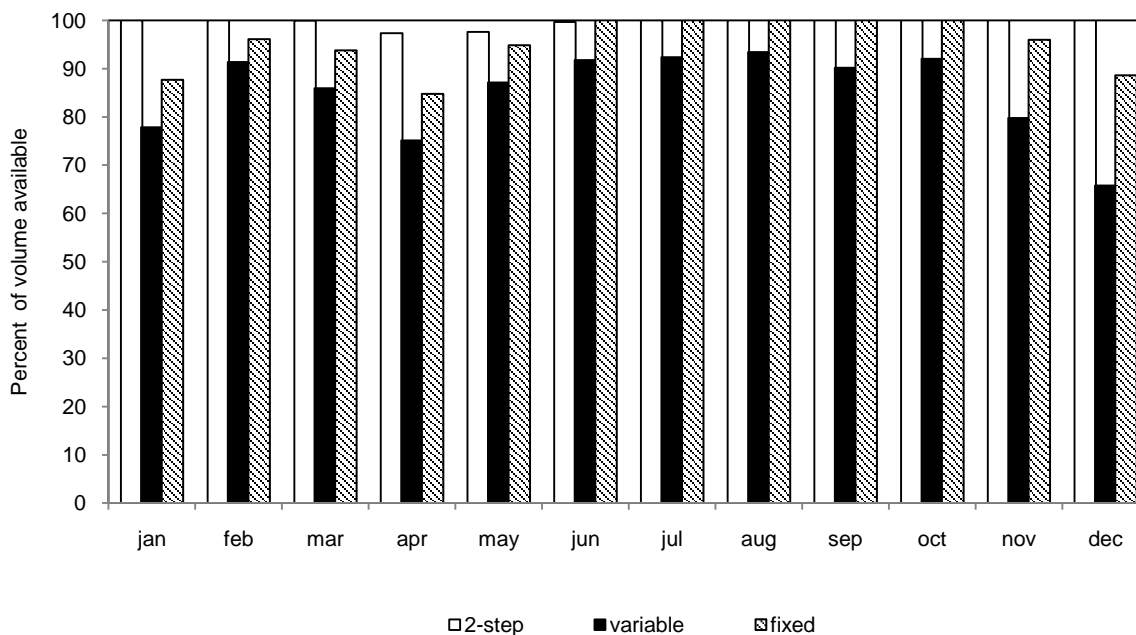due to the predicted increase in Walawe River flows. As the primary release of water

Fig. 4.8 Average monthly percentage of volume available in the flood control zone in reservoir R 1 under variable, fixed, and 2-step power generation modes for A1B emission scenario in 2041-50.

from the reservoir R 1 is for hydropower generation, its flood control capacity is

dependent on the selection of power generation mode. Figure 4.8 shows the average

monthly availability of flood control zone in reservoir R 1 under the three power

generation modes for A1B scenario.

Up to 60% of the reservoir's flood control zone is available throughout the year

irrespective of the power generation mode employed. Under the 2-step mode, the flood

control zone is completely available throughout the year, except in the months of April

and May. The fixed mode leaves the flood control zone empty during June to October.

For the rest of the year the flood control zone is available between 80 - 90% of its

capacity. The variable mode leaves the least available volume in the flood control zone

throughout the year. Finally this analysis indicates that under all three modes, more than

75% of the flood control zone remains empty during the months of January-February and

July-August that proceeds the high rainfall season.

Municipal and Industry Water Demands

The pipe borne municipal water demands in the study area are significantly low

when compared to the industrial demands and can be supplied under A1B scenario

without shortage. The overall domestic water demand (estimated based on an annual

population growth rate of 0.904 % and per capita water consumption of 50 liters/day)

ranged from 38.4 mcm/year to 41.6 mcm/year for the 2041-50 period. The estimated

groundwater recharge (10 % of rainfall over the catchment area) in both A1B and A2
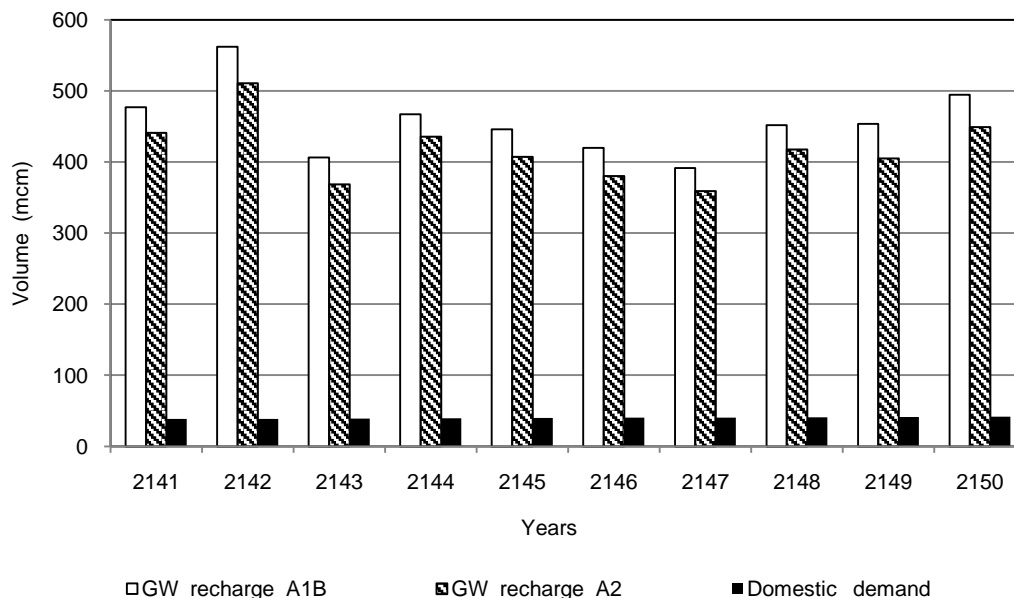
scenarios can easily surpass this demand (Fig. 4.9).

Fig. 4.9 Comparison of basin groundwater recharge with estimated domestic water demand in 2041-50 (under A1B and A2 scenarios: ECHAM5).
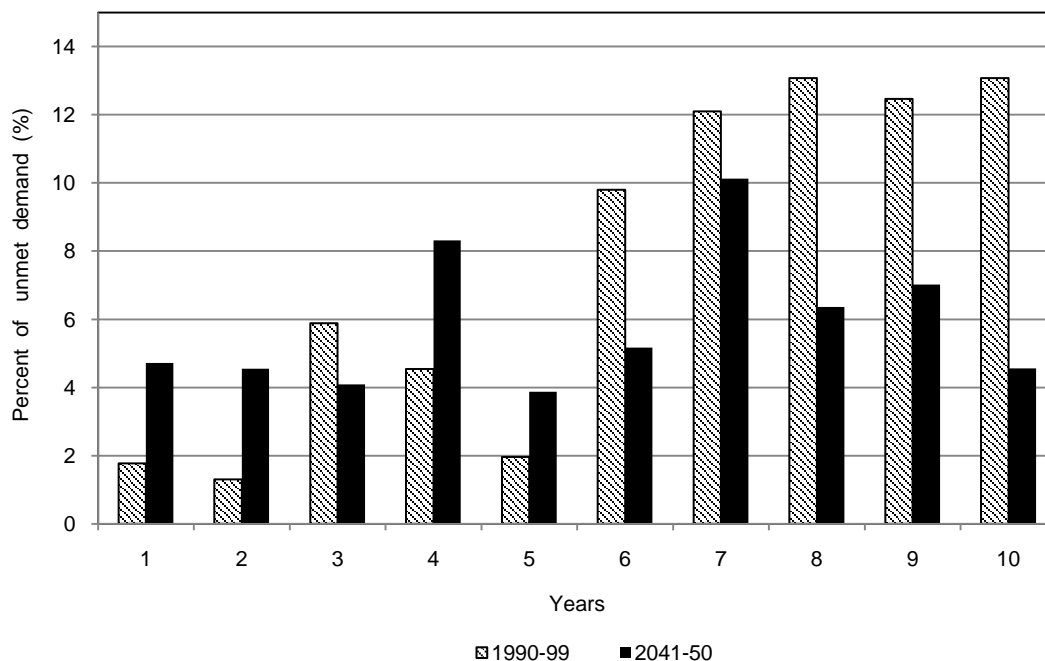
Fig. 4.10 Percentage of industrial demand deficits under baseline (1990-99) and future ECHAM5-A1B (2041-50) scenarios

Figure 4.10 shows the percentage of industrial water deficits under baseline and future (ECHAM5-A1B) scenarios. Although the figure indicates that an increased percentage of demand can be satisfied in most of the future years, it also shows that annual industrial water shortage can reach up to 10% of the demand during dry years.

A detailed analysis at a weekly time step indicates that maximum weekly shortage does not exceed 0.5 % of the demand. This indicates the presence of frequent but low magnitude shortages throughout the analysis period. The possibility of overcoming these shortages by incorporating additional storage capacity to the supply network was analyzed. As part of this analysis the annual river flows under A1B scenario in the Walawe River near the water abstraction point for industry was calculated. These flows are then compared to the predicted annual industrial water demands. The average annual flows surpass the industrial demand by several times in all the 10 years of analysis, indicating the feasibility of the proposed solution.

The effects of additional storage in the system are evaluated by incorporating a reservoir with the capacity of 15 MCM to the supply network. The maximum storage capacity was selected arbitrarily. However the topography of the region and the increasing demand on land resources prohibit construction of a larger reservoir at this location. Results from this analysis indicated that by increasing the storage capacity all the industrial water deficits can be mitigated. Moreover simulation results indicate that by creating a 15 MCM storage reservoir at the lower reaches of Walawe River, up to threefold increase of municipal and industrial demands can be accommodated without incurring water deficits in either sector under the A1B scenario in future.

Summary and Conclusions

The current GCM models have low spatial resolutions in their predictions of future rainfall and temperatures. While majority of these predictions agree on global means of climate change, the regional level predictions vary within a wide range. In the absence of regional climate models, water resources planning in the developing world river basins need to incorporate effects of climate change, based on the downscaled GCM predictions. Employing detailed downscaling methods can be as data intensive as building regional climate models. Therefore the use of simple statistical methods is preferable for predictions in rural river basins of the developing world.

The analysis indicates an increase of rainfall over the basin in all future emission scenarios. The last five months of the year are predicted to receive increased precipitation. This implies an increase of precipitation during the latter months of SWM and early months of NEM seasons. This change in inflow seasonality affects the basin water availability for users.

The irrigation water demand in the basin has a seasonal variation. Current cropping seasons are attuned to the monsoon rainfall pattern of the past decades. Moreover the selection of crop type, number of cropping seasons, farming techniques, water use efficiencies etc., are all dependant on the timing and the magnitude of monsoon rainfall. The anticipated changes in seasonality of rainfall calls for an overall reorganization of the crop cultivation process in the basin.

The individual effects of temperature and precipitation increase on crop water demand were analyzed separately for a selected irrigation system. The influence of increased Co_2 levels was not considered in this analysis. The results show that crop

irrigation demand increases by 1% in response to the anticipated 2° C temperature increase. The increase of rainfall over the command area easily compensates the additional evapotranspiration demand created by increased temperatures. In fact, due to increased precipitation the overall irrigation demand is reduced between 3-16% during the analysis period. Simulation results do not indicate water deficits in the irrigations systems in the Walawe River basin in future.

The hydropower generation in Walawe River basin is mainly constrained by the flow availability. Due to the high demand for electricity in the country, reservoir R 1 power plant is required to produce hydroelectric power at its maximum capacity. The possibility of increasing the power generation under baseline and future scenarios were evaluated using different demand configurations (operation modes). The results show that increased inflows in future years can considerably enhance the annual power production under all three demand configurations tested. However each configuration has a different effect on the reservoir spills, unmet power demand, flood control zone availability etc. The analysis indicates that current infrastructure can be utilized to significantly enhance hydropower generation under future climate conditions.

Flood control plays an important role in the case of increased future inflows. The flood control capacity of reservoir R 1 is studied to understand the implications. Hydropower generation necessitates keeping elevated reservoir levels while flood control concerns require keeping the flood control zone free in the months preceding high rainfall season. Results from the analyses indicated that 75% of the flood control zone remains empty before the rainy season. It also showed the influence of hydropower generation mode (demand configuration) on the flood control capacity.

The municipal water demand both pipe borne and groundwater based, can be fully supplied under baseline as well as future climate scenarios. The water quality requirements are not considered in this work. However past records show increased salinity levels (due to backwater effects) affecting the municipal water abstraction during dry periods. A climate change driven sea level rise may aggravate this situation.

Industrial water requirements in the Walawe basin face water deficits under baseline as well as future climate scenarios. The shortages in the baseline scenario reach up to 14% of the annual demand. Provision of storage capacity can mitigate the shortages in both scenarios. This also enables to increase municipal and industrial water supply by several times.

The above discussed indicate the possible impacts of climate change on the water availability for basin water uses in the example of Walawe river basin in Sri Lanka. It also describes some mitigation measures which could be useful in minimizing the negative effects. This work also demonstrates how large scale predictions by GCM models can be used to formulate basin scale water allocation decisions.

References

Aggrawal PK (2009) Determinants of crop growth and yield in a changing climate. In: Wani SP, Rockstrom J, Oweis T (ed) Rainfed agriculture: unlocking the potential. CABI International, Wallingford, UK

Alcamo J, Doll P, Kaspar F, Siebert S (1997) Global change and global scenarios of water use and availability: An application of WaterGap 1.0. Repoer A9701, University of Kassel, Germany

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration- guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, Rome, Italy

Arnell N (1996) Global warming, river flows and water resources. John Wiley & Sons Ltd, West Sussex, UK

Ashfaq M, Shi Y, Tung W, Trapp RJ, Gao X, Pal JS, Diffenbaugh NS (2009) Suppression of south Asian summer monsoon precipitation in the 21st century. Geophys Res Lett 36, L01704

Asseng S, Jamieson PD, Kimball B, Pinterc P, Sayre K, Bowden JW, Howden SM (2004) Simulated wheat growth affected by rising temperature, increased water deficit and Elevated atmospheric CO_2. Field Crops Res 85:85-102

Basnayake BRSB, Fernando TK, Vithanage JC (2002) Variation of air temperature and rainfall during Yala and Maha agricultural seasons. In: Proceedings of the 58th Annual Session of Sri Lanka Association of Advancement of Science (SLASS), Section E1, Sri Lanka Association of Advancement of Science (SLASS),Sri Lanka

Boer GJ, Flato G, Ramsden D (2000) A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate for the 21th century. Clim Dyn 16: 427-450

Brouyere S, Carabin G, Dassargues A (2004) Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. Hydrogeol J 12:123–134

Burke EJ, Brown SJ, Christidis N (2006) Modeling the recent evolution of global drought and projections for the 21st century with the Hadley Centre climate model. J Hydrometeorol 7:113-1125

Carter TR, Parry ML, Nishioka S, Harasawa H (1994) Technical guidelines for assessing climate change impacts and applications. Intergovernmental Panel on Climate Change, University College of London and Center for Global Environmental Research, Tsukuba

Cosbey A (2009) Developing country interests in climate change action and the implications for a post-2012 climate change regime. UNCTAD Climate Change Programme, United Nations, New York and Geneva

Diaz G, Thomas E, Brown C, Sveinsson O (2000) Aquarius: a modeling system for river basin water allocation. General Technical Report RM-GTR-299-revised, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO

Drake BG (1992) Impact of rising CO_2 on ecosystem production. Water Air Soil Pollut 64:25-44

Droogers P (2004) Adaptation to climate change to enhance food security and preserve environmental quality: example for southern Sri Lanka. Agric Water Manage 66:15-33

Easterling WE, Aggarwal PK, Batima P, Brander KM, Erda L, Howden SM, Kirilenko A, Morton J, Soussana JF, Schmidhuber J, Tubiello FN (2007) Food, fibre and forest products. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (ed). Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK

Ewert F, Rodriguez D, Jamieson P, Semenov MA, Mitchell RAC, Goudriaan J, Porter JR, Kimball BA,Pinter PJ, Manderscheid R, Weigel HJ, Fangmeier A, Fereres E, Villalobos F (2002) Effects of elevated CO_2 and drought on wheat: testing crop
simulation models for different experimental and climatic conditions. Agric Ecosyst Environ 93:249–266

Fischer G, Tubiello FN, van Velthuizen H, Wiberg D (2006) Climate change impacts on irrigation water requirements: global and regional effects of mitigation, 1990-2080. Technol Forecast Soc 74

Gautier C (2008) Oil, water, and climate: An Introduction. Cambridge University Press, Cambridge, New York

Giorgi F, Mearns LO (1991) Approaches to simulation of regional climate change: A review. Rev Geophys 29(2): 191-216

Gordon C, Cooper C, Senior CA, Banks HT , Gregory JM, Johns TC, Mitchell JFB, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim Dyn 16:147-168

Gordon HB, Rotstayn LD, McGregor JL, Dix MR, Kowalczyk EA, O'Farrell SP, Waterman LJ, Hirst AC, Wilson SG, Collier MA, Watterson IG, Elliott TI (2002) The CSIRO Mk3 Climate system model. CSIRO Atmospheric Research technical paper 60.
http://www.dar.csiro.au/publications/gordon_2002a.pdf. Accessed 12 May 2007

Government of Sri Lanka (GOSL) (1997) The master plan study for southern area development in the democratic socialist republic of Sri Lanka. Final project report, Government of Sri Lanka

Herath S, Ratnayake U (2004) Monitoring rainfall trends to predict adverse impacts-a case study from Sri Lanka (1964-1993). Global Environ Change 14:71-79

Hiscock K, Tanaka Y (2006) Potential impacts of climate change on groundwater resources: from the high plains of the U.S. to the Flatlands of the U.K. National Hydrology Seminar 2006. The Irish National Committees for the International Hydrological Programme (IHP) of UNESCO

Intergovernmental Panel on Climate Change (IPCC) (2000) Special report on emissions scenarios, Summary for policymakers. Intergovernmental Panel on Climate Change, Geneva

Intergovernmental Panel on Climate Change (IPCC) (2001) Climate change 2001: impacts, adaptation and vulnerability: summary for policy makers. A report of Working Group II of the Intergovernmental Panel on Climate Change, Geneva

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: Synthesis report: Summery for policy makers. A summary of working groups contributions to the Fourth Assessment Report (AR4), Intergovernmental Panel on Climate Change, Geneva

Intergovernmental Panel on Climate Change (IPCC) (2008) Climate change and water, IPCC Technical Paper VI. Intergovernmental Panel on Climate Change, Geneva

Jayatillake HM, Chandrapala L, Basnayake BRSB, Dharmaratne GHP (2005) Water resources and climate change. In: Wijesekera NTS, Imbulana KAUS, Neupane B (ed). Proceedings of Workshop on Sri Lanka National Water Development Report. World Water Assessment Program (WWAP), Paris, France

Kimball BA, Mauney JR, Nakayama FS, Idso SB (1993) Effects of increasing atmospheric Co_2 on vegetation. Vegitatio 104/105: 65-75

Kripalani RH, Oh JH, Kulkarni A, Sabade SS, Chaudhari HS (2007) South Asian summer monsoon precipitation variability: coupled climate model simulations and projections under IPCC AR4. Theor Appl Climatol 90:133-159

Kumar KR, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB (2006) High-resolution climate change scenarios for India for the 21st century. Curr Sci 90(3):334-345

Leavesley G, Hay L (1998) The use of atmospheric and hydrological models for water resources management in headwater basins. Hydrology, Water Resources and Ecology in Headwaters, IAHS Publication

McCartney M, Ibrahim YA, Sileshi Y, Awulachew SB (2009) Application of the water evaluation and planning (WEAP) model to simulate current and future water demand in the Blue Nile. Challenge Program Project Workshop Proceedings,

International Water Management Institute (IWMI), Addis Ababa, Ethiopia

Pinstrup-Andersen P, Lorch PR, Rosegrant MW (1997) The world food situation: Recent developments, emerging issues, and long term prospects. Food Policy Report. International Food Policy Research Institute (IFPRI), Washington, DC

Roeckner E, Bäuml G,Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornblueh L, Manzini E, Rhodin A, Schlese U, Schulzweida U, Tompkins A (2003) The atmospheric general circulation model ECHAM5. Part I: Model description. Report 349. Max Planck Institute for Meteorology, Hamburg

Rosegrant MW, Cai X, Cline SA (2002) Averting an impending crisis, Global water outlook to 2025. Food Policy Report. International Water Management Institute (IWMI), Colombo, Sri Lanka

Somatilake HS (2002) Water for Energy. In: Imbulana KAUS, Makin IW, Droogers P (ed) Proceedings of workshop on Ruhuna basins, International Water Management Institute (IWMI), Sri Lanka

Stakhiv EZ (1993) Water resource planning and management under climate uncertainty. In: Proceedings of the First National Conference on Climate Change and Water Resources Management. US Army Corps of Engineers

Suppiah R (1996) Relationships between the southern oscillation and the rainfall Sri Lanka. Int J Climatol 9:601-618

Trenberth KE, Dai AG, Rasmussen RM, Parsons DB (2003) The changing character of precipitation. Bull Am Meteorol Soc 84: 1205-1217

U.S. Congress (1991) Energy in developing countries. Office of Technology Assessment OTA-E-486. U.S. Government Printing Office, Washington, DC

U.S. Geological Survey (2000) Water: the potential consequences of climate variability and change for the water resources of the United States. Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change for the U.S. Global Change Research program. U.S. Geological Survey

Vardavas IM, Fountoulakis A (1996) Estimation of lake evaporation from standard meteorological measurements: application to four Australian lakes in different climatic regions. Ecol Model 84:139-150

Vairavamoorthy K, Gorantiwar SD, Pathirana A (2008) Managing urban water supplies in developing countries – Climate change and water scarcity scenarios, Phys Chem Earth 33: 330–339

Vorosmarty C, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Sci 289:284 – 288

Washington WM, Weatherly JW, Meehl GA, Semtner Jr AJ, Bettge TW, Craig AP, Strand Jr. WG, Arblaster JM, Wayland VB, James R, Zhang Y (2000) Parallel climate model (PCM) control and transient simulations. Clim Dyn 16: 755-774

Wetherald RT, Manabe S (2002) Simulation of hydrologic changes associated with global warming. J Geophys Res 107(D19): 4379

World Meteorology Organization (WMO) (2007) World climate program-water. Final report of the expert meeting on water manager needs for climate information in water resources planning. WCASP-74.World Meteorology Organization, Geneva

World Meteorology Organization/ Global Water Partnership (2009) Flood management in a changing climate: a tool for integrated flood management. APFM Technical Document No. 13. Flood Management Tools Series. World Meteorology Organization, Geneva

Wilby RL, Hay LE, Gutowski WJ, Arritt RW, Takle ES, Pan Z, Leavesley GH, Clark MP (1999) Hydrological responses to dynamically and statistically downscaled climate model output. Geophys Res Lett 27(8):1199-1202

Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. Prog Phys Geog 21(4):530-548

Xu CY (1999) From GCM to river flow: a review of downscaling methods and hydrologic modeling approaches. Prog Phys Geog 23(2):229-249

Yates D, Seiber J, Purkey D, Annette Huber-Lee (2005) WEAP21-A demand-priority and preference driven water planning model part 1: model characteristics. Water Int 30(4):487-500

Zubair L, Siriwardhana M, Chandimala J, Yahiya Z (2008) Predictability of Sri Lankan rainfall based on ENSO. Int J Climatol 28:91-101

Appendix

Table 4.3 Characteristics of emission scenarios A1B, A2 and B1

Emission scenario characteristic	A1B	A2	B1
Population growth	Low	High	Low
GDP growth	Very High	Medium	High
Energy use	Very High	High	Low
Land use changes	Low	Medium/High	High
Resource availability	Medium	Low	Low
Phase of technological change	Rapid	Slow	Medium

Source: IPCC Special Report on Emissions Scenarios, 2000

Formulae for downscaling GCM predictions of precipitation and temperature:

EQUATION 1.

$$P_{GCM,fut} = P_{obs} \left(\frac{\bar{P}_{GCM,fut}}{\bar{P}_{GCM,his}} \right)$$

where

$P_{GCM,fut}$ - transformed future precipitation (future time period)

P_{obs} - observed precipitation (baseline time period)

$\bar{P}_{GCM,his}$ - GCM estimated average historical precipitation (historic time period)

$\bar{P}_{GCM,fut}$ - GCM estimated average future precipitation (future time period)

EQUATION 2.

$$T_{GCM,fut} = T_{obs} + \left(\bar{T}_{GCM,fut} - \bar{T}_{GCM,his} \right)$$

where

$T_{GCM,fut}$ - transformed future temperature (future time period)

T_{obs} - observed temperature (baseline time period)

$\bar{T}_{GCM,his}$ - GCM estimated average historical temperature (historic time period)

$\bar{T}_{GCM,fut}$ - GCM estimated average future temperature (future time period)

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This dissertation analyses the challenges to water allocation in the rural river basins of the developing world in the example of Walawe River basin, Sri Lanka where multiple water users compete for limited water resources. A methodology is developed to analyze the water supply demand situation in rural river basins under priority based water allocation which is observed in majority of developing world river basins. This methodology which utilizes a network flow simulation technique, allows calculating allocation schedules under different priority settings. The objectives of water allocation in the basin are expressed in terms of priority settings. The resulting allocation schedules are used to estimate the socio economic consequences. The methodology is applied to analyze the water allocation in Walawe basin under a baseline (1990-1999) and a future (2041-2050) demand-supply conditions. Different demand management options are also evaluated using the proposed methodology. This chapter provides a summary of the study, conclusions and recommendations for future research.

Summary

Initial Assessment of Water Supply,
Demand, and Scarcity Issues

The first major chapter of this dissertation is focused with the analysis of water supply and demand situations found in the rural river basins of the developing world, in the typical example of Walawe River basin. First, the quantities and patterns of water supply and demands in each water use sector are established based on available data.

Second, the current water scarcity issues and possible reasons for their existence in the basin are identified. Finally some commonly proposed solutions to the water shortages in the basin are analyzed.

The water availability in the basin is analyzed by calculating the annual water budgets at upper, middle and lower reaches of the Walawe basin. The average annual values of water inflows and depletion are used in this calculation. The analysis indicates that between 27-44 % of inflows are available for use in the basin at selected locations on an annual basis. The seasonal variation of the supply is then analyzed based on 40 years of monthly inflows to reservoir R 2. Two high inflow periods are identified during March to May and October to December periods. The irrigation and hydropower demands in the Walawe River basin are highly seasonal. Comparison of demand and supply patterns indicates that, despite surplus water availability on an annual basis, shortages can occur due to seasonal variation of supply and demand. The period of July to September is identified as critical for both hydropower and irrigation water supply. In addition, the spatial locations of demand sites in relation to the water source can trigger water shortages.

The reasons for current water shortages in the basin are identified as (1) non-availability of water at the source or the allocation to high priority users; (2) increased crop areas with time and high cropping intensity; (3) limitations in the physical infrastructure design, construction, operation, and maintenance; (4) absence of a strict water management practice; and (5) emergence of new water users with increasing demand. The results suggest that management interventions are preferable compared to

capital intensive infrastructural improvements and this may be the situation with other river basins of the developing world.

Several management options are analyzed to identify their impact on mitigating water deficits in the basin. The irrigation water use efficiencies in rice cultivation are considered low due to highly permeable soil conditions, extended land preparation periods and inefficient farming techniques. Replacement of rice crop with banana at the Walawe basin indicated an annual reduction of irrigation demand up to 50%. However the food security in the country is largely dependent on rice production. Moreover there are cultural and social impacts of such decisions. The low water use efficiency in irrigation leads to investigate the possibility of reallocation water to hydropower generation. Analysis indicated a 5 fold increase in net economic gain from 1 m^3 of water reallocated from irrigation to hydropower at Walawe basin. In Walawe a complete reallocation of irrigation water is not possible due to the holding of senior water rights by the irrigation water users. It was also found that changing the hydropower generation mode from *variable* to *fixed* mode enables a 5% increase in annual power output utilizing the current infrastructure. This mode of operation allowed of releasing the supplemental irrigation flows to the downstream reservoir during the dry months of the year.

Food production remains the main economic activity of the population in developing countries, which is generally undertaken within the rural areas. Analyses carried out in this section of the dissertation indicate that there are many common causes for the water allocation challenges faced by agriculture and other water users in a rural river basin of the developing world. Improved water allocation methods and demand management strategies can provide affordable and sustainable solutions to the allocation

problems. However, solutions should consider the specific characteristics and socio-economic constraints of each basin.

Evaluation of Water Allocation and
Demand Management Strategies

The second major chapter of this dissertation develops a methodology to evaluate the water allocation and demand management strategies on basin water users and the socio-economic impacts of such actions. The allocation strategies are formulated under the preference based allocation method commonly observed in developing world rural river basins. First a water balance study is conducted to ensure that supply conditions in the basin are correctly identified. Second, a methodology is developed to enable simulating the selected water allocation strategies and estimating the corresponding supply and deficit situation at each water user. Simulations were conducted for water allocation strategies selected based on the regional and national priorities of water resources development in the study area. Finally the impacts of allocation strategies are evaluated using a set of indices that reflect the system's performance (in satisfying the demands) and the corresponding socio-economic impacts.

The water supply to the Walawe basin is estimated as the runoff from 11 sub catchments.   Weekly rainfall data from 11 rain gauges in the basin for a 10 year period was used in this analysis. Conversion coefficients established by previous studies were used to calculate the runoff. The flows estimated are compared to the measured river flows at two locations of the main river reach. In 8 out of 10 years, the estimated and measured annual flows agree above 80%. Considering the limited data availability this

agreement is assumed adequate for the purpose of this analysis. The calculated river and tributary flows represent the supply situation in the basin for the analysis period.

The allocation simulations were conducted based on the proposed methodology and used a network flow simulation model (WEAP) where, the water courses connecting the water users and reservoirs are represented in a network consisting of arcs and nodes. The preference based allocation is simulated by assigning a priority number to each water user in the network. The physical conditions in the water distribution network are formulated as a set of flow constraints in the network model. The network flow simulation software tool iteratively simulate allocation to each water user in each consecutive week throughout the simulation period.

The supply (and deficit) volumes under different allocation and demand management strategies are compared using *shortage, reliability, resilience* and *vulnerability* indices. According to the results, prioritizing of irrigation over hydropower generation is beneficial in Walawe. First, it allows preserving the senior water rights of the irrigation system IRR 1. Second a 38% reduction in annual irrigation deficits can be achieved during the 10 year analysis period. In addition, the annual reduction in hydropower generation due to such prioritization is less than   0.5% in each year of this period. Prioritizing irrigation between the left and right bank command areas of IRR 2 allows to increase the paddy yield by 2% , reduce the number of farmer families affected due to irrigation deficits by 30% and increase the overall economic gain by 15.2 million dollars during the study period. Demand management options evaluated for hydropower generation indicates the possibility of increasing the annual power output up to 40% in each year of the study period. The analysis in the previous section indicated the

possibility of reducing the irrigation demand by 50% in IRR 1 by changing crop type from paddy to banana. This reduction in water demand at irrigation system IRR 1 showed a decline in shortages (shortage index reduced from 0.25 to 0.07), increased reliability in supply (reliability index increased from 0.72 to 0.97), increased system resilience to shortage (resilience index increased from 0.42 to 0.83) and reduced system vulnerability to deficits (volume vulnerability reduced from 0.85 MCM to 0.43 MCM and time vulnerability reduced from 9 weeks to 2 weeks). Upgrading the irrigation system (resulting in a 30% reduction in irrigation demand) showed the possibility of satisfying the water demands of all the users below the reservoir R 2 without shortage.

The work conducted under in this chapter indicated that (1) data available from multiple sources and different analysis / interpolation techniques can be successfully used to estimate the water allocation options under data scarce conditions commonly found in the developing world; (2) a network flow based simulation technique such as the WEAP simulation model, can be used to evaluate different water allocation strategies and estimate their socio-economic impacts; (3) Improvement to water management (allocation prioritization, demand management etc.) can reduce the water shortages, increase productivity and reliability of the Walawe basin water uses. Overall this chapter demonstrated a methodology that, while catering to the site specific conditions, draws on the strengths of simulation based techniques to evaluate typical management improvement options and their socio-economic consequences for water allocation in rural river basins.

Assessment of Climate Change Impacts on Water
Supply, Demand, and Scarcity with Corresponding
Mitigation Measures

The final major chapter of this dissertation analyses the impacts of global climate change on the water resources and demands in the Walawe River basin. The Walawe river basin is located in the tropical region, where an increase in both temperature and precipitation is predicted by majority of general circulation models under the emission scenarios considered (A1B, A2 and B1). First, a range of GCMs are analyzed based on their estimation of historical climate (1961-1990), to identify the models that best predict the rainfall and temperature over the Walawe basin. Second, rainfall and temperature predictions from selected models for the future time period (2041- 2050) are used to calculate the future water supply and demands in the basin. The impacts of non-climate driven changes (population growth, urbanization, industrialization etc.) are also considered in projecting the future water demands. Finally, the water demand supply situation is simulated for the future time period and is compared with the baseline time period (1990-1999). Possible impact mitigation and productivity improvement options are analyzed for each water use sector.

The best estimations of historical precipitation over the Walawe river basin are given by ECHAM5 and PCM models. The best historical temperature estimation is given by the PCM model. The ECHAM5 model predicts higher temperature and rainfall values for the future period. Moreover the variability of these values is high when compared to the PCM model. Therefore the ECHAM5 model predictions are selected for estimating the future water supplies and demands. The A1B and A2 emission scenarios (under which ECHAM5 model demonstrate extreme values of rainfall and temperature) are

selected for the analysis. ECHAM5 predicts a 25% increase in the mean annual rainfall over the Walawe basin for the future period. The maximum temperature increase over the basin is about 2° C. The model predicted climate data are downscaled using a commonly used downscaling method (Chapter 4) to relate them to catchment scale. Rainfall data are converted to runoff assuming no major change in basin land use and land cover between baseline and future time periods.

Due to land resource limitations an agricultural area expansion is not expected in the Walawe irrigation command area. The results show a reduction in average monthly irrigation demand due to increased rainfall over command area. This reduction varies between 3 to 36% for A1B and A2 in the irrigation system IRR 2. However the increase in evapotranspiration demand (due to temperature increase) is just 1% of mean monthly irrigation demand. Therefore the increased rainfall compensates the increase in evapotranspiration demand. Accordingly no irrigation water deficits are observed in the future time period and the reduction in irrigation requirement between the baseline and the future periods vary between 3 to 16% during the 10 years of analysis.

The increase in annual inflows to the hydropower reservoir is 30% in A2 and 40% in A1B scenarios. Under different operational modes an increase between 18 to 43% in power generation can be achieved in the future under A1B. The more restrictive A2 scenario allows an increase between 8 to 24% in power generation utilizing the current infrastructure. The available flood control capacity of the reservoir R 1 is dependent on the power generation mode. The 2-step power generation modes leaves flood control zone free throughout the year except in the months of April and May. The variable power generation mode is the least favorable for preserving flood control capacity. The

154

domestic water demands in Walawe face no deficits in the future time period. The

increased recharge of groundwater easily surpasses the predicted domestic demands in

2041-2050. The annual industrial water demands will face deficits up to 10% during the

future period. However theses deficits can be fully eliminated (and demands can be

expanded up to 3 times) by providing a 15 MCM storage capacity in the low reaches of

the basin.

Overall the water resources supply and demand situation for Walawe river basin

has a positive outlook up to the middle of next century. The enhanced supply surpasses

anticipated demand increase in all major water user sectors. However this analysis does

not consider water quality and environmental aspects that may significantly influence

actual availability of water for allocation. Moreover the situation at the Walawe basin

may not be representative of the many rural river basins in the developing world, where

extreme climatic variability (severe droughts and floods) is predicted. However this

analysis provides an insight into how currently available climate predictions can be

incorporated to improve the water allocation decisions made in rural river basins.

Conclusions

The analysis and simulation of water allocation in the Walawe river basin was

conducted under limited data availability, which is a common phenomenon in river

basins of the developing world. However all possible measures were taken to ensure the

assumptions made herein are consistent with the realities observed in the basin. The

simulations of water allocation conducted here does not represent a comprehensive

optimization analysis where allocation schedules are optimized to achieve a specific

objective (net economic benefit, social gains etc). On the contrary the current study analyses the possibilities for improvements to prioritization and demand management options, that increase the socio economic and environmental benefits with the use of a network flow based simulation technique. The conclusions drawn from this study can be summarized as follows:

1. Annual water balance indicates that up to 44% of inflows are still available for water users. However due to the monsoonal climate significant seasonal variations are observed in supply. The rice-based agricultural systems in Walawe are partly rainfed and are sensitive to this seasonal variation of rainfall. In addition, the low efficiency in irrigation water use (conveyance, distribution and application) produces significantly high water use that leaves no carry over storage in the reservoirs from year to year. Poor water management, physical infrastructure deficiencies, and other socio-economic factors also contribute to the irrigation deficits that are observed in the Walawe basin.

2. Preference based water allocation remains a feasible option for water allocation among competing water users in the Walawe River basin. Prioritization of water allocation to selected sectors enables achieving water resources development goals. Prioritizing irrigation over hydropower generation at reservoir R 1 reduces the average annual irrigation deficits in system IRR 1 by 38% while the corresponding reduction in annual hydropower production is insignificant due to the differences in volumes involved. Prioritization also affects the economic and social outcomes. By prioritizing allocation to the left bank crop area of IRR 2, an average increase of 1 million US dollars in economic benefits can be achieved

annually. The number of farmer families affected by water deficits can be minimized by prioritizing the allocation to cropping areas on either bank of the irrigation system IRR 2. Giving similar priorities to both bank increases the number of farm plots and families affected by water deficits.

3. Demand management through water use efficiency increase in agriculture remains an attractive option for reducing irrigation water deficits and finding opportunities for water re-allocation to other sectors in the basin. Crop changes at IRR 1, enable irrigation water savings up to 50%. This increases supply reliability (reliability index increase from 0.72 to 0.97), reduces water shortages (shortage index reduces from 0.25 to 0.07) and increases the system resilience to deficits (resilience index increases from 0.42 to 0.83). A 30% irrigation demand reduction achieved through irrigation system upgrade can eliminate deficits in all user sectors below reservoir R 2. This also increases the annual flows in the lower reaches of Walawe River by 49%, providing more opportunities for expansion in industrial and municipal sectors.

4. The economic gain from 1 m^3 of water allocated to hydropower generation is about 5 times more when compared to irrigation. Therefore hydropower remains an attractive option for increasing economic gain. However the competition between hydropower and irrigation water demands in Walawe is minimal, due to the upstream location of the power plant. The mode of power generation can influence the power output, flood control capacity and irrigation releases to downstream from reservoir R 1. Complete reallocation of water to hydropower generation under fixed mode of operation can enable releases to downstream.

Theses releases may be used to supply 3%, 6% and 29% of the downstream irrigation demands in the water short months of July to September. The increased flows predicted due to climate change can also be utilized using different operation modes. While variable and fixed modes can generate maximum power output the stepwise operation mode provides enhanced flood protection at reservoir R 1.

5.   All 5 climate models considered agree that rainfall over Walawe basin will either remain same or increase by the middle of next century. Models that estimate the historical rainfall with higher success predict a 25% increase in average annual rainfall compared to the baseline period. The predicted maximum increase in temperature over the basin is 1.9 °C. The overall effect of rainfall and temperature change on crop water requirement indicates that Walawe agricultural systems will require supplemental irrigation even under the future climate. The increased rainfall will reduce the irrigation demands between 3 to 16 % during the 2041-2050 period. The current irrigation infrastructure is able to cater for the future demands without the need for capacity expansion.

6.   Network flow simulation techniques can be used to analyze the water allocation in river basins with multiple water resources and users. Currently available simulation and optimization models can be used to successfully represent site specific conditions of a given basin. These mathematical models allow efficient estimation of allocation schedules under different management objectives. The models also allow evaluating solutions to water allocation problems under current and future supply-demand conditions.

Recommendations

Based on the limitations encountered during the current study, the following directions for future research can be recommended.

1.   Improved climatic and hydrologic data monitoring should be conducted in the study area to enhance the estimation of current and future water resources availability. In addition a database of historic data (climate, hydrology, water demands and supply and other related socio-economic data) needs to be established from the number of currently available sources to facilitate future research.

2.   Distributed hydrologic models that represent the catchments response to current and future climatic should be developed for the study river basin. It is expected that some data limitations will be encountered in the process. However the aforementioned establishment of a historic database will reveal the data gaps that need to be filled with additional monitoring, remote sensing, and other available techniques.

3.   The current study is mainly concerned with the surface water resources in the basin. However with the increase of scarcity of water, groundwater resources in the basin will come to play a major role in future water resources development. A detailed assessment of groundwater resources in the basin is required for acquiring data needed for future studies on groundwater use.

4.   The network flow simulation techniques used in the current study does not incorporate the optimization capabilities for water allocation. Optimal water allocation decisions can be computed when demand supply forecasts can be

incorporated in to the analysis. Moreover the ability to incorporate demand management rules (restriction levels) in to the allocation schedules is highly useful.

5.   The water quality of the Walawe River plays a detrimental role in of domestic water supply. Increased salinity levels due to backwater flows prevent water abstraction at the lower reaches of Walawe during the dry years. The limited data availability prevented incorporation of water quality concerns in to the current analysis. Studies on water quality of the Walawe River basin and its tributaries are needed for future water allocation studies. In addition, the estimation of environmental flow requirements is required. This information will reveal additional constraints that need to be considered in water allocation.

6.   Methods for estimating the future water demands in the basin should be improved. Research needs to be conducted to establish, how the processes of population growth, urbanization, industrialization will affect the future water demands in the basin. This information with improved climate predictions can provide more accurate estimates of future demand-supply situation in the basin.

CURRICULUM VITAE

Neelanga D.K.Weragala, Ph.D.

Utah Water Resources Laboratory
Department of Civil and Environmental Engineering
Utah State University
8200 Old Main Hill, Logan, Utah 84322-8200
E-mail) neelanga.w@aggiemail.usu.edu, iwmi.neelanga@gmail.com

EDUCATION
- Ph.D., Civil and Environmental Engineering (April 2010)
  Utah State University, Logan, UT
- Bachelor in Information Technology - 2nd class upper division (2004)
  University of Colombo, Sri Lanka
- M.Sc., Civil Engineering – Honors (1996)
  Peoples' Friendship University, Moscow, Russia
- B.Sc., Civil Engineering (1993)
  Peoples' Friendship University, Moscow, Russia

PROFESSIONAL EXPERIENCE
Sri Lanka Land Reclamation & Development Corporation (SLLRDC), Colombo, Sri Lanka
Civil Engineer (Research & Design Division), 1999 - 2001
- Storm water drainage design and land reclamation in Godagama, Galle, and Horana town development projects
- Design of flood gates at Beira Lake sea outfall in Colombo, Sri Lanka
- Member of the team for drainage studies of Colombo-Katunaike expressway and Southern Highway Project in Sri Lanka
- Leader of local counterpart team for storm water drainage master plan for Western Province (JICA funded) project

International Water Management Institute (IWMI), Colombo,Sri Lanka
Research Officer (Global Research Division), 2001 – 2005
- Distributed hydrological modeling of Walawe river basin in southern Sri Lanka
- Use of flow duration curve analysis for environmental flow estimation for Walawe River Basin in Sri Lanka
- Estimation of drought indices based on rainfall data for South West Asia
- GIS modeling at Tsunami flood damage and livelihood needs assessment project
- Development of a Smallholder Model Tool- Kit for land and water management
- Development of climatology related software *i*WXGEN

RESEARCH EXPERIENCE

Civil Engineer, Sri Lanka Land Reclamation Corporation (SLLRDC)
♦ Established rating curves for Colombo city storm water drainage canal system
♦ Designed flood gates for Beira Lake sea outfall in Colombo
♦ Designed a rainfall and river flow gauging network for Kalu Ganga basin

Research Officer, International Water Management Institute (IWMI)
♦ Developed a distributed rainfall-runoff model for the Walawe River Basin in Sri Lanka, using SWAT
♦ Estimated river flows in ungauged basins using regional flow duration curves in Southern Sri Lanka
♦ Estimated rainfall based drought indices for India, Pakistan and Iran
♦ Developed software for disaggregation of monthly rainfall data in to daily using station statistics
♦ Developed a Smallholder Model Tool Kit software for land and water management

Graduate Research Assistant, Utah State University (USU)
♦ Reviewed basin water allocation with the use of simulation and optimization techniques
♦ Developed a priority based optimization model for water allocation in Walawe river basin in Sri Lanka using WEAP
♦ Evaluated the socio-economic and environmental impacts of priority based water allocation
♦ Compared priority based water allocation with a market based water allocation in Walawe river basin with the use of WEAP and AQUARIUS models

TEACHING EXPERIENCE

Part Time IT Lecturer
Skills Lanka Private Ltd.,Colombo, Sri Lanka
Developed curriculum for the following undergraduate courses including instruction, grading and preparing tests:
♦ Systems Analysis and Design
♦ Visual Basic Programming
♦ Introduction to JAVA Programming
♦ Database Management

TECHNICAL SKILLS
♦ Programming: Visual Basic,VBA, Java, VB script, Java script, ASP, MATLAB, Mathcad
♦ Client –Server Technologies and Data Base Management Systems: MS SQL server
♦ Systems engineering Software: STELLA, VENSIM, SIMULINK
♦ Optimization Software / Languages: LINGO, GAMS
♦ GIS Software:ARC View, ARC GIS
♦ Hydrologic Modeling Software:HEC HMS, HEC RAS, HEC Res Sim, SWAT, DAMBRK, PCSWMM
♦ Water Allocation Software:WEAP, REALM, AQUARIUS
♦ Desktop Graphics Software:Photoshop, Corel Draw

LANGUAGE SKILLS
- Sinhala (native)
- English (fluent)
- Russian (fluent)

PUBLICATIONS/ CONFERENCES

Weragala, N. and Smakhtin V. 2004. *Simulating the hydrology of Walawe river basin, Sri Lanka*. Paper presented at Stakeholder Network Meeting of IWMI-Ruhuna Benchmark Basin, 20 May 2004, Hambantota, Sri Lanka.

Weragala, N. 2004. *The use of RS/GIS technologies in Distributed Hydrological Modelling of the Walawe River Basin.* Conference proceedings of the First National Symposium on Geo-Informatics, 30 July 2004, PGIA University of Peradeniya, Sri Lanka.

Weragala, N., Smakhtin V. and Hughes, D. 2004. *Regional Analysis on Drought Risk in South West Asia,* Paper presented at the International Workshop on Drought Assessment and Mitigation in South West Asia, 7-8 October 2004,Colombo, Sri Lanka.

Weragala, N. and Smakhtin V. 2004. *Simulating Hydrological Alterations in the conditions of limited data: Lessons from the Walawe River Basin of Sri Lanka.* Proceedings of the International Conference on Sustainable Water Resources Management in Changing Environment of the Monsoon Region.17 -19 November 2004, BMICH, Sri Lanka.

Weragala, N. *Estimation of Monthly River flows for un-gauged catchments in Sri Lanka :A non-linear spatial interpolation approach.* Proceedings of the Conference on Sri Lanka: Current Challenges. 17 -18 December 2004, Faculty of Graduate Studies, University of Colombo, Sri Lanka.

Weragala, N. and N. Gamage, 2005. *Definition of a Tsunami Safe Boundary for Sri Lanka : A case study in Galle, Matara and Hambantota districts.* LOICZ-II,Zigmond Ann Zee, The Netherlands.

Smakhtin, V. and N. **Weragala,** 2005. *Quantifying drought characteristics in South West Asia using observed rainfall data*. IWMI Research Report.

Weligamage, P., P. Jayakody, N. **Weragala,** 2005. *A Post-Tsunami Livelihoods Needs Assessment of Hambantota District in southern Sri Lanka*. IWMI Research Report.

Weragala, N., J. Kaluarachchi and V. Smakhtin, *Water Resources Management Under Competing Irrigation and Hydropower Demands in the Walawe River Basin-Sri Lanka* , Proceedings of the UCOWR/NIWR Conference on International Water Resources and Water Resources Education,22 -24 July 2008, Durham, North Carolina.

Weragala, N., J. Kaluarachchi and V. Smakhtin, *The use of Optimization modeling in Adaptive Water Resources Management: A case study from Walawe River Basin-Sri Lanka* , Proceedings

of the American Water Resources Association (AWRA) 2009 Summer Specialty Conference on Adaptive Management of Water Resources II, 29 June- 1 July 2008, Snowbird, Utah.

PROFESSIONAL MEMBERSHIPS
Member –International Association of Hydrological Sciences (IAHS) [M.No: 7905]
Corporate Member – Geo-Informatics Society of Sri Lanka (GIS-SL) [M.No: LM/04/046]
Member – International Association for Environmental Hydrology (IAEH)
Member – Golden Key International Honor Society [M.No:5728496]
Student Member – American Water Resources Association (AWRA)
Member-American Geophysical Union [M. No: 10867445]

AWARDS
Inland Northwest Research Alliance (INRA) fellowship for Subsurface Science Research 2008/09