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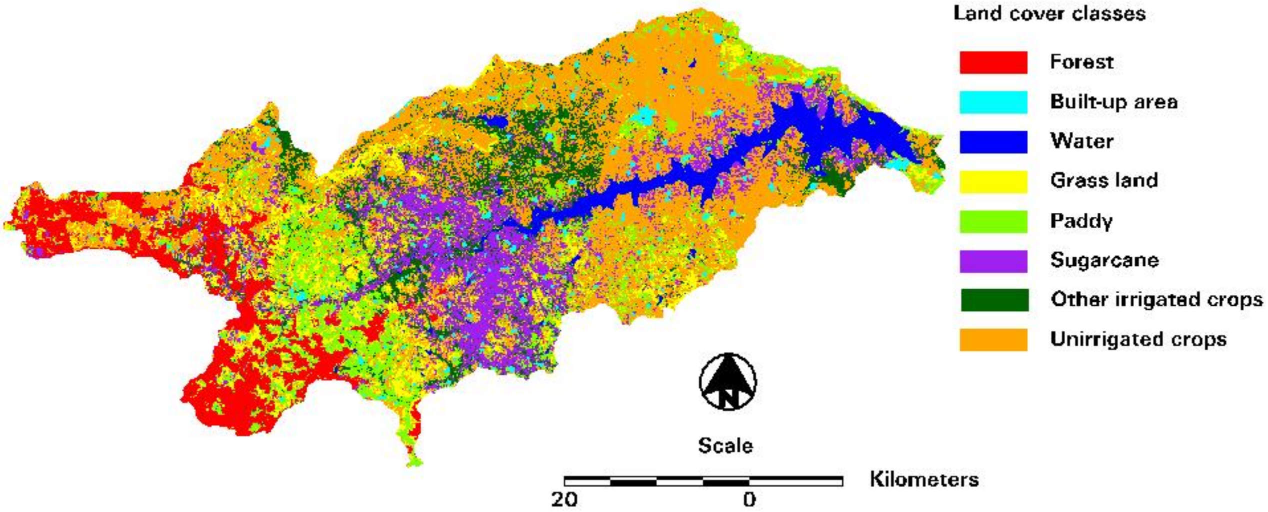
Hydrology and Water Allocation in Malaprabha

Comprehensive database and integrated hydro economic model for selected water services in the Malaprabha river basin



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REPORT

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Abstract

Malaprabha river basin has been the study area for the development of comprehensive database on the status of water sector and the development of integrated hydro economic model for selected water services.

For the purpose of studying the feasibility of Payment for Watershed Services (PWS) to improve water availability, a detailed analysis of the historic hydrologic data is done and a hydro-allocation model is developed using ArcView SWAT (AVSWAT) and MIKE-BASIN models.

4 keywords, Norwegian	4 keywords, English
1. Hydrologi	1. Hydrology
2. Vannallokering	2. Water allocation
3. Økonomisk optimalisering	3. Economic optimisation
4. Irrigasjon	4. Irrigation

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Hydrology and water allocation in Malaprabha

Comprehensive database and integrated hydro economic model for selected water services in the Malaprabha river basin

Preface

This report describes the two following deliverables:

- Development of comprehensive database on status of water sector in the study area
- Development of integrated hydro-economic model for selected water services

The development of a comprehensive database was the first issue to be addressed during this part of the project. The database includes the data regarding precipitation, evaporation, discharge, land use, soil types, irrigation information, socio-economic characteristics etc. Second, but the main, objective was to develop a hydrological and water allocation model. The comprehensive database forms the primary input to the integrated hydro and water allocation model (the interaction between AVSWAT and MIKE-BASIN).

During this project, extensive field survey has been carried out by CISED and vast amount of information has been collected through field surveys and from local/regional administrative/ agricultural/ irrigation departments. Data from various sources were aggregated to build the comprehensive database. AVSWAT set up was developed for the Malaprabha reservoir catchment to simulate the hydrological processes viz., stream flow, evapotranspiration, recharge and transmission losses. Land use change scenarios were built in the model assuming both increase and decrease in the irrigated area. This was used to study the impacts of land use and irrigation practices on the water scarcity in the area, more specifically monthly stream flow time series at specific locations in the catchment (the model and the associated comprehensive database is available at CISED). The land use land cover map was generated by Elizabeth Eby Heller, a CISED visiting master's student from McGill University, Canada.

MIKE-BASIN model was set up by NIVA for the basin to simulate water allocation (irrigation and domestic drinking water). The economic optimization tool, which was available in the older version of MIKE-BASIN, was not available in the recent version. The economic optimization in MIKE-BASIN was therefore not completed. Instead issues regarding economically optimal water trades are discussed using the model outputs from AVSWAT and MIKE-BASIN's Irrigation module.

The report therefore describes an approach to study the impact of land use and agricultural practices on the water regime of an area and an approach to do economic analysis of water allocation based on the information available, which can be used online when data on the upper catchment becomes available and the model optimisation tool becomes available.

The NIVA-CISED project team would like to thank the Norwegian Embassy in India for its financial support for this work.

Oslo, 30.11.2008

David N. Barton

Contents

Summary

Malaprabha river basin has been the study area for the development of comprehensive database on the status of water sector and the development of integrated hydro economic model for selected water services. Malaprabha river is a tributary river to the Krishna river and flows through the state of Karnataka in India. Malaprabha dam is constructed in the stream with a live storage capacity of 870 MCM to meet the irrigation demand in the area as well as to supply drinking water to the nearby towns. Catchment area of the Malaparbha dam is 2204 km^2, which is divided into 3 main hydrological zones: upper catchment (zone-1), middle catchment (zone-2) and lower catchment (zone-3). Due to variation in the hydro-meteorological characteristics and unsustainable land-use practices, the area is experiencing water stress across all sectors, thereby making the inter-sectoral water allocation a challenging issue. Almost 80% of the monsoon river flow is generated from zone-1. On the other hand, almost 60% of the post-monsoon runoff is generated from zone-2 and zone-3. Most of this water is extracted for irrigation in zones-2 and zone-3, which were traditionally rainfed areas, but now under extensive irrigation thereby resulting in water scarcity in the area.

For studying the feasibility of Payment for Watershed Services (PWS) to improve the water availability, in this study a detailed analysis of the historic hydrologic was carried out and a framework of hydrologic and water allocation model is developed. A detailed database of the catchment is developed for hydrological analysis and modelling. Terrain characteristics, land use and land cover, soil characteristics, crop characteristics and yield, hydro-meteorological data, stream flow and reservoir water level information were collected from various sources and assimilated in the database.

Objectives of the hydro-allocation modelling is to set up a catchment-scale model to simulate core hydrologic processes, develop different land use scenarios to assess the impact of land use changes on the stream flow, and carry out the optimum allocation of water among irrigation and drinking water uses as well as among various geographical areas within the irrigation sector. ArcView-SWAT (AVSWAT) and MIKE-BASIN models were selected for the current study. AVSWAT is a hydrologic simulation tool built within GIS environment that is used for modelling the catchment hydrologic processes as well as to study the impact of different land use scenarios on the stream flow.

From the studies carried out it was found that MIKE-BASIN cannot prioritize the water allocation within a single sector i.e., irrigation across different crops across different areas. Consequently, it could not be applied to obtain an optimum water allocation scenario in the Malaprabha catchment. In addition, the recent version of MIKE-BASIN lacks the Excel-based optimization tool which was present in the older version. Therefore, the irrigation module available in the MIKE-BASNI is used to simulate the crop yield response to water availability under different conditions across the catchment as described in the FAO-33 Irrigation and Drainage Manual. Given the model limitations, economic optimization is

discussed in an example which uses estimates of efficiency of water application by using the AVSWAT (stream flow, evapotranspiration in the catchment, transmission loss) and MIKE-BASIN (evapotranspiration in the command area and crop yield) simulation results. The example is used to discuss issues concerning the feasibility of water trades between the the reservoir catchment and the catchment downstream, specificallt the command area of the reservoir.

From the study, it has been found that extensive irrigation extraction in zone-2 and zone-3 has resulted in drastic reduction in the inflow to the Malaprabha reservoir, especially udirng the dry season. A comparison between the stream flow and the drinking water supply requirement, taking Bailhongal town in the lower catchment as a case study, shows that the stream flow in the past decade is less than the demand at the intake point during the peak summer (2-4 months) in dry years. Different land use scenarios have been developed and the corresponding simulation results shows that the current trend of irrigation intensification could lead to more months of water scarcity. An average 35% increase in the degree of water scarcity could result from 56% conversion to sugarcane from the current rainfed areas. Improvement scenarios, where the increase in stream flows can result from reduction in the irrigated areas (sugarcane) have also been studied. It has been found that a 10% change would halve the current duration of water scarcity. An average 50% reduction in the intensity of water scarcity can be achieved with 56% reduction in the sugarcane area.

Due to the evaporation and transmission losses along the channel, it is concluded that for the economic benefit from one cubic meter of water, crop yield in the command area may have to be up to several times that in the upper catchment, assuming cropping pattern, prices and farming costs are similar in the command area and in the upstream catchment. A calculated example shows that upstream-downstream water trading, if it were possible from an institutional and technical point of view, would not be economically feasible during June-October (due to surplus water supply) and March-May (due to water scarcity). From the analysis economic water trade is found feasible during the period November-February if yield at downstream is more than that at upstream.

1. Introduction

Malaprabha basin in Belgaum district, Karnataka, India is one of the deficit sub-basins in the Krishna River Basin. Total area of the Malaprabha basin till it joins the main Krishna river is 11549 sq.km. Malaprabha river originates from Sahyadri hill range (at an altitude of 792 m) at 16 km to the west of Jamboti village in Khanapur taluka. The Malaprabha reservoir was commissioned in 1974 and has a gross storage capacity of 1070 MCM and a live storage capacity of 830 MCM. The project also has eleven foreshore lift irrigation schemes with a total irrigation potential of more than 270 km^2 for those villages affected by the Malaprabha project. The irrigated area in the Malaprabha catchment has increased from 10% in 1970s to 30% of the total cultivable land in 2003 (Statistical Abstract, Government of Karnataka, 2004). The catchment area of the Malaparbha dam is 2204 sq.km (which is called the Malaprabha catchment hereafter) and is in the semi-arid climate zone. Location map of the Malaprabha catchment is shown in Fig. 1.

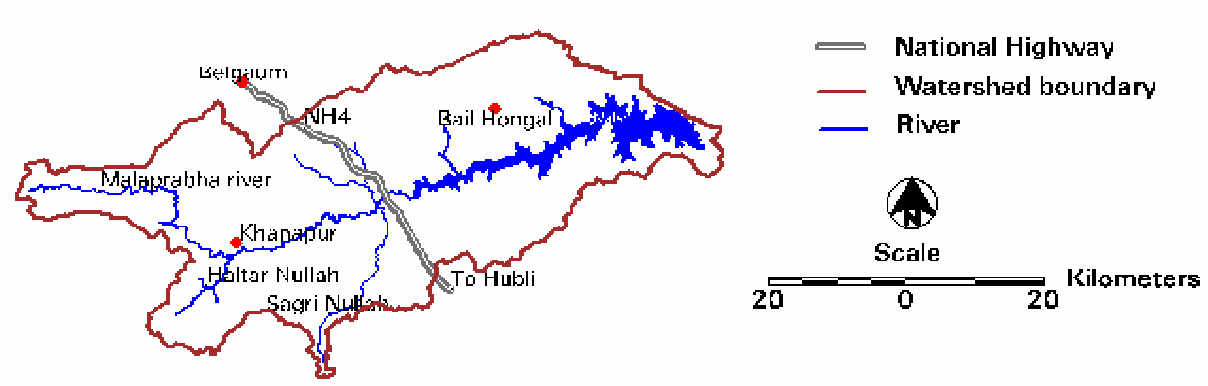


Fig. 1.1 Base map of the upper Malaprabha catchment

Due to increasing unsustainable land use practices the area is experiencing water scarcity, thereby making the inter-sectoral water allocation a challenging issue. Water availability in the lower catchment is closely related to the land use practices and water extraction in the upstream. In order to study the feasibility for Payment for Watershed Services (PWS) in the Malaprabha catchment, hydrological analysis of the catchment response to land-use was carried out. This includes study of the hydrological characteristics of the catchment and setting up the hydrological and water allocation model for the catchment area.

Hydrological analysis of the catchment includes the study of topography, soil characteristics, historic data related to rainfall and stream flow, its spatial and temporal variability, cropping pattern and agricultural practices in the area related to water resources. Hydrologic modelling helps understand the current resource availability as well as the impact of agricultural practices on the overall water availability in the catchment. The allocation model is used to study the optimal allocation of the water resources among different geographical areas as well as different sectors.

1.1 Catchment characteristics

The area is characterized by the heterogeneity in topography, hydro-meteorology, soil and land use conditions. To simplify the heterogeneity of the catchment, it can be divided into three agro-hydrological zones as shown in Fig. 2.

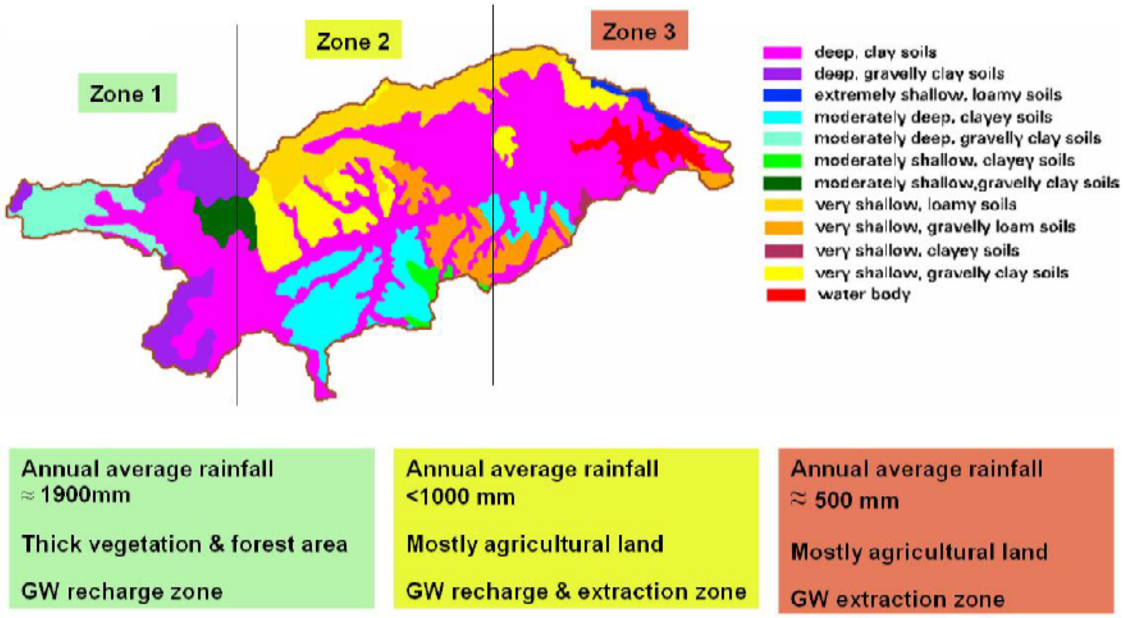


Fig.1.2 Hydrological zones in the upper Malaprabha catchment

Zone-1 and parts of zone-2 are characterized by hilly terrain and gravely soil, cracking clay or loamy soil that assists percolation. Fairly dense forest covers almost 60% of the zone-1. Zones-2 and 3 are dominated by agricultural areas, which were initially under rainfed cultivation. However most of these areas are now converted into irrigated cultivation by extracting stream water or pumping the groundwater through private borewells. Annual average rainfall in the area varies from 2000mm in zone 1 to 500 mm in zone 3. Due to the variation in rainfall distribution, land use conditions and geological characteristics of the catchment, almost 80% of the stream flow and the ground water recharge from the catchment occurs from zone-1. On the other hand almost 60% of the post-monsoon runoff is resulted from zone-2. Much of the stream flow generated from zones 1 and 2, as well as the groundwater is extracted by zones 2 and 3, for irrigation. This results in reduced flow in the river especially during the dry season.

1.2 Objectives of the hydrological modelling

Objectives of the hydrological modelling is to set up a catchment-scale model to simulate various hydrologic processes, and to develop different land use scenarios in the model so as to study the impact of land use change on the stream flow.

While modelling the catchment hydrology, long term simulation of the various components of the hydrologic cycle viz., rainfall, surface runoff generation, ground water recharge, evaporation and transpiration, transmission losses and irrigation are essential processes to be understood. Calibration of the model parameter by using the observed data is prerequisite step in customizing the model components for the catchment. With the larger framework of PWS feasibility analysis, in order to study the feasibility of inter-sectoral water allocation, development of various land use scenarios to study the impact of land use change on stream flow is also one of the objectives of the study.

1.3 Objectives of the water allocation modelling

The objectives of the water allocation modelling were to identify and simulate the different water users in the Malaprabha river basin and to find the optimal water allocation between different users. In this study, irrigation and drinking water supply are considered as the water demand within the basin. Economic analysis of the water reallocation is also one of the objectives of the study.

1.4 Organization of the report

In this report, model selection procedure is explained in Chapter 2, Chapter 3 presents a detailed description of AVSWAT. A detailed description of the MIKE-BASIN model is given in Chapter 4. Data assimilation for the current hydrologic study and the model application in Malaprabha catchment are presented in Chapters 5 and 6 respectively. Results obtained from the catchment area are presented in Chapter 7. Economic optimization and economic feasibility study for PWS are presented in Chapter 8. Chapter 9 presents the summary of the work and the major conclusions derived from the study.

2. Overall modelling concept

A simulation-based allocation model is proposed in this study for the modelling of the Malaprabha catchment. Simulation tool is used to model the catchment hydrological processes, whereas the allocation tool is used to understand how the simulated runoff can be best allocated between different geographic areas as well as between different sectors.

2.1 Selection of modelling tools

With the objective of analyzing the feasibility of Payments for Environmental Serices, PES, in Malaprabha catchment, hydrologic modelling is required to understand the water availability and demand in the area. Modelling of the hydrological processes taking place in the catchment under the current land use scenario and the impact of any possible change in the land use practices on the stream flow are the major interests of the current study. Once the water availability is estimated, water allocation model can be used to understand the most productive way of distributing the water among different geographical locations as well as different sectors. In addition, various watershed service scenarios, in the form of land use change and irrigation cut off, need to be built in the model to study the effectiveness of each service in improving the water availability. The results from the hydrological model can be used in the PES analysis to identify the potential service providers and beneficiaries as well as to identify the feasibility of PES in the watershed.

A detailed review of state of the art in hydrologic and water allocation modelling was carried out to select the appropriate model for the current study. Description of available modelling tools and approaches is given in the report "Integrated River Basin Modelling Framework to Support Payments for Watershed Services" (Badiger and Tor Hakkon, 2007). From the review the following set of criteria were used in the selection of the models:

- Ability to use spatially distributed information related to soil, land use and hydro-meteorological data
- Reasonably comprehensive to include surface and subsurface interaction
- Reasonably user-friendly to set up the model and implement
- Not too demanding in terms of input data.

- Affordability for similar implementations in developing country context or available as a public domain package

The primary goal of the review exercise was to identify a modelling tool that can implement a fairly rigorous hydrological analysis and water allocation with an optional module to assess economic implications. Due to non-availability of such a single modelling package, a two level selection approach was used. At the first level a suitable hydrological model has been singled out based on the critical processes it can model more specifically, enabling upstream-downstream hydrological linkage. At the second level, one of the available water accounting and allocation packages that can assess selected scenarios has been considered. The two models together will be the core components of the tool box for assisting the PES.

SWAT - Soil and Water Assessment Tool (Arnold et al., 2000) was selected for the hydrologic modelling of the watershed. SWAT is semi-distributed model based on the algorithms describing physical processes in a watershed. It is a simple, but robust model which simulates various components of the hydrological cycle from weather simulation to deep aquifer recharge. The model is designed as a continuous time series model with daily time step, which can be used for estimating the long term impacts of watershed management programs. AVSWAT has a GIS front-end using Arcview that provides the flexibility to use spatially referenced data directly thereby facilitating the modelling with spatially varying parameters (Di Luzio et al., 2002).

Key features that result in the wide applicability of SWAT are the following.

- modelling based on physical process associated with soil and water interaction
- flexible to incorporate crop characteristics, cropping stage and duration
- flexibility on input data requirement
- dynamic - Capable of modelling the changes in land use and management practices
- computationally efficient
- capable for long-term simulations
- freely available.

MIKE-BASIN developed by the DHI (www.dhigroup.com) is selected for carrying out the water allocation modelling. When the selection of modelling packages was carried out, a prime factor in identifying MIKE-BASIN was its ability to carry out economic optimization of water allocation. However, the version used in the study which is much more recent lacks this feature. The figure below shows how Arcview-SWAT (AVSWAT) and MIKE-BASIN should work together in this India-PES project.

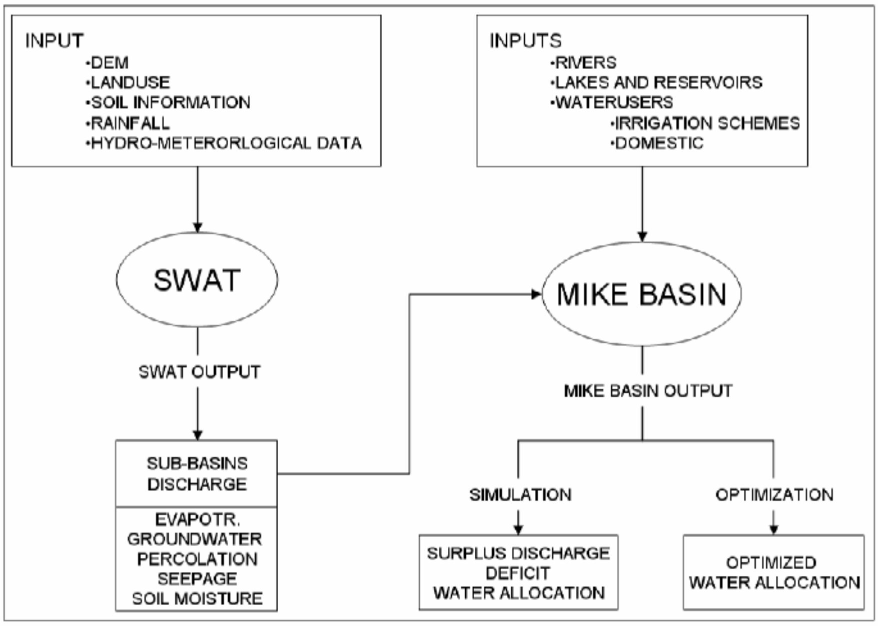


Fig. 2.1 Schematic representation of the proposed integrated hydro-allocation model

The figure also includes the economic application that was included in the previous version of MIKE-BASIN. It has been understood from the developers that the economic optimization module is currently under development.

3. Hydrological modelling – AVSWAT

SWAT simulate various hydrological processes viz., surface runoff, infiltration, direct evaporation from soil, plant transpiration, soil moisture storage, percolation, shallow and deep aquifer recharge, revaporation, return flow, transmission losses, bank storage, retention storage, ponds, reservoirs and wetlands as well as water routing through the channels. The whole process can be considered in two phases: land phase and routing phase. These are described in detail in the following subsections.

3.1 Water balance in the land phase

In the land phase, SWAT considers water storage in four different layers viz., canopy storage, root zone storage, shallow aquifer storage and deep aquifer storage (Fig.1). It also considers surface runoff, infiltration, soil moisture redistribution, evapotranspiration, lateral sub-surface flow, storage in reservoirs and ponds, and transmission losses. This determines the amount of water reaching the stream from different subbasins. Water balance of the land phase is given in Eqn. 3.1 (Neitsch et al., 2005)

$$SW_t = SW_o + \sum_{i=1}^{t}\left(P_i - Q_{surf,i} - E_{a,i} - w_{seep,i} - Q_{gw,i}\right) \tag{3.1}$$

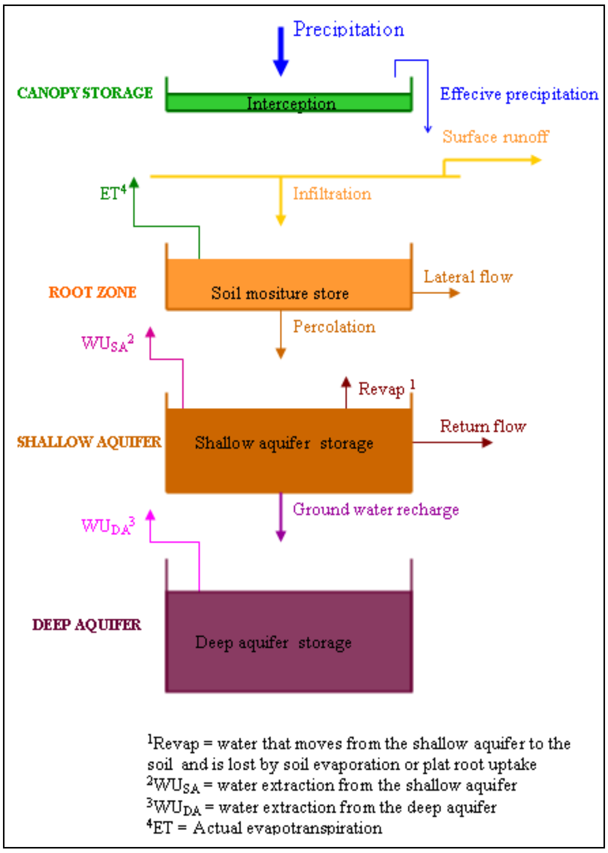
Where, SW_0 and SW_t are the initial and final soil moisture content, respectively. P_i, $Q_{surf,i}$, $E_{a,i}$, w_{seep} and $Q_{gw,i}$ are the rainfall, surface runoff, evapotranspiration, water entering into the vadose zone from the soil profile and the amount of return flow happening on i^{th} day.

Surface runoff

Surface runoff and infiltration are estimated by using USDA Natural Resources Conservation Services (previously known as Soil and Water Conservation Services) curve number (SCS-CN) method (SCS, 1972). A modified form of SCS-CN method, that consider daily variation in soil moisture for the estimation of potential maximum retention (*S*) is used in SWAT (Arnold et al., 2000)

Lateral subsurface flow

Lateral subsurface flow (interflow) originates from the vadoze zone depending on the hydraulic conductivity of the soil layer, slope and soil moisture content. It is estimated by using a kinematic storage model based on the water balance in the layer (Neitsch et al., 2005).



[1] Revap = water that moves from the shallow aquifer to the soil and is lost by soil evaporation or plat root uptake
[2] WU_{SA} = water extraction from the shallow aquifer
[3] WU_{DA} = water extraction from the deep aquifer
[4] ET = Actual evapotranspiration

Fig. 3.1 Schematic representation of the hydrologic processes in SWAT at the land phase

Percolation

Water is allowed to percolate from one layer to the underlying layer, when the soil moisture content exceeds the field capacity (*FC*). It is estimated as shown in Eqn. 3.2

$$Percolation = (SW - FC)\left(1 - \exp\left(\frac{-\Delta t . K_{sat}}{(SAT - FC)}\right)\right) \qquad (3.2)$$

Where, *SAT* is the moisture content in the soil layer at saturation Δt is the length of time step and K_{sat} is the saturated hydraulic conductivity of the soil.

Evapotranspiration

Hargrave’s method (Hargraves et al., 1985) included in SWAT is selected for the estimation of potential evapotranspiration (PET). The expression used for estimating PET is shown below.

$$\lambda . PET = 0.0023 H_o (T_{mx} - T_{mn})^{0.5} (\overline{T_{av}} + 17.8) \qquad (3.3)$$

Where, λ is the latent heat of vaporization (MJ kg^{-1}), H_o is the extraterrestrial radiation (MJ m^{-2}d^{-1}), T_{mx}, T_{mn} *and* $\overline{T_{av}}$ are the maximum, minimum and average air temperatures for a day (^{o}C). The actual evapotranspiration is calculated from PET. SAWT considers direct evaporation from the water intercepted by the plants, plant transpiration as well as direct evaporation from the soil (sublimation) (Neitsch et al., 2005).

Revaporation

Revapopration (*Revap*) is the water that travels from the shallow aquifer to the soil upper soil layer due to capillary action, and is lost through direct evaporation or root uptake. *Revap* is assumed to be a fraction of potential evapotranspiration (PET) and is estimated by specifying the revaporation coefficient.

Return flow

Return flow is the groundwater flow from shallow aquifer to the stream when the storage threshold limit is exceeded. Expression for the estimation of return flow is given below (Hooghoudt, 1940).

$$Q_{gw} = \frac{8000.K_{sat}}{L_{gw}^2}.h_{wtbl} \tag{3.4}$$

Ground water recharge

A fraction of the daily recharge to the shallow aquifer is assumed to be percolating to the deep aquifer. It is estimated by using the deep aquifer percolation coefficient for each subbasin. Amount of water percolating to the deep aquifer is assumed to be lost from the system and is added to the deep aquifer storage.

Reservoir & ponds

The model provides an option to incorporate the impact of reservoirs and ponds in the catchment hydrology. Water balance is used to estimate the outflow from the ponds, whereas reservoir operation rules can be specified to estimate releases (Neitsch et al., 2005).

Cropping practices and water management

Various agricultural practices starting from planting to harvesting, including fertiliser application and irrigation can be specified in SWAT in terms of heat units or by date. Similarly, in case irrigation, irrigation scheduling can be done by heat units or by date. The source of irrigation water can also be specified in SWAT, so that the irrigation is applied only when water is available in the specified source (as simulated by the model).

3.2 Flood routing

Water yield is estimated separately for each Hydrological Response Units (HRUs) separately. HRUs can be understood as homogeneous areal unit characterized by certain similar land use and soil combination. Sum of the water yield from each HRU in a subbasin, and the stream discharge from the upstream river reach are taken as the inflow to any channel reach. Once the water reached any channel, it is routed to the watershed outlet. As the water flows through the channel, a portion of it may go as transmission loss or direct evaporation. In addition to this is the pumping for agricultural or domestic use. Water balance in the channel reach is shown below.

$$V_{stored,t} = V_{stored,0} + V_{in,i} - V_{out,i} - tloss_i - E_{ch,i} + div_i + V_{bank,i} \tag{3.5}$$

where, $V_{stored,t}$ and $V_{stored,0}$ are the volume of water stored in the reach at the beginning and end of the time step *i*. $V_{in,i}$ and $V_{out,i}$ are the volume of water flowing into and out of the reach, respectively during the time step *i*. Transmission loss and direct evaporation from the channel reach are represented by $tloss_i$, and $E_{ch,i}$, respectively. Volume of water added or removed from the reach is represented by the term *div*. $V_{bank,i}$ represents the volume of water added to the reach from back storage via return flow.

Transmission loss

During dry periods, with no groundwater contribution to the stream flow, a part of the water flowing in the stream gets percolated through the sides and bottom of the stream. This loss from the stream water during transmission is termed as transmission loss. Transmission loss is proportional to the channel hydraulic conductivity (K_{ch}), length and wetted perimeter of the channel, and the travel time.

Evaporation loss

Evaporation loss from the channel is assumed proportional to PET and is determined by using a coefficient known as the reach evaporation adjustment factor.

Bank storage

A fraction of the transmission loss is assumed to be stored in the banks. This bank storage contributes flow to the reach within the subbasin, and this volume that reaches back to the stream is estimated by using a coefficient bank flow recession constant (α_{bank}) as shown below (Neitsch et al., 2005).

$$V_{bank} = bnk.\left(1 - e^{-\alpha_{bank}}\right) \tag{3.6}$$

Where, *bnk* is the total amount of water in the bank storage. V_{bnk} is the volume of water added to the bank storage via return flow.

Variable storage coefficient method developed by William (1969) is further selected for the channel flood routing. It is based on the continuity equation in a channel reach and is expressed shown below.

$$V_{out,2} = SC.\left(V_{in} + V_{stored,1}\right) \tag{3.7}$$

Where, *SC* is the storage coefficient for the channel reach.

3.3 GIS Interface for SWAT

In order to facilitate the modelling using spatially distributed data viz., land use, soil characteristics, meteorological characteristics, SWAT was later on integrated with the Geographic Information System (GIS) software ArcView (www.esri.com) developed by ESRI. AVSWAT (Di Luzio et al., 2002) with its GIS framework and a user friendly interface, facilitates the input of geographically referenced data as well as the hydro-meteorological data at multiple stations within the catchment. Fig. 3.2 shows the schematic representation of AVSWAT. Modules available in AVSWAT, input data requirements, input and output data formats are shown in the Fig. 3.2.

In order to facilitate modelling incorporating spatially distributed data, the watershed is partitioned into small units called sub-basins and hydrological response units (HRUs). Important functional components in AVSWAT are the following (Di Luzio et al., 2002): watershed delineation; definition of HRUs; input parameterization; editing and scenario management; model execution and calibration tools.

By using the DEM (Digital Elevation Model), the model identifies the catchment area that drains through the specified outlet point. The catchment area is further divided into subbasins and HRUs based on the user specified outlet points within the catchment. Finally the output is generated in the form of tables showing the various components of the hydrologic cycle at the land phase (both subbasin and HRU level) and along different channel reaches.

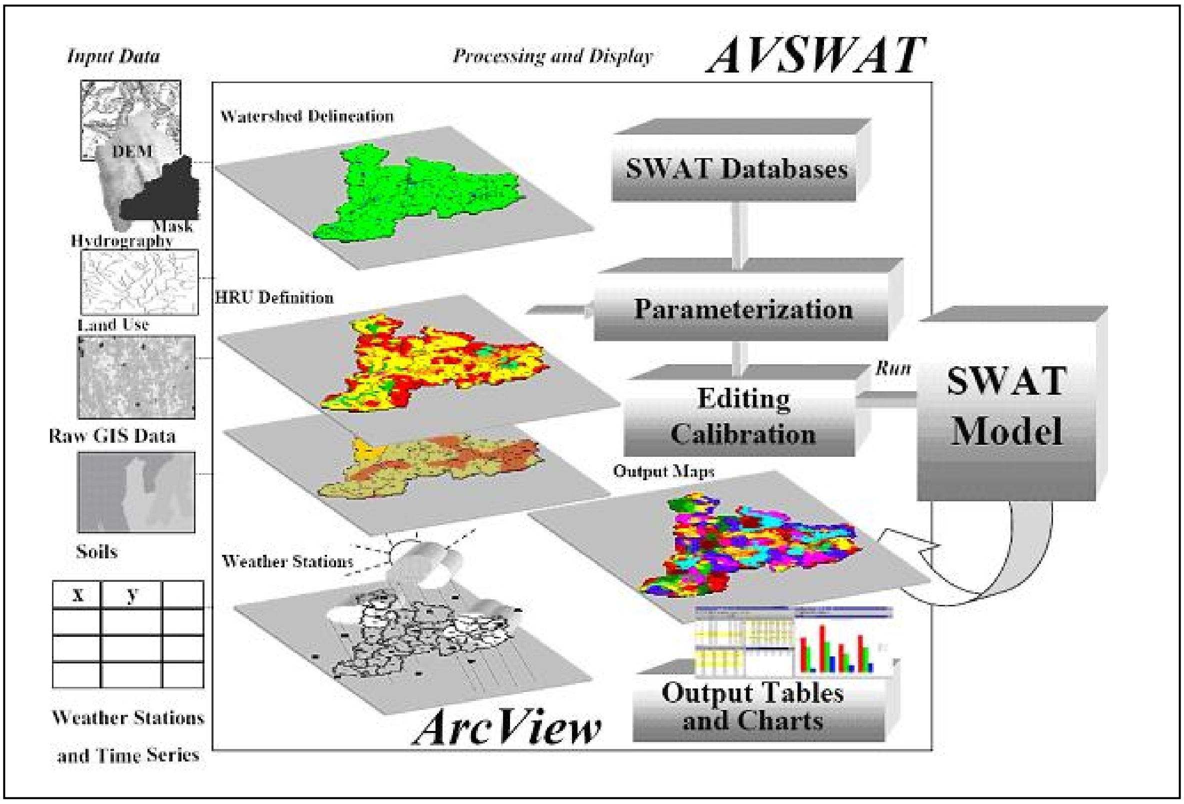


Fig 3.2. Schematic diagram of the integration of ArcView with SWAT (Di Luzio et al., 2002)

3.4 Input data

The following input data is required for AVSWAT.

- DEM: Digital elevation model of appropriate resolution
- Soil: Map showing the soil type and detailed information about each soil type including depth, percent of sand and clay content, water holding capacity of the soil, bulk density, hydraulic conductivity etc.
- Land use/ land cover:
- Stream network
- Hydro-meteorological data: Temperature, rainfall, relative humidity, sun shine hours and wind velocity
- Stream flow observations
- Pond and reservoir data: catchment area, storage capacity and release rules (if any).
- Channel characteristics: Length, width, channel hydraulic conductivity, Maning's roughness coefficient
- Cropping & irrigation schedule

4. Water allocation modelling- MIKE-BASIN

MIKE-BASIN is software developed by Danish Hydrologic Institute, DHI. MIKE-BASIN uses the ESRI software ArcEditor as a basis (www.dhigroup.com). MIKE-BASIN is a versatile, GIS-based decision support tool for integrated water resources management and planning. MIKE-BASIN is used for addressing water allocation, conjunctive use, reservoir operation, or water quality issues.

MIKE-BASIN couples the power of ArcGIS with comprehensive hydrologic modelling to provide basin-scale solutions. The MIKE-BASIN philosophy is to keep modelling simple and intuitive, yet provide in-depth insight for planning and management.

4.1 MIKE-BASIN in general

For hydrologic simulations, MIKE-BASIN builds on a network model in which branches represent individual stream sections and the nodes represent confluences, diversions, reservoirs, or water users. The ArcGIS interface has been expanded accordingly, e.g., such that the network elements can be edited by simple right-clicking. Technically, MIKE-BASIN is a quasi-steady-state mass balance model, however allowing for routed river flows.
Typical areas of the MIKE-BASIN application:

- Water availability analysis: conjunctive surface and groundwater use, optimization thereof.
- Infrastructure planning: irrigation potential, reservoir performance, water supply capacity, waste water treatment requirements.
- Analysis of multisectoral demands: domestic, industry, agriculture, hydropower, navigation, recreation, ecological, finding equitable trade-offs.
- Ecosystem studies: water quality, minimum discharge requirements, sustainable yield, effects of global change.
- Regulation: water rights, priorities, water quality compliance.

MIKE-BASIN modelling setup consists of river nodes, river links, catchments, irrigation nodes, water user nodes and reservoir nodes. In addition water channels lead water to and from water user nodes and irrigation nodes. River nodes and river links are the main elements in the river modelling. River nodes are placed wherever input data should be given or results should be extracted in addition to water extraction points and return flow points. In other words, wherever some changes regarding water amount occur. River links are given between the river nodes. Catchment nodes and areas represent inflow to the model. Catchment area properties include inflow time series.

4.2 Model components

Irrigation tool

Irrigation water demand is calculated based on the FAO-56 model. If the calculations indicate that there are water shortages, there are several rules that can describe how the available water should be distributed onto the specific field.

1. Equal shortage: the fields get the same percentage of the demand covered.
2. By priority: the water is distributed according to the specific priority
3. By yield stress: the water is distributed according to how sensitive the crops are for water stress during the specific crop stage.

MIKE-BASIN calculates the accumulated yield according to the irrigation model and the climatic conditions.

Yield model

The yield model is used to calculate the crop outcome or yield from the specified crops. The yield model depends on the water availability for the crops and how efficiently they are irrigated. The yield model is based on FAO-33 (Doorenbos et al., 1979) and the following parameters are required:

- Potential yield: Maximum potential yield under perfect conditions [kg/ha].
- K_y: It is the Yield response factor that determines how sensitive the yield is to water stress at a given crop stage.

ET component

MIKE-BASIN uses the FAO 56 Soil water model (Allen et al., 1998) in the irrigation module. The FAO56 model uses the original Penman-Monteith equation for calculating reference evapotranspiration (ET_0). It is also possible to specify observed values for ET_0 in a time series.

Crop model

The crop model is used to specify the parameters for the crops based on FAO-56 guidelines. The following are the parameters required for the crop model.

- Stage length: Crop stages are divided into an initial, development, middle and late crop stage and the periods are given in number of days.

- Crop coefficient (K_{cb}): It is the ratio of the crop evapotranspiration over the reference evapotranspiration when the soil surface is dry but transpiration is occurring at potential rate. This coefficient is specified for every crop stage.
- Root depth: Root depth is specified for initial and middle stage.
- Maximum vegetation height
- Depletion fraction: Average fraction of total available soil water that can be depleted form the root zone before moisture stress

The model is closely linked to a yield model and a crop sequence model.

Crop sequence model

Crop sequence model specifies the crop rotation on a given field i.e., when a crop is planted or sowed. The following are the parameters required in the crop sequence model.

- Crop type
- Sowing date for the specific crop type
- Specify if the crop is irrigated by the irrigation method or by rainfall only.
- Irrigation method.

Though it is difficult to arrive at a fixed sowing date for most crops, as it depends on the onset of monsoon every year in the Indian context, reference dates of sowing were used from www.fao.org.

Calibration tool

Calibration is based on observed discharge and observed reservoir water level. In addition, the irrigation nodes can be tested to meet the observed water release from the reservoir or stream flow.

4.3 Model input

The following elements can be given as input to MIKE-BASIN:

- Rivers represented by river reaches and nodes
- Catchment area
- Reservoirs of 3 different types: lakes, rule curve reservoirs and allocation pool reservoirs
- Water users, including irrigation, represents any user that abstract, consumes and returns surface and/or groundwater.
- Hydrologic information at different catchments viz., stream flow, rainfall, reservoir water level.

- Soil conditions (Field capacity, wilting point, depth of evaporable layer and porosity) must be specified to calculate the soil water content in the root zone and thereby the available water for transpiration
- Land use and land cover characteristics
- Water demand at different nodes (eg., drinking water demand)
- Crop characteristics
- Irrigation schemes and methods

4.4 Difficulties in the MIKE-BASIN application in Malaprabha catchment

One of the main objectives of choosing MIKE-BASIN for the water allocation modelling was that the software was marketed as being capable of running economic optimization of allocation of water between uses. This was true for older versions of the software running on an ArcGIS platform. However the latest version of MIKE-BASIN running on ArcGIS turned out not to have this functionality. DHI are currently developing an excel application that can do an Economic optimization of MIKE-BASIN results. The Excel based application will ideally be used for optimal water allocation between different water users such as irrigation, hydropower, water supply and industrial processing. In the course of our study in Malaprabha we were able obtain data on water use, yields and economic returns to downstream irrigated agriculture, as well as domestic water supply demand in towns and cities of the catchment. The Excel application currently available for MIKE-BASIN can do an analysis with regards to allocation between different kinds of water users, but not water allocation between one type of water user, such as agriculture upstream and downstream.

Also, upon further inspection it turned out the irrigation module in MIKE-BASIN was not adequate for modelling paddy irrigation, which is based on standing water rather than irrigation applications. This only became clear after NIVA visited DHI in Denmark, September 2008, to clarify the limitations of the model directly with the programmers. This is currently being rectified by DHI, but unfortunately came too late for the project finalisation. The knowledge gained in the current limitations and future potential of MIKE-BASIN will however be useful in future modelling of water allocation in the Basin.

Other authors have also completed water allocation modelling in the Malaprabha. (George et al. 2008), using the SYMHYD and REALM models. These models do not have economic optimisation capability either at present. While MIKE-BASIN was found lacking in our application, it still seems to be one of the better water-allocation based models available for economic assessments. However, integration of a specialised economic optimisation models for irrigation (Reddy and Kumar 2008) with AVSWAT should be evaluated in future as it may prove to be an approach that is better adapted to irrigation water allocation optimisation, than using MIKE-BASIN.

Apart from these technical aspects of modelling, a closer evaluation of the water allocation problem in Malaprabha suggested that economic optimisation between different water uses was not as economically relevant an issues as originally thought. The main water user in the catchment is irrigation water and to a much lesser extent domestic water user. In the water optimisation module currently available, domestic water as drinking water is always given priority 1 by the model, with all domestic water demand being met before water is allocated to irrigation. Drinking water demand is modelled as a "constraint" on irrigation, and no real trade-off is possible. Also, the amount of drinking water is small and demand will always be met either by available river water or by groundwater.

Considering both technical and socio-economic arguments we decided that the approach available was to apply the MIKE-BASIN Irrigation Module.

4.5 Integration with AVSWAT

The MIKE-BASIN Irrigation module covers the whole irrigation aspect from soil and climate conditions, crops and cropping pattern, as well as the irrigation canals and the distribution of water. The Irrigation Module calculates average agricultural yields across these different irrigation schemes in the basin. It also calculates crop yield given irrigation recommendations based on FAO-56 Irrigation and Drainage manual (Allen et al., 1998), the theoretical crop coefficients of different crops and soils and the available water for irrigaiton. Irrigation demand will be based on these calculations and the availability of water both from precipitation and from the river stream/reservoir. The differences between yield reported by farmers, average and potential yields can be used to construct irrigation scenarios in the upstream and downstream and assess trade-offs between yields. Assuming that crop prices and costs of inputs are similar in the upper and lower catchment, crop yield differentials can be used to evaluate whether shifting water between parts of the catchment is economically optimal. Fig. 4.1 shows the integration of AVSWAT and MIKE-BASIN irrigation model with the economic optimization model.

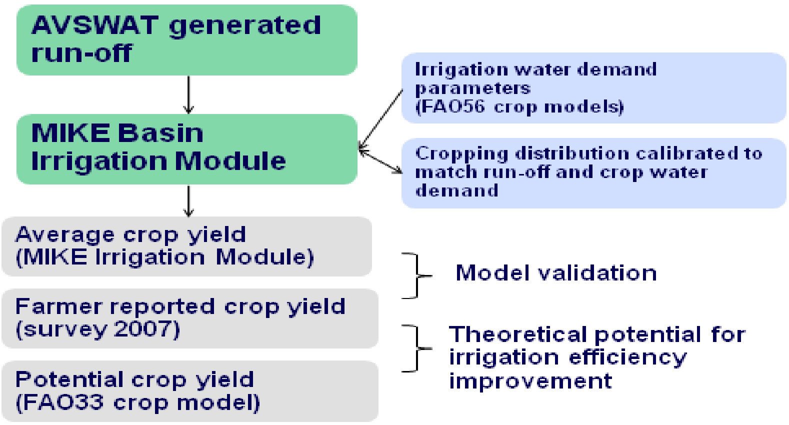


Fig. 4.1 Interaction between AVSWAT, MIKE-BASIN Irrigation Module, observed yield and potential yield.

5. Database assimilation

Data related to the topography, terrain characteristics, climatic conditions, land use and management practices are collected from various sources and aggregated for the application of the hydro-allocation model in the Malaprabha catchment. The data includes both spatial and attribute data. All the spatially referenced data are first georegistered and brought to a common scale. The attribute data viz., time series of rainfall, stream flow, and hydro-meteorological data are further assigned to the corresponding geographic locations. Comprehensive data aggregated for this study are described in the following sections. Fig. 5.1 shows the Malaprabha basin and the catchment area.

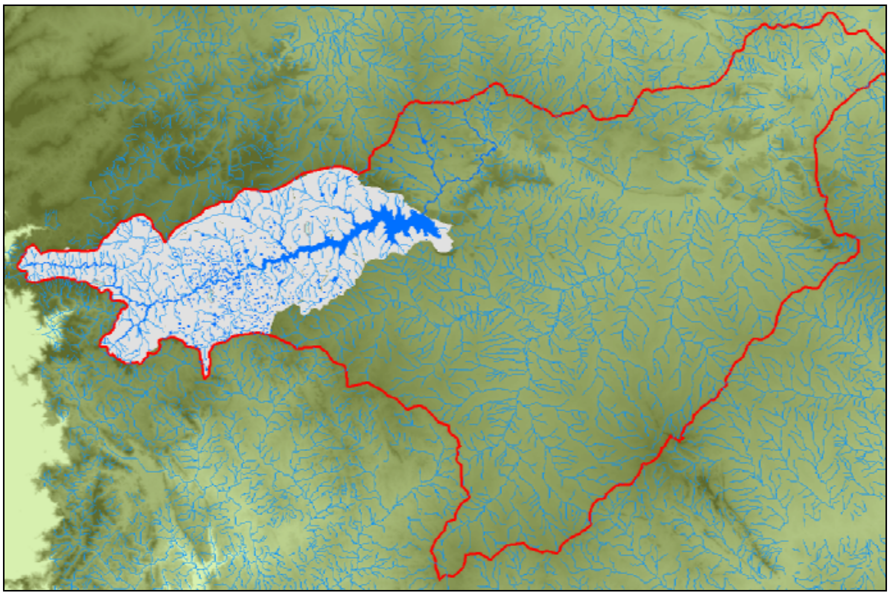


Figure 5.1 Malaprabha river basin (red) and the modelling area (grey)

5.1 Spatially reference data

Digital elevation model

Shuttle Radar Topography Mission (SRTM) data of 90m spatial resolution is used to generate the Digital Elevation Model of the area. The data is primarily corrected for depressions and georegistered according to the stream network obtained from the topographic sheets of scale 1:50,000. In order to assure the simulated concentrated flow lines in close match with the natural flow paths, the DEM is further corrected with respect to the channel network during the drainage delineation process Fig. 5.2. It is a typical upstream catchment with hilly terrains marking the catchment boundary. The elevation above mean sea level varies from 1900m at the upper catchment to almost 620 m near the watershed outlet.

Channel network

Digital channel network of the catchment is generated by digitizing the major stream lines from the topographic sheets of 1:50,000 scale (Fig. 5.3).

Land use/ land cover

Land use map of the area is generated from remote sensing satellite imagery through a rigorous supervised classification incorporating the several ground truth points. IRS P6 LISS III imageries of January, March and November 2007 were used to develop the land cover information, particularly the broad cropping patterns based on water-use intensity. In the present study 8 land cover classes are generated with four are agricultural classes and four non-agricultural classes. These classes are shown in Fig 5.4. Entire agricultural area is divided into 4 classes based on the agricultural practices and crop characteristics. Areas under paddy (water intensive crop) and sugarcane (perennial irrigated crop) are grouped into two separate classes. All other irrigated crops (wheat, maize, etc…) are considered in a single class called “other irrigated crops”. Less water intensive, rainfed crops like ragi, bajra and jowar are classified into “unirrigated crops”. From the land cover map, most of the irrigated crops were identified in zone 2, which extracts a large part of the stream flow for irrigation. Further, paddy cultivation is concentrated mostly in the upper catchment only, where the rainfall is good enough to support paddy cultivation. Entire forest cover in the catchment is located in zone 1 (upper catchment) which coincides with the hilly terrain and very high annual rainfall. A detailed description of the methodology adopted for extracting the land use/ land cover information from the satellite imagery is explained in section 5.2.

Soil

Hydraulic characteristics like percentage of sand and clay content, hydrologic group, bulk density, number of layers, depth of each layer, and available water content of each of the soil type are obtained from the National Bureau of Soil Survey (NBSS) (Fig. 5.5). Description of the soil classes are given in Appendix I. Gravelly soil and cracking clay, that helps infiltration, were found in the upper catchment and along the ridge areas in zone 2. Deep layers of clayey soil are dominant over the other areas.

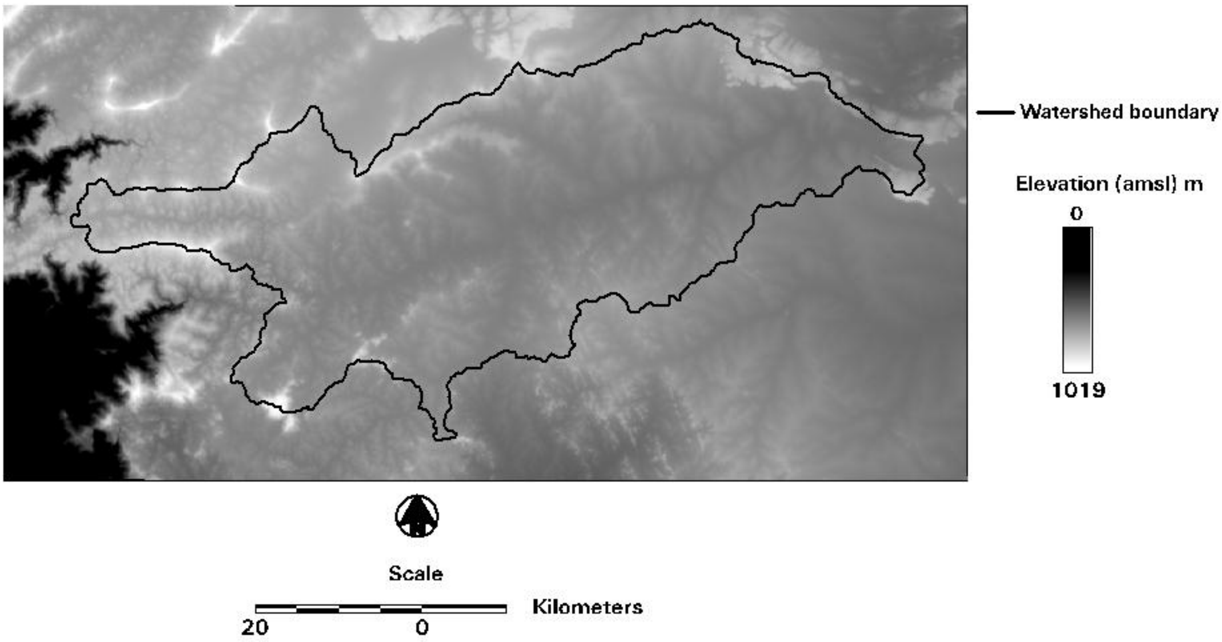


Fig 5.2 Digital elevation model of Malaprabha catchment

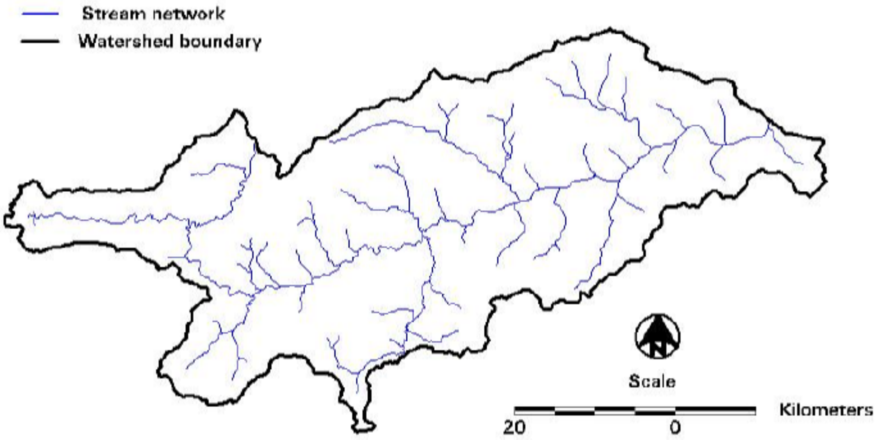


Fig 5.3 Drainage network of the Malaprabha catchment

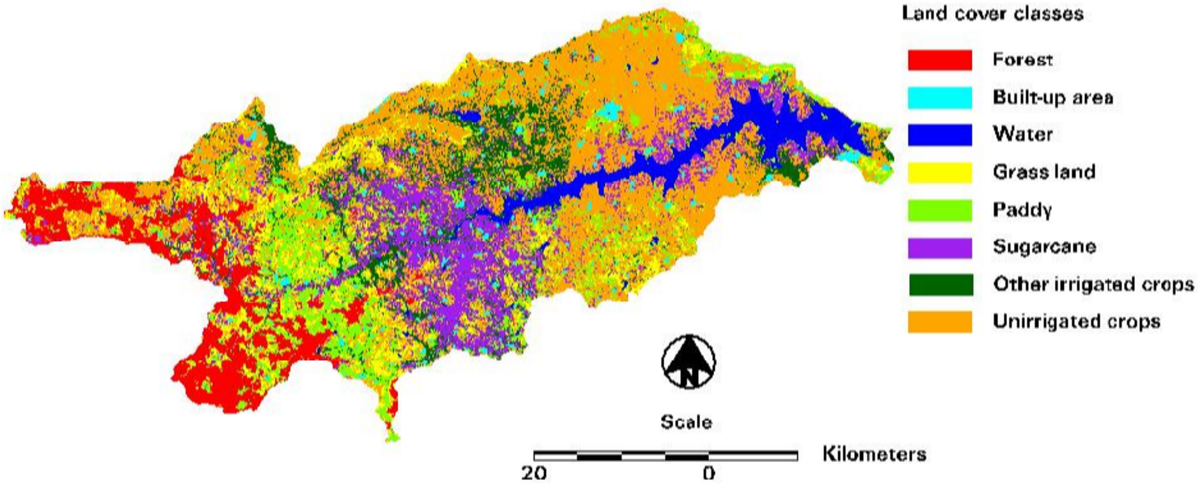


Fig 5.4 Land use and land cover map of Malaprabha catchment

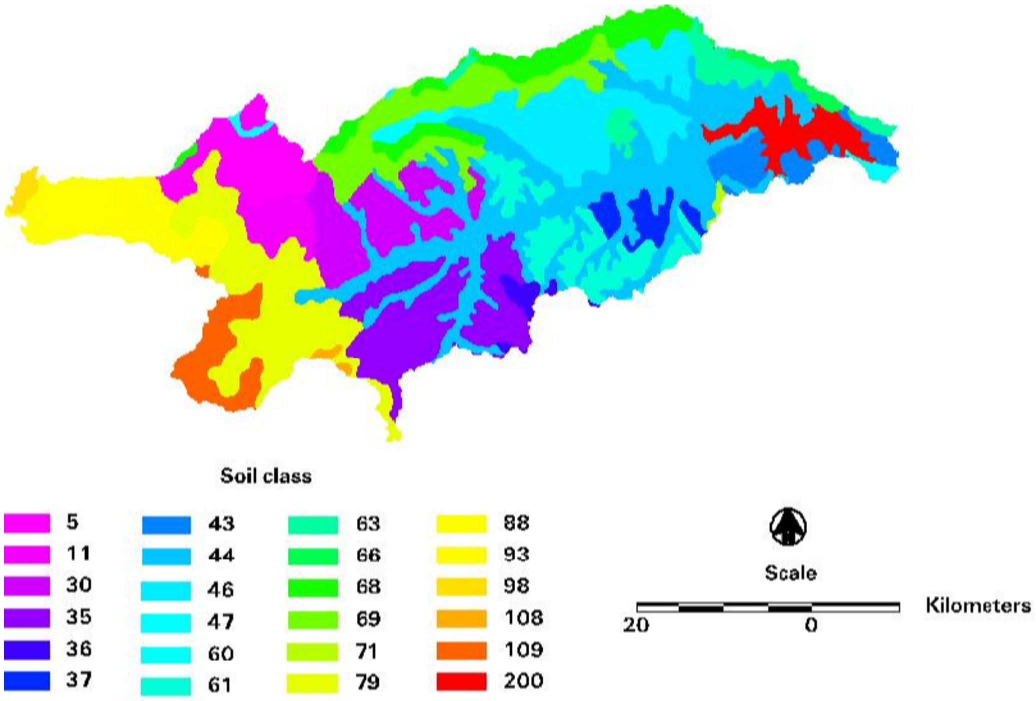


Fig 5.5 Soil map of the Malaprabha catchment

Climate stations

Climate station, representative of the entire watershed is selected for simulating the climate condition in the catchment. In the present study, the observatory located near the Malaprabha Dam is selected (Fig 5.6).

Rain gauge stations

Since the rainfall shows drastic variations over the catchment area, rainfall data from the maximum possible number of raingauge stations are incorporated in the present study. In this study 18 stations are used with more or less one station per subbasin, assuring proper accounting for the spatial variation in rainfall (Fig 5.6).

Watershed outlet

The reservoir outlet point is selected as the watershed outlet and its geographic location was fed as input to the model (Fig 5.6).

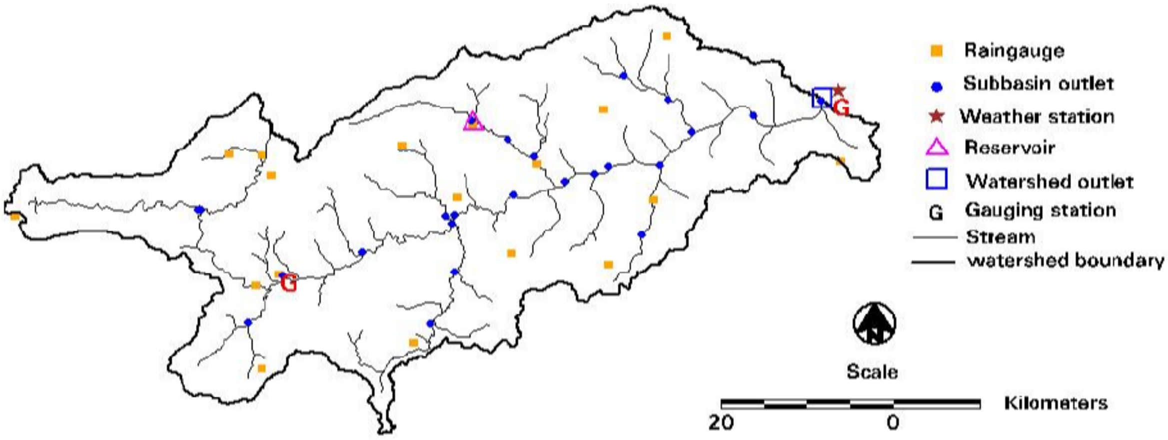


Fig 5.6 Observatories and subbasin outlet points in the Malaprabha catchment

5.2 Extraction of land use/ land cover data from imagery

For the purposes of the hydrological model, it is necessary to create a map that not only distinguished between different broad categories of land cover, such as forest, water bodies and agricultural land, but also between certain land uses within the agricultural land cover class. Specifically, it was important to differentiate water intensive crops, such as paddy rice and sugarcane, from dryland crops. Land use and land cover data from the official records (Indiastat, 1999) indicate that about 20% of the basin is under sequential multiple cropping. In addition, many crops may have similar spectral signatures at various points within their growth cycle. Therefore multiple satellite images within a single calendar year, in conjunction with detailed field knowledge about the cropping cycles of the region, were used to identify areas of multiple cropping, and also to distinguish sugarcane (a perennial crop) from paddy rice (an annual crop). Images from November (very end of kharif season), January (rabi season) and March (summer season) from the Linear Imaging and Self-Scanning Sensor (LISS-III) on the IRS satellite RESOURCESAT-1 (IRS-P6) is chosen for the study. The spatial resolution of this sensor produces images of 24m by 24m pixel size and spectral data is given in four bands, one each of green, red, near infrared, and mid infrared wavelengths. Two images were required to cover the entire watershed, therefore a total of six images were obtained for the 2007 calendar year. Exact image dates are noted in Table 1.

Table 5.1: Satellite Image dates used for the analysis

Season	**West Image: Path/Row 96/62**	**East Image: Path/Row 97/62**
Kharif	22 November 2007	27 November 2007
Rabi	14 January 2007	19 January 2007
Summer	3 March 2007	8 March 2007

Preprocessing of the imagery included both geometric and radiometric corrections. Georectification of the images was done to the topographic maps of the region (1:50000 scale) and further georectified based on ground control points (GCPs) taken in the field. RMS error for all georectifications was between 13m and 21m (less than one pixel error). The images were then radiometrically corrected using the Dark Object Subtraction *cos(t)* method as outlined by Chavez (1996) and as provided as a module within IDRISI Andes Edition (www.clarklabs.org).

A series of unsupervised classifications were run on individual dates and combinations of multiple dates, for each side of the basin. This provided information on the spectral variation across the basin. The primary outcome of the unsupervised classification was to give a sense of what classes would be possible to expect from a supervised classification. Water was masked out using a supervised classification. Village areas were masked out using the map of "built-up" areas in the map of land use developed by KSRSAC (2004). Forest areas were masked out using a combination of two methods: a supervised classification and manual image inspection. These three masks were used to define water bodies, built-up areas, and forested areas before supervised classification began.

In order to classify the images using supervised techniques, groundtruth (GT) data was collected beginning in December 2007 and finishing in July 2008. A total of 622 separate groundtruth points were taken. In order to perform a supervised classification within Idrisi, it was necessary to transform the groundtruth points into polygons. A total of 273 polygons were digitized, approximately evenly distributed across the basin. After groundtruth data was finalized, supervised classification was carried out on the unmasked areas (only agricultural and grassland areas). The maximum likelihood algorithm was deemed to be the most robust. Each side of the basin was classified separately. All 4 bands for all three dates (12 bands total) were used as inputs within the classification. Various classifications were run, trying different class combinations. The first class breakdown, which was the most detailed attempted, is shown and explained in the first column of Table 2. In addition, ground truth points were grouped into broader classes (as shown in the final column of Table 2), and the supervised classification was run again, in an effort to increase robustness of the classification.

The maps were analysed for internal consistency using the accuracy assessment module available in Idrisi, using the GT points that had been used in the classification itself. Based on this, it was decided that the broader classes classification would be used as the final classification for the model. The two post-classification images were mosaiced together to create the final map (Figure 1). The overall Kappa index of agreement statistic for the west portion of the image (zones 1 and 2) is 92.2% and for the east portion (zone3) is 88.6%.

Table 5.2 Detailed Agricultural Classes

Detailed classes	**Description**	**Broad Classes**
Grassland	Permanent grassland, not irrigated	Grassland
Paddy, unirrigated	Single crop of paddy in kharif	Paddy
Paddy + Other, unirrigated	Paddy crop in kharif, followed by a second crop in rabi, neither crop is irrigated	Paddy
Paddy + Other, irrigated	Paddy crop in kharif, followed by a second crop in either rabi or summer, at least one of the two crops is irrigated	Other irrigated crops
Perennial, irrigated	Year long crops, irrigated at least part of the year, mostly sugarcane and banana	Sugarcane
Perennial, unirrigated	Year long crops, not irrigated, mostly cashew and mango plantations	Other unirrigated crops
Other, unirrigated	Single crop other than paddy in kharif, not irrigated	Other unirrigated crops
Other + Other, unirrigated	Crop other than paddy in kharif, followed by a crop in rabi, neither crop is irrigated	Other unirrigated crops
Other + Other, irrigated	Crop other than paddy in kharif, followed by a crop in either rabi or summer, at least one of the two crops is irrigated	Other irrigated crops

5.3 Attribute data

Rainfall

Daily rainfall data at the 18 raingauge stations across the catchment (Fig 5.6) is collected from the Directorate of Economics and Statistics (DES). Much of the rainfall received in the catchment is from south-west monsoon that is spread from June to November. Fig 5.7.a shows the variation in the amount of rainfall received in different months of a year. Fig. 5.7.b shows the weighted annual average rainfall recorded for the catchment area for a period 1972-2003. Though the annual average rainfall during the last 3 decades seems to be decreasing, long term moving averages for the region suggest no change in the annual average rainfall.

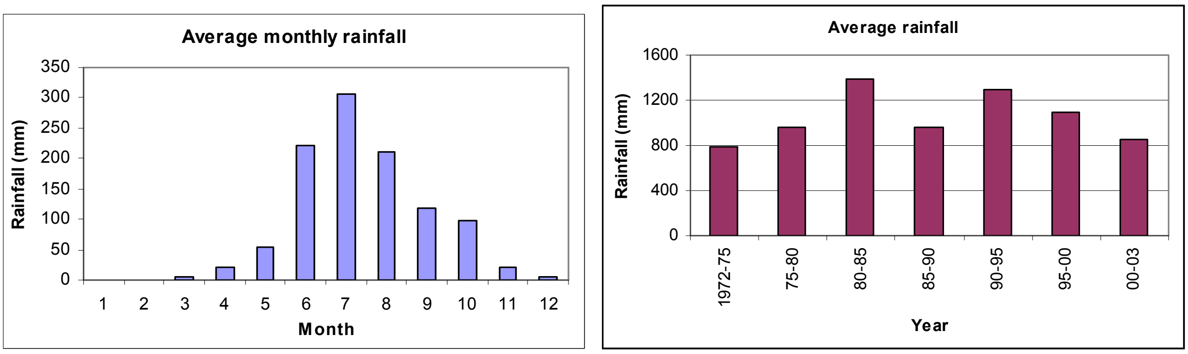


Fig 5.7 Average rainfall (a) in different months of a year (b) for the period 1972-2003.

The area experiences drastic spatial heterogeneity in the rainfall distribution. Annual average rainfall recorded at different stations varies from about 4000 mm at Kankumbi (upper catchment) to about 800 mm at M.K. Hubli (in zone 2) and about 490 mm at Soundatti (near the reservoir, zone 3). Fig 5.8 shows the spatial distribution of the precipitation based on ArcGIS Spatial Analyst analysis.

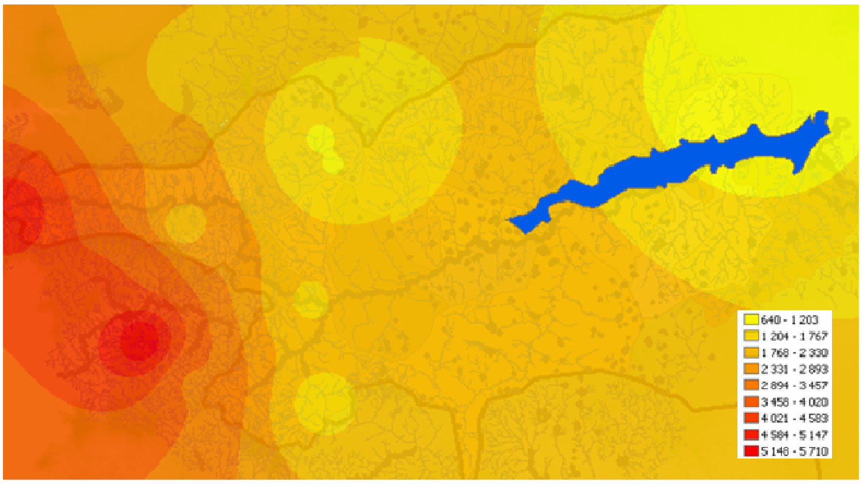


Fig. 5.8 Precipitation in mm/year based on precipitation stations in the area

Hydro-meteorological data

Hydro-meteorological data for the estimation of PET include daily maximum and minimum temperature, wind velocity, and sunshine hours. These data at the observatory located near the Navilutheertha dam was collected from various sources including Indian Meteorological Department (IMD)

Stream flow

Daily stream flow observations at the Khanapur gauging station are collected from the Irrigation Department, Govt. Karnataka. In addition to this, the reservoir inflow (estimated from the water balance) is collected from the Karnataka Neeravari Nigama Ltd. (KNNL), Navilutheertha. From the data, the stream flow was found to be reduced drastically in the last two decades (Fig 5.9 a). Though a corresponding reduction in rainfall is also observed, the average stream flow recorded at the reservoir during the period 2000-2003 was found to be much less than the period 1972-75 where the average rainfall is almost same. Further, runoff coefficient (C), which is the ratio of runoff to rainfall is plotted along with rainfall in Fig 5.9.b to study the change in the runoff generating characteristics of the catchment. For the same rainfall periods, C was found decreasing in the recent years. Thus it is found that reduction in stream flow is not only due to the decrease in rainfall, but also changes in the land use and irrigation practices.

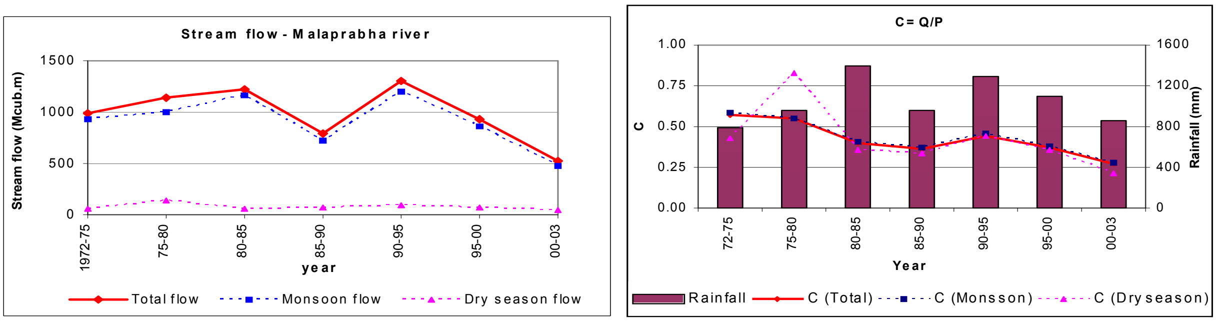


Fig 5.9 Variation in a) stream flow and b) runoff coefficient in Malaprabha catchment

Irrigation practices

Irrigation practice in the area was collected through field observations and interview with the farmers. From the field survey, as well as from the census data conducted by the Government, it has been found that the area shows a fast trend of shift from rainfed to irrigated crops by over-extracting both stream and ground water resources. Fig 5.10 shows the increase in the irrigation and the change of dependency from surface water to ground water that happened since 1970 in the Belgaum district (The entire catchment comes under Belgaum district in Karnataka, India).

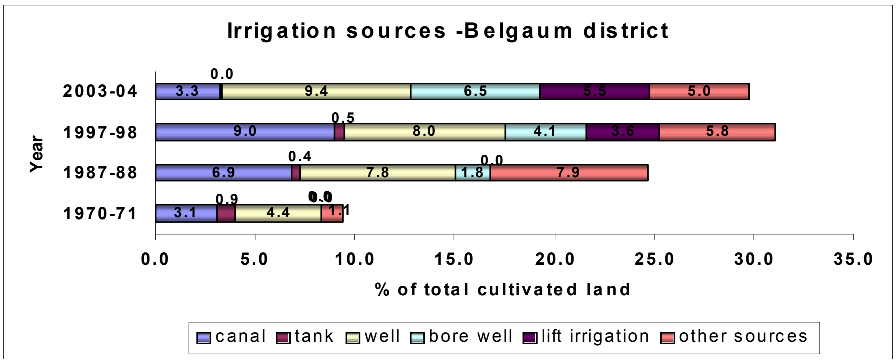


Fig 5.10 Area under irrigation and sources of water supply in Belgaum district, Karnataka (source: District at a glance, Gov. Karnataka)

Domestic water users - Drinking water

Electicity bill at the Bailhongal water supply intake point was collected to estimate the normal pumping rate, which was estimated as 494 LPCD (assuming a pump efficiency of 50%) for a population of 48,000. This converts to 0.275 cub.m/sec, and is assumed as the water requirement at the intake point.

Irrigation schemes

For the water allocation modelling, 5 irrigation nodes are considered in the Malaprabha basin. Two of the irrigation schemes are collections of irrigation schemes. Irrigation occurs all along the river. To include this in MIKE-BASIN, two irrigation collections have been created. There are no exact numbers of how large these areas are, but it is estimated that about 1 km on each side of the river is irrigated. Irrigation node “Upstream Khanapur” includes an area upstream Khanapur and the irrigation scheme “Downstream Khanapur” includes irrigation area downstream Khanapur but upstream of the Malaprabha reservoir.

Table 5.3 Irrigation schemes considered in the Malaprabha basin

Irrigation node	Area [km2]	Precipitation station	Evaporation	Soil
Irrigation upstream Khanapur	80	Khanapur	$E_{\text{upper area swat}}$	Clay
Irrigation downstream Khanapur	40	Khanapur	$E_{\text{middle area swat}}$	Clay
Lift irrigation	350	Bailhongal	$E_{\text{middle area swat}}$	Clay
MLBC	531	Bailhongal	$E_{\text{lower area swat}}$	Clay
MRBC	1400	Saundatti	$E_{\text{lower area swat}}$	Clay

Crop model

Crops considered and the crop characteristics used in MIKE-BASIN is shown in the table below.

Table 5.4 Crop characteristics

	Crop stages [days]					K_{cb}			
	Initial	Development	Middle	Late	Total	K_{cb} initial	K_{cb} middle	K_{cb} late	Hmax
Sugarcane	15	70	220	140	445	0.4	1.25	0.75	3
wheat	15	25	50	30	120	0.3	1.15	1.4	1
Paddy/Rice	30	30	60	30	150	1.05	1.2	0.7	1
Cotton	30	50	60	55	195	0.35	1.15-1.2	0.7-0.5	1.2-1.5
Groundnut	35	35	35	35	140		1.15	0.6	0.4
Sunflower	25	35	45	25	130		1.15	0.35	2
Maize	20	35	40	30	125		1.15	1.05	1.5

Potential yield for the selected crops are shown in the table below. The parameters are derived from www.fao.org

Table 5.5 Yield response factor for the selected crops

	Yield response factor, K_y			
	Initial	Middle	Late	Potential Yield [kg/ha]
Sugarcane	0.75	0.5	0.1	70000
wheat	0.2	0.65	0.55	2600
Cotton	0.2	0.5	0.25	600
Groundnut	0.2	0.8	0.6	900
Sunflower	0.4	1	0.8	2000
Maize	0.4	1.5	0.5	1900

Type of data, source and processing methods used in this study are summarized in the table below.

Table 5.6 Summary of the database assimilation for the Malaprabha catchment

Data	**Source**	**Methodology**
DEM	SRTM	Georectification, correction for depression and stream burning
Land use/ land cover	IRS LISS III imagery	Supervised classification
Soil	NBSS	
Channel network	Topographic sheet	Digitization
Meteorological data	IMD	
Rainfall	DES	
Stream flow	Irrigation dept., Govt. Karnataka and KNNL	
Irrigation practices	Field observations & census data	
Drinking water supply requirement	Electricity bill	
Crop characteristics & yield	FAO	

6. Model application in the Malaprabha catchment

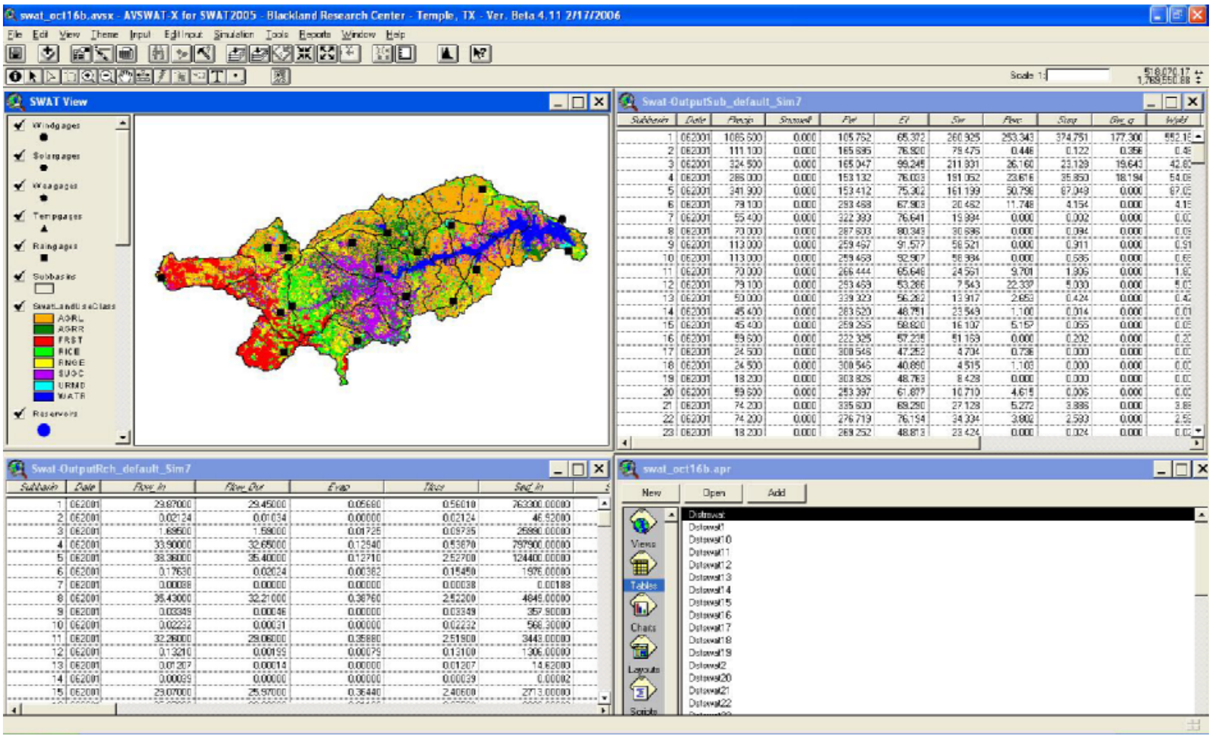
6.1 AVSWAT

AVSWAT is applied to the Malaprabha catchment to simulate the core hydrological processes as well as to study the impacts of land use changes in the stream flow. As a first step the SRTM and the digital channel network is used to identify the flow direction, and further to define the watershed and subbasins. Digital soil and land cover map of the area are used as the input to delineate different HRUs based on the hydrological properties. Each land cover class is customized to the corresponding default classes in SWAT and this helps the model to identify the type of vegetation and the crop characteristics from the default database. Similarly the soil classes are also decoded to SWAT readable format by defining the soil characteristics. Geographic locations of the raingauge stations and the meteorological stations are fed as input to the model. Observed meteorological data collected from the observatory are used to customize the climate station. Further, the observed data for the study period are given as input to the model.

AVSWAT considers the attributes in 9 different classes viz., soil, weather station, subbasin, HRU, channel routing, groundwater, consumptive use, pond data and surface water quality. Model parameters in each of these classes can be modified for each HRUs from the SWAT interface.

AVSWAT simulates the runoff from different layers at the land phase and traces it towards the channel as the inflow to the channel. Further, the water is routed along the channel to the watershed outlet, during which process the direct evaporation and transmission losses are considered. This information about transmission loss at various sections helps to arrive at optimal water allocation plans along the catchment by using the economic optimization tool. AVSWAT produces results at three different levels: HRU, subbasin and reach. The water yield estimated at the subbasin level is used as the input to the water allocation model, MIKE-BASIN.

In the present study a period June 2001-May 2004 is selected as the study period. Though the rainfall and stream flow data is available for a much longer period, due to the lack of information about the earlier land use pattern in the area, the study could not be extended to pre-2000 period. Fig 6.1 shows the model set up for the Malaprabha catchment.



Subbasin	Date	Precip	Snowmelt	Pet	Et	Sw	Perc	Surq	Gw_q	Wyld
1	062001	1085.500	0.000	105.752	65.372	260.925	253.343	374.751	177.300	552.1
2	062001	111.100	0.000	165.695	76.920	79.475	0.446	0.122	0.356	0.4
3	062001	324.500	0.000	165.047	99.245	211.831	26.160	23.129	19.643	42.8
4	062001	286.000	0.000	153.132	76.033	191.052	23.616	35.850	18.194	54.0
5	062001	341.900	0.000	153.412	75.302	161.199	50.798	87.049	0.000	87.0
6	062001	79.100	0.000	293.468	67.903	20.462	11.748	4.154	0.000	4.1
7	062001	55.400	0.000	322.393	76.641	19.994	0.000	0.002	0.000	0.0
8	062001	70.000	0.000	287.603	80.343	30.696	0.000	0.094	0.000	0.0
9	062001	113.000	0.000	259.467	91.577	58.521	0.000	0.911	0.000	0.91
10	062001	113.000	0.000	259.468	92.907	58.984	0.000	0.585	0.000	0.6
11	062001	70.000	0.000	266.444	65.648	24.561	9.701	1.906	0.000	1.8
12	062001	79.100	0.000	293.469	53.286	7.543	22.337	5.030	0.000	5.0
13	062001	50.000	0.000	339.323	56.282	13.917	2.653	0.424	0.000	0.4
14	062001	45.400	0.000	283.520	48.751	23.549	1.100	0.014	0.000	0.01
15	062001	45.400	0.000	259.265	58.820	16.107	5.157	0.055	0.000	0.0
16	062001	59.600	0.000	222.325	57.235	51.169	0.000	0.202	0.000	0.2
17	062001	24.500	0.000	308.546	47.252	4.704	0.736	0.000	0.000	0.0
18	062001	24.500	0.000	308.545	40.890	4.515	1.103	0.000	0.000	0.0
19	062001	18.200	0.000	303.826	48.763	8.428	0.000	0.000	0.000	0.0
20	062001	59.600	0.000	253.397	61.877	10.710	4.615	0.006	0.000	0.0
21	062001	74.200	0.000	335.600	69.290	27.128	5.272	3.886	0.000	3.8
22	062001	74.200	0.000	276.719	76.194	34.334	3.802	2.593	0.000	2.5
23	062001	18.200	0.000	269.252	48.813	23.424	0.000	0.024	0.000	0.0

Subbasin	Date	Flow_in	Flow_Out	Evap	Tloss	Sed_in
1	062001	29.87000	29.45000	0.05680	0.56010	763300.00000
2	062001	0.02124	0.01034	0.00000	0.02124	46.92000
3	062001	1.69500	1.58000	0.01725	0.09735	25890.00000
4	062001	33.90000	32.65000	0.12940	0.53670	797900.00000
5	062001	38.36000	35.40000	0.12710	2.52700	124400.00000
6	062001	0.17630	0.02024	0.00382	0.15450	1976.00000
7	062001	0.00038	0.00000	0.00000	0.00038	0.00188
8	062001	35.43000	32.21000	0.38760	2.52200	4849.00000
9	062001	0.03349	0.00046	0.00000	0.03349	357.90000
10	062001	0.02232	0.00031	0.00000	0.02232	568.30000
11	062001	32.26000	29.06000	0.35880	2.51900	3443.00000
12	062001	0.13210	0.00199	0.00079	0.13100	1306.00000
13	062001	0.01207	0.00014	0.00000	0.01207	14.62000
14	062001	0.00039	0.00000	0.00000	0.00039	0.00002
15	062001	29.07000	25.97000	0.36440	2.40600	2713.00000

Distrswat
Dstswat1
Dstswat10
Dstswat11
Dstswat12
Dstswat13
Dstswat14
Dstswat15
Dstswat16
Dstswat17
Dstswat18
Dstswat19
Dstswat2
Dstswat20
Dstswat21
Dstswat22

Fig. 6.1 AVSWAT model setup for the Malaprabha catchment

6.2 Accuracy assessment

Statistical indices viz., correlation coefficient, relative error, and Nash-Sutcliffe Efficiency Index (NSE) are used here to evaluate the AVSWAT model efficiency to simulate runoff (Nash and Sutcliffe, 1970).

Nash-Sutcliffe Efficiency index

NSE is used to assess the accuracy of the model estimation. It is estimated as shown below.

$$NSE = 1 - \frac{\sum_{i=1}^{t}\left(Q_{o,i} - Q_{s,i}\right)^2}{\sum_{i=1}^{t}\left(Q_{o,i} - \overline{Q_o}\right)^2} \tag{6.1}$$

NSE varies from -∞ to 1. Values closer to 1 indicate better efficiency or agreement of simulated values with observed values.

Relative error

Relative error represents the error as a percentage of observed values and is represented as shown below.

$$RE = \frac{\left(Q_o - Q_s\right)}{Q_o} \times 100 \tag{6.2}$$

6.3 Land use scenario

In order study the impact of land use changes on the stream flow in the catchment, various land use scenarios were built in AVSWAT. The four set of scenarios studied here are base scenario, current scenario, scenario showing current trend in land use change and betterment scenario.

Current scenario

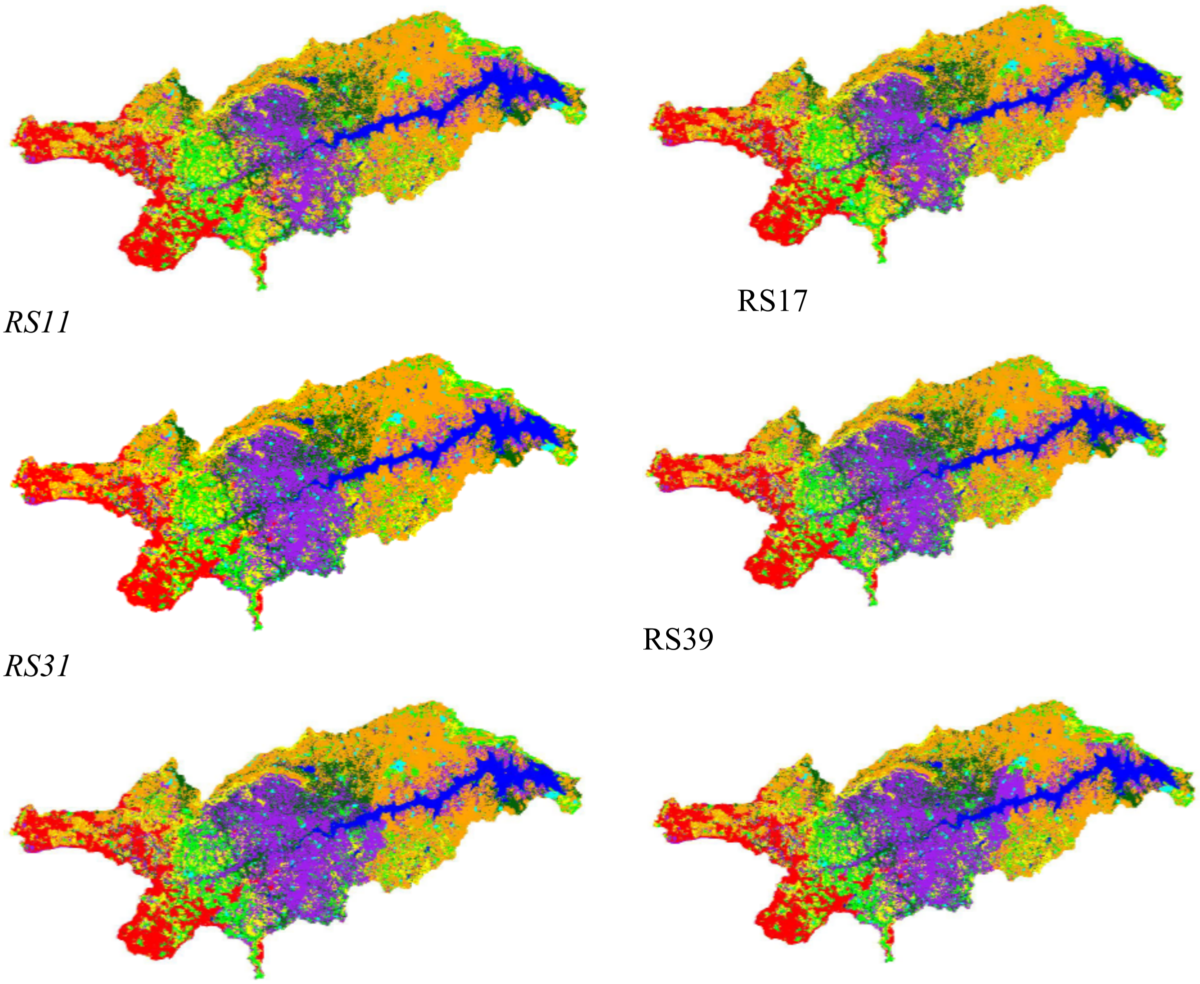
In the current scenario, the existing land use/land cover and irrigation scenario are assumed. The simulated stream flow is compared with the observed stream flow at Khanapur as well as with the reservoir inflow, and the model parameters are calibrated. The results show the stream flow under existing conditions in the catchment, and help to understand the spatio-temporal variation in the water availability in the catchment.

Base scenario

The calibrated model parameters are used to develop further scenarios. Base scenario is developed by using the current land use/land cover map, however assuming rainfed cultivation in all the agricultural areas. Assuming no-irrigation in the area, this scenario shows the maximum water available by simulating naturalized flows in the catchment, which may be available for reallocation including irrigation at different geographical areas along the catchment.

Current trend

The current trend of irrigation intensification is simulated in this scenario, where a gradual variation from rainfed cultivation to irrigated crops is assumed. All the rainfed crops are considered on one side and sugarcane on the other side as irrigated crop. A gradual variation from rainfed to sugarcane, starting from 11 to 56%, is assumed and the resulted stream flow is simulated. These scenarios are termed as RS11, RS17, RS31, RS39, RS49, and RS56 respectively, where RS indicate the change from rainfed to sugarcane and the number followed indicate the percentage area converted. Land use/land cover maps for each of these scenarios are shown in Fig. 6.2.



RS11

RS17

RS31

RS39

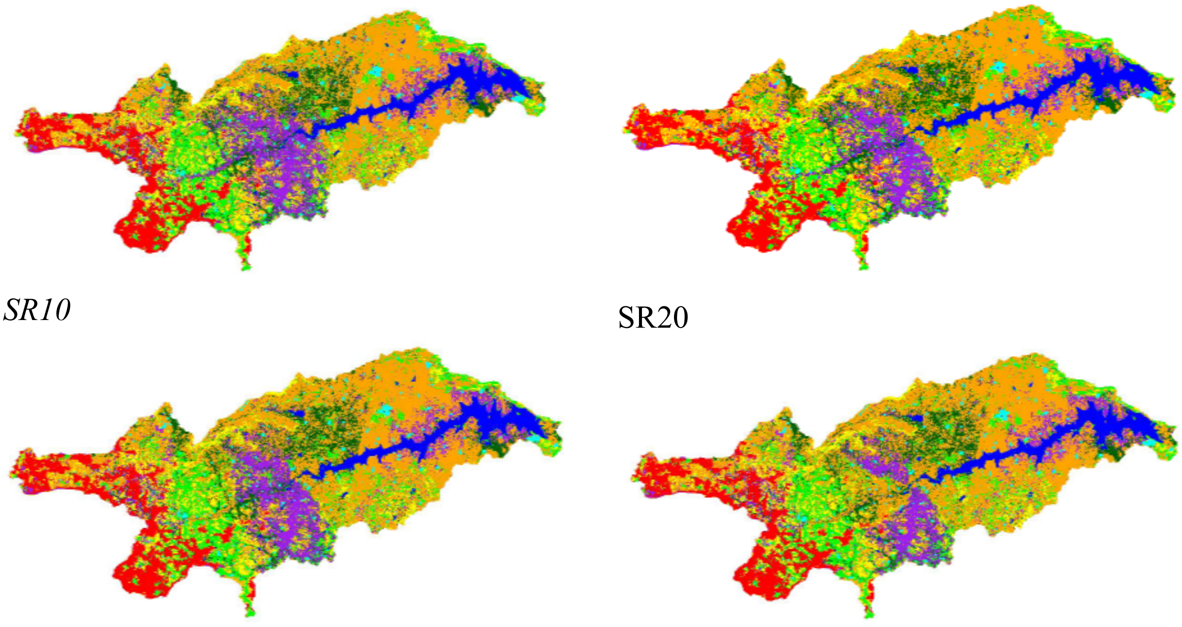
RS49

RS56

Fig 6.2 Land use scenario- Change from rainfed to sugarcane

Betterment scenario

The increased irrigation extraction in the catchment has been identified as one of the reasons for the reduced dry season flow in the Malaprabha river. Hence, betterment scenarios have been studied by assuming reduction in irrigation in the catchment (Fig. 6.3). A set of scenarios has been built by changing the sugarcane areas to rainfed crops. A change from 10 to 47 % is assumed and the these scenarios are called SR10, SR20, SR30 and SR47, respectively where SR indicated the change from sugarcane to rainfed crops followed by the percent area. The corresponding land use/land cover maps are shown in Fig. 6.3.



SR10

SR20

SR 30

SR47

Fig 6.3 Land use scenario- Change from sugarcane to rainfed

6.4 MIKE-BASIN for Malaprabha river basin

MIKE-BASIN is applied in the Malaprabha basin to achieve optimal allocation of the water resource among various demand nodes. Modelling area covers the catchment area as well as the command areas along the left and right bank canals. Both irrigation and drinking water demands are considered in this study. Various demand points are setup as demand nodes. Fig. 6.4 shows the MIKE-BASIN set up for the Malaprabha catchment. In MIKE-BASIN, three sub-catchments (regarding inflow to the model) are considered in the Malaprabha catchment area. The upper catchment represents the area upstream of Khanapur, middle catchment is the area between Khanapur and the Bailhongal, area from Bailhongal to the Malaprabha reservoir is the lower sub-catchment. The Malaprabha reservoir is a long stretching lake but in MIKE-BASIN it is represented as a reservoir node. All water users that withdraw water from this reservoir should be linked to this node even though the actual placements of the withdrawal points are at another place. There are an extensive number of irrigation schemes in the basin. To make the model more user friendly and simple – irrigation schemes have been grouped according to crops and water use in addition to the geographic placement of the scheme. In addition to the irrigation schemes located in the Malaprabha catchment, irrigation from Malaprabha Right Bank Canal (MRBC) and Malaprabha Left Bank Canal (MLBC) are also considered in this study for water allocation. MRBC has irrigation area of 1400 km2 and the MLBC has an area of 531 km2.

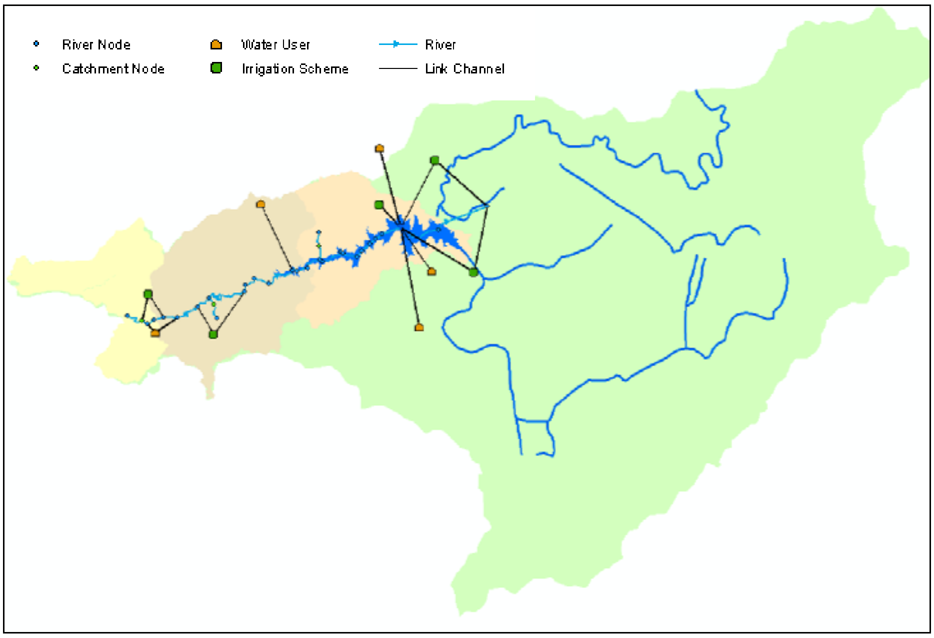


Fig 6.4 MIKE-BASIN model setup for the Malaprabha basin

Thus, totally five irrigation schemes and three drinking water schemes are considered in this study. The irrigation schemes are: Upstream Khanapur, between Khanapur and the inlet to the Malaprabha reservoir, around the Malaprabha reservoir, MLBC and MRBC. Drinking water schemes considered in this study are: Bailhongal, Hubli-Dharwad and Saundatti. For water allocation, all the drinking water schemes are given first priority, whereas all the irrigation schemes as uniformly assigned a priority 2. Drinking water demand (m^3/s) is low compared to the irrigation demand. Drinking water demand uses both stream water and groundwater. In MIKE-BASIN, drinking water demand that is not met by stream flow is assumed met by groundwater.

MIKE-BASIN Irrigation module is used to simulate the crop yield based on the water availability. Discharge time series (from June 2001 to May 2004) at different sub-catchment are obtained from AVSWAT and is given as point inflow in three different locations in MIKE-BASIN. No-irrigation condition is assumed in AVSWAT to estimate the maximum runoff availability in the catchment. AVSWAT was set up with 24 sub-basins. Due to landcover/ landuse and discussions with the AVSWAT modeller, 3 collections of sub-basins are represented in MIKE-BASIN. Fig.6.5 shows the sub-basins from AVSWAT and the corresponding catchments that are used in MIKE-BASIN.

MIKE-BASIN sub-atchment	AVSWAT subbasins
Upper catchment	1, 2, 3 and 4
Middle catchment	4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15
Lower catchment	16, 17, 18, 19, 20, 21, 22, 23 and 24

Fig. 6.5 Sub-catchments used in MIKE-BASIN

Though AVSWAT is setup using 18 raingauge stations spreads over the entire catchment area, three precipitation stations (Bailhongal ARS, Saundatti SF and Khanapur) have been selected in MIKE-BASIN based on the location of the station and the irrigation schemes. Khanapur is located near the Khanapur village and are used for irrigation schemes upstream Malaprabha reservoir. Bailhongal is used for lift irrigation along Malaprabha reservoir and for Malaprabha Left Bank Canal. Saundatti is used for Malaprabha Right Bank Canal. Annual average rainfall at these stations is 625 mm, 510 mm and 1816 mm, respectively.

The soil parameters are assumed uniform throughout the area. Parameters for clay soils (field capacity = 0.35, wilting point = 0.2, initial soil moisture= 0.25, depth of evaporable layer = 0.01, porosity = 0.16) are assumed in all the irrigation schemes.

Irrigation water demand is calculated based on the FAO-56 guidelines. If the calculations indicate that there are water shortages, there are several rules that can describe how the available water should be distributed onto the specific field viz., equal shortage, by priority, or by yield stress.

The crop yield model is used to estimate the yield based on the water availability and the same is compared with the actual yield (derived from a farmers survey conducted in the command area in 2007) and the potential yield found in www.fao.org

MIKE-BASIN has been calibrated to meet the observed water level in Malaprabha reservoir.

7. Results and Discussion

7.1 AVSWAT

Current scenario

In hydrologic modelling, the model was initially setup for the current land use and irrigation scenario. Land cover map shown in Fig 5.4 was assumed as the current land use scenario. Areas classified as sugarcane, paddy or other irrigated crops are assumed to be irrigated from the stream directly. However in reality some of these areas are irrigated by using borewells.

The model was calibrated by using observed stream flow data from Khanapur as well as the reservoir inflow data. Fig.7.1 shows the comparison between the observed and simulated stream flow at Khanapur and at the reservoir. When compared with the observed reservoir inflow for the study period, the simulation result was found to be giving a correlation coefficient of 0.95 and with a NSE of 0.71. However, the model was found over estimating runoff as indicated by an average relative error of -137.18 %. RMSE of the simulation was found to be 81% average daily runoff.

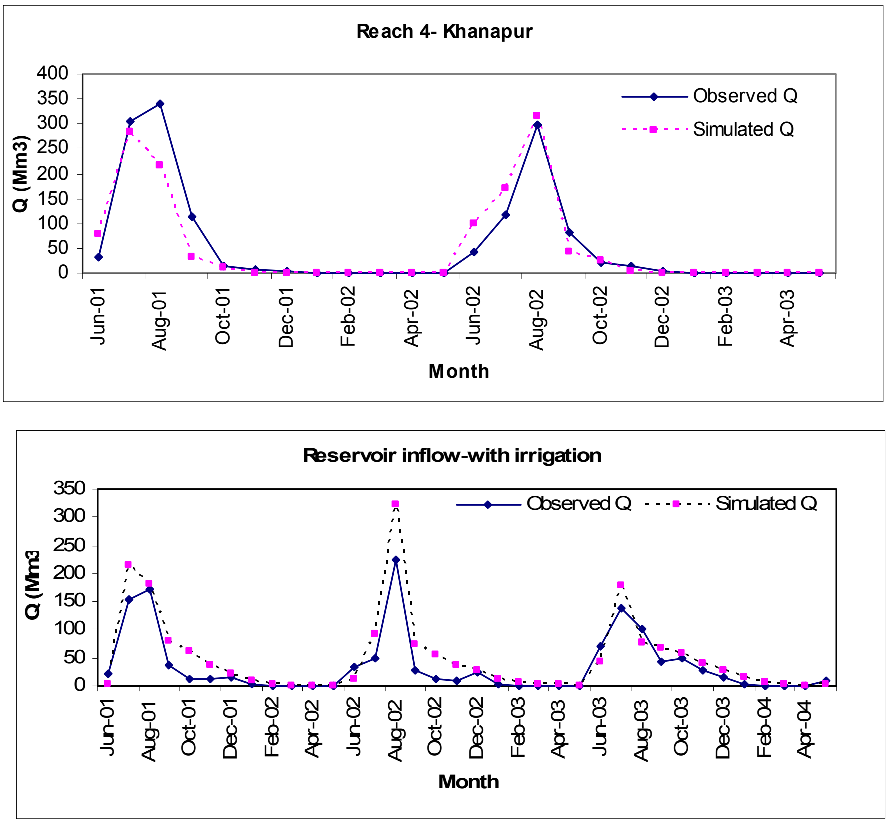


Fig 7.1 Comparison between observed and simulated flow in the river

Base scenario

Current scenario shows water scarcity in the stream, with the stream flow during the peak summer of the dry years less than the production requirement at the Bailhongal intake point. In order to find the effect of irrigation extraction on the stream flow, a base scenario was built in the model, where the entire area was assumed to be under rainfed cultivation. Assuming zero irrigation extraction from the stream, the resulted reservoir inflow is shown in Fig 7.2 along with the observed inflow data.

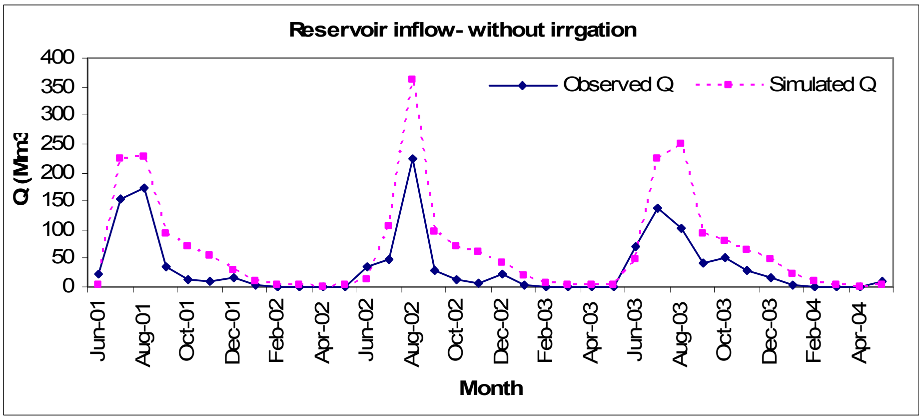


Fig 7.2 Comparison between observed and simulated inflow to the reservoir for base scenario

This base scenario indicates the maximum stream flow that can be generated under the current land cover condition. From the base scenario, 98% of the total stream flow in the year 2002-2003 (normal rainfall year) was observed during the monsoon period (June-November). Dry season flow was found to be only 2 % of the total annual stream flow. Water yield from the subbasins was studied separately for each zones and found that 82.5% of the water reaching the stream during monsoon period is from zone 1, whereas the contribution from zones 2 and 3 are 11.8% and 4.7%, respectively. On the other hand much of the dry season flow was found to be from zone 2. Walter yields from zones 1, 2 and 3 during the dry season were found to be 7.2%, 62% and 30.8%, respectively in 2002-03.

From the sensitivity analysis, the model was found to be most sensitive to the parameters ESCO, CN, channel hydraulic conductivity, threshold for groundwater flow, coefficient of deep aquifer percolation, soil depth, soil water holding capacity and soil hydraulic conductivity.

Fig 7.3 shows the difference between the reservoir inflows in the current and base scenarios. When the irrigation is withdrawn, water availability was found to be improved significantly. This was further used in the water allocation and the economic optimization model to estimate how best the water can be allocated for irrigation in different areas, without facing any scarcity at the Bailhongal intake point.

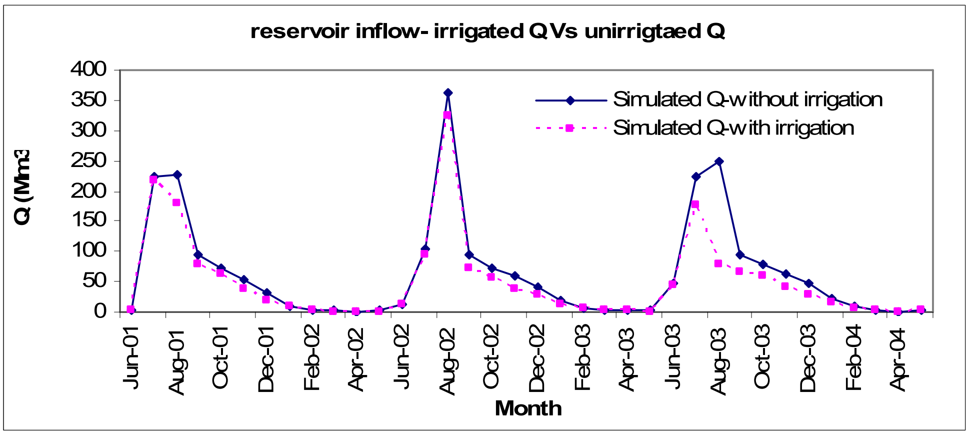


Fig 7.3 Comparison between reservoir inflow of base and current scenarios

In this study, the effect of current as well as base scenario on the stream flow at the Bailhongal water supply intake point is studied. Fig 7.4 shows the comparison between the two scenarios. Irrigation extraction was found to be reducing the stream flow in both monsoon as well as dry season. During the three years of time considered in this study, when irrigation water was extracted from the stream with the current land cover scenario, Bainhongal water supply requirement was found difficult to meet during the peak summer of below normal rainfall years.

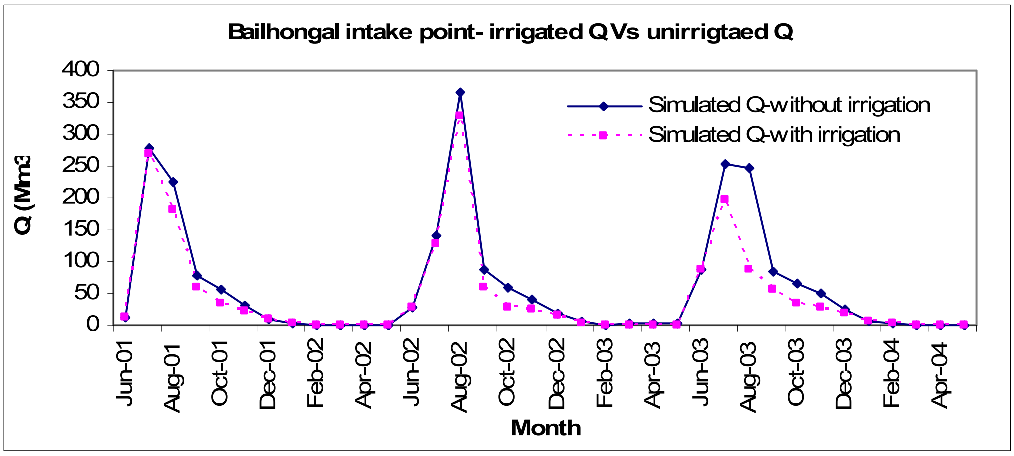


Fig 7.4 Comparison between the base and current scenario at the Bailhongal intake point

As observed in the field an average 2-4 months during the dry years were found to be critical periods where the simulated stream flow was found to be less that 0.275 m3/sec (estimated requirement) as shown in the table below. However for the base scenario, water availability was found to be meeting the demand in all the months considered in this study, except Mar-April of dry years (table 7.1).

Table 7.1 Water scarce periods at the Bailhongal intake point

	Stream flow (m3/sec)	
	Base Scenario	Current scenario
Month	(with no irrigation)	(with irrigation)
Feb-02	0.303	0.273
Mar-02	0.134	0.037
Apr-02	0.195	0.046
May-02	0.492	0.264
Mar-04	0.216	0.116
Apr-04	0.138	0.014

Land use scenario analysis

The land use scenario analysis is divided into two parts. In the first part the trend of shift from rainfed to irrigated sugarcane cultivation was assumed and its impact on the stream flow was studied. Six scenarios were setup by changing 11, 17, 31, 39, 49 and 56 percent of the current rainfed areas to sugarcane and these are names SR11, SR17, SR31, SR39, SR49 and SR56, respectively. Stream flow variation at the Bailhongal intake point for the scarce months (March-May 2002, May 2003, March-April 2004) are shown in Fig 7.5.

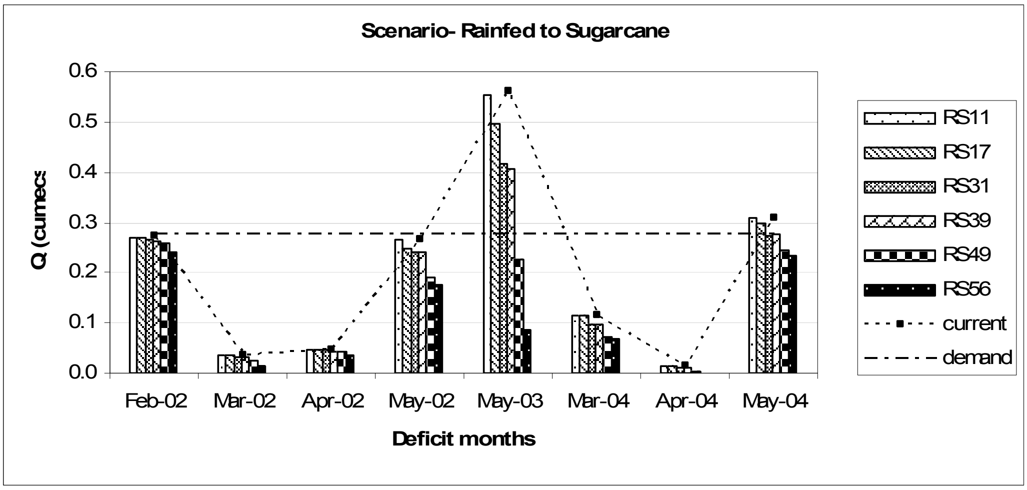


Fig 7.5 Impact of irrigation intensification on stream flow

Reduction in the stream flow due to the effect of increased irrigation was observed from the result. For the current scenario, in May 2003 and 2004, simulated stream flow was higher than the demand. With increase in the extent of irrigation, more periods of water stress was observed eg., May 2003 and May 2004. With the intensification/ extensification of irrigation, there is a risk of prolonged water scarcity in the catchment. In addition to this, an average 35% increase in the intensity of scarcity is observed when 56% of the rainfed areas are converted to sugarcane. Appropriate measures are therefore needed to be taken to prevent unsustainable change in the agricultural practices leading to water scarcity.

In the second part, improvement in the stream flow was studied by gradually changing the sugarcane areas back to rainfed cultivation. Four scenarios were considered where 10, 20, 30 and 47% of the current sugarcane area is assumed to be converted to rainfed cultivation (SR10, SR20, SR30 and SR47, respectively). Stream flow at the Bailhongal intake point for the six scarce months (February-May, 2002 and March-April, 2004) is shown in Fig. 7.6. For the below average rainfall years 2002 and 2004, significant improvement in the stream flow was observed when 10% of the existing sugarcane areas are converted into rainfed cultivation. With SR10 scenario, water scarcity was found to be reduced from four months to two months (April-May) in 2002. In addition to this an average 50% reduction in the intensity of scarcity was observed by replacing 47% of the sugarcane areas by rainfed crops.

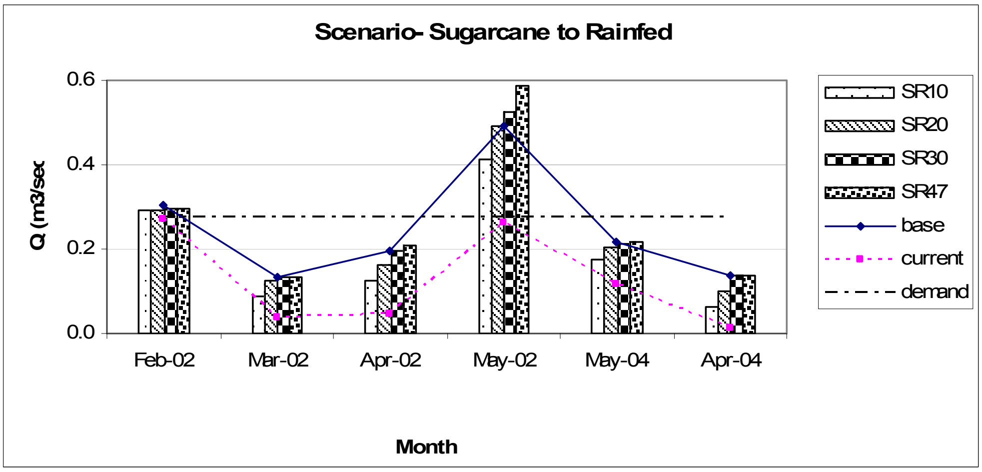


Fig 7.6 Improvement in stream flow due to land use changes

The results show the impact of land use changes on the stream flow, particularly the dry season flow, in the Malaprabha catchment. With the shift from traditional rainfed cultivation to irrigated cultivation and the increased pumping from the stream to meet the irrigation requirement has resulted in inequitable water supply between different sectors. It is found that if the current trend of unsustainable land use change, in the form of extensification of irrigation, if continued will result in more severe water scarcity affecting the drinking water supply to the largest settlement in the catchment area. However, the scenario can be improved by reducing the extent of irrigation.

7.2 MIKE-BASIN and Irrigation Module

AVSWAT produce surface runoff (mm) from each sub-basin. Runoffs from all subbasins in a sub-catchment are aggregated to find the inflow to the catchment. Fig. 7.7 shows the resulting discharge from the three sub-catchments.

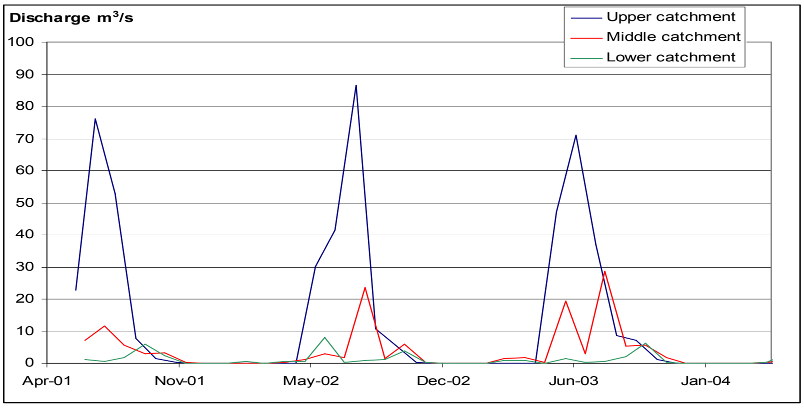


Fig. 7.7 Discharge sub-catchments

MIKE-BASIN model use SWAT results as input and the model is calibrated to meet the observed water level at Malaprabha reservoir. Fig. 7.8 shows the comparison between observed and simulated reservoir water level.

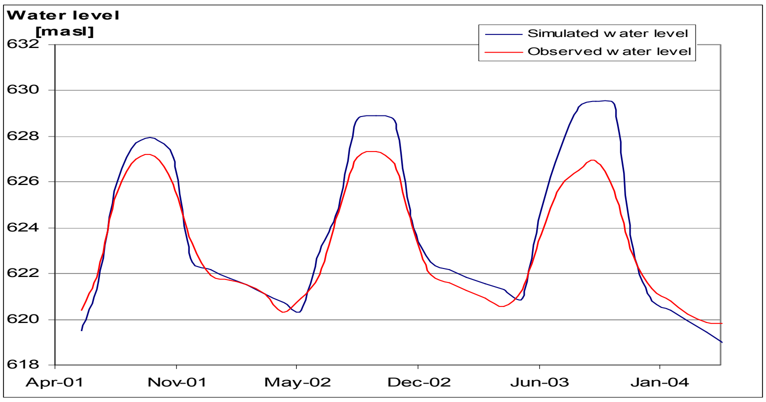


Fig. 7.8 Simulated and observed water level in Malaprabha reservoir

The irrigation nodes have been tested to meet the observed water release from the Malaprabha reservoir to the command areas. Due to lack of information regarding the amount of water used for irrigation (only the release of water for the canals is available) irrigation water demand can not calibrated, but the model is calibrated so that the irrigation water demand follows the relative amount of water released for the area. Fig. 7.9 shows the comparison between the observed and simulated irrigation demand along MLBC and MRBC.

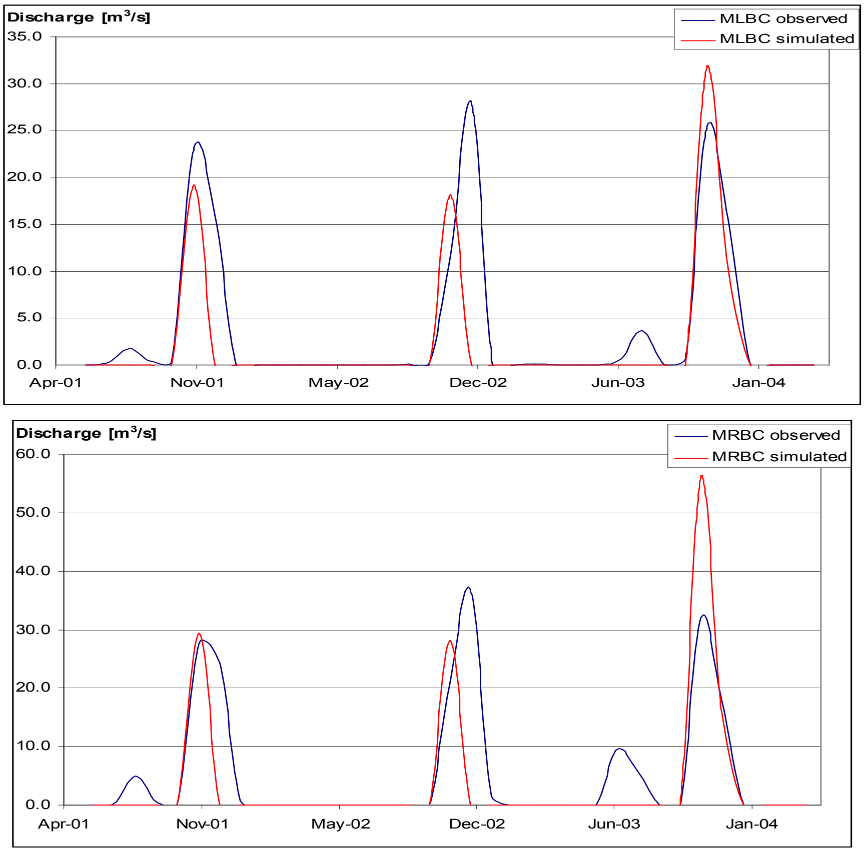


Fig. 7.9 Irrigation water demand and observed release for (a) MLBC and (b) MRBC

It is important to note that only one type of crop is irrigated in each field and that this type of crop does not correspond to the actual crop grown in the command area. The results show that the cropping period and the amount of water is close to the actual situation.

Accumulated yield

MIKE-BASIN calculates the accumulated yield according to the irrigation model and the climatic conditions. During calculations of average yield, the same crop was used for all irrigated area in the model. The model was run for the different crops across the catchment and compared the yields to the actual yield reported from a farm survey conducted in the command area (2007), and the potential yield found in www.fao.org. Potential, actual and simulated yield of the selected crops are shown in the table below and in Fig.7.10.

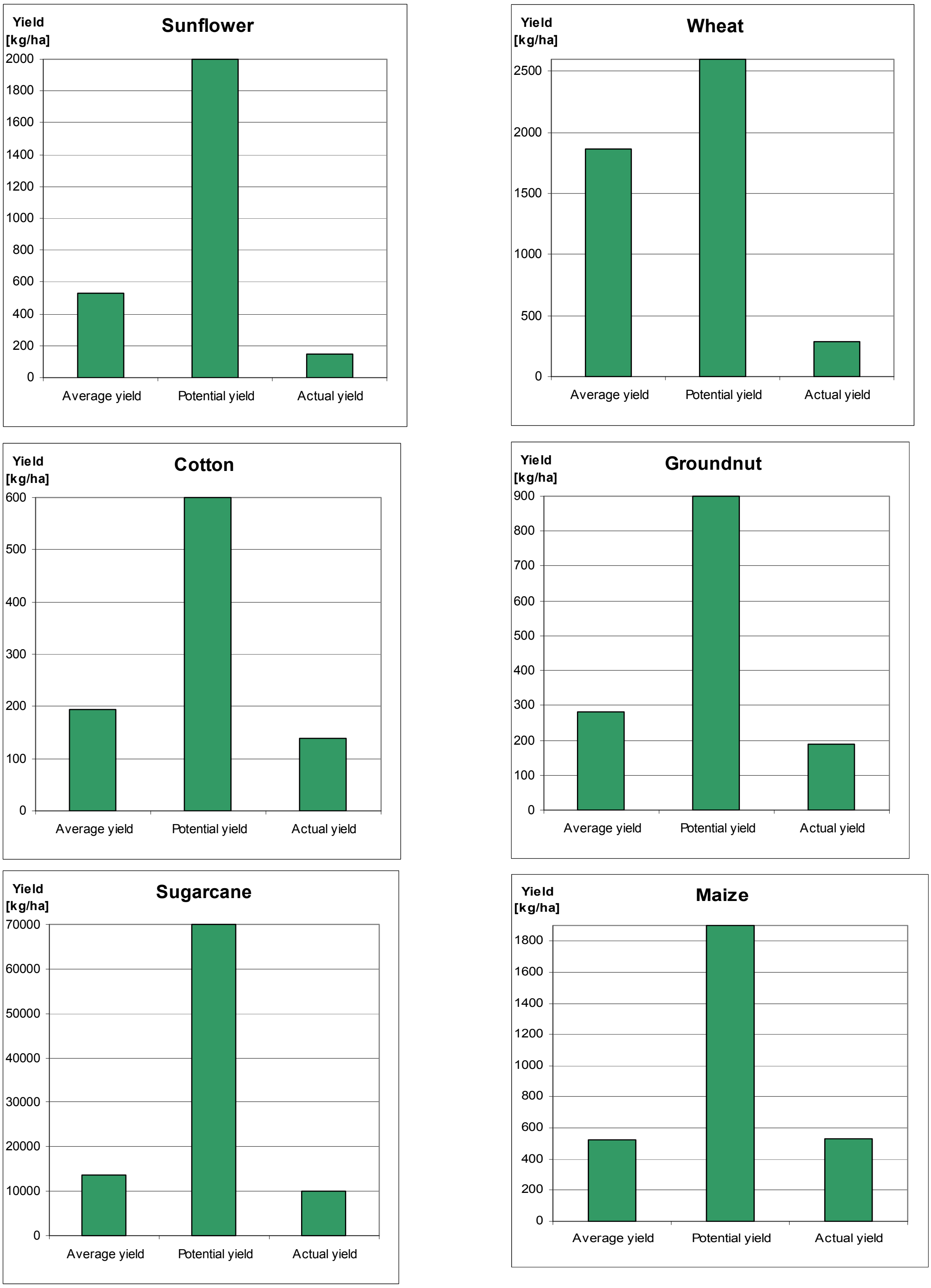


Fig. 7.10 Aerage yield from MIKE-BASIN, Potential yield (FAO) and Actual yield (Farmers survey)

Table 7.2 Comparison of actual and modelled yields

Crop	Potential yield FAO Yield kg/ha	Farmers survey Yield kg/ha	MIKE-BASIN Yield kg/ha
Sugarcane	70000	9988	13518
wheat	2600	283	1863
Cotton	600	140	193
Groundnut	900	187	283
Sunflower	2000	144	526
Maize	1900	532	524

As can be seen from the figures, the simulated yield from MIKE-BASIN and the actual yield from Farmers survey correspond quite well. This indicates that MIKE-BASIN is suitable to simulate irrigation water demand and the corresponding yield. Yield data from MIKE-BASIN is based on average yield for all irrigation schemes when only one type of crop is grown.

MIKE Irrigation Module computes optimal irrigation yields. The model was used to evaluate whether there would be water scarcity and impact on yields if command area irrigation was optimal, under different upstream land-use scenarios. The scenarios are summarised in table 7.3.

Table 7.3 Scenarios analysed in MIKE Irrigation Module

Catchment scenario	B. Base case	C. Current land use	S. Sugarcane future (AVSWAT scenario RS56)
Sugarcane area upstream reservoir	15%	15%	56%
=>Inflows to reservoir	Obtained from AVSWAT simulations		
Command area scenario Using MIKE-BASIN Irrigation module			
1.Design moderate irrigation cropping (cropping areas in Table 7.4 Reddy and Kumar 2008)	Scenario B-1	Scenario C-1	Scenario S-1
2.56% crops in (1) replaced by sugarcane		Scenario C-2	Scenario S-2

Figure 7.11 shows discharges from Malaprabha basin near irrigation intake for command area based on reach results in the end of the AVSWAT model (reach 24). Figure 7.11 shows that catchment discharge in current scenario and RS56 scenario is more or less the same. Table 7.6 gives the exact figures. The yearly discharge is found to be reduced by 24% from Base scenario to Current scenario and 25% from Base scenario to RS56 Scenario. The reduction is about 1.8% from Current scenario to RS56 scenario.

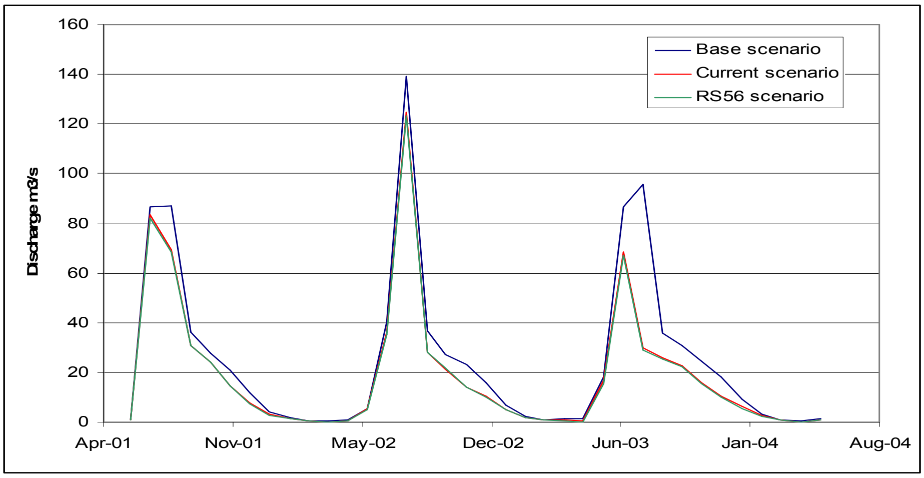


Figure 7.11 Water discharge in Scenario B, C and RS

Command area land-use scenarios modelled

Discharge from scenario B, C and RS is used as input to the water allocation distribution shown in table 7.4. This is the area distribution in the command area in MIKE-BASIN.

Table 7.4 Area distribution for MIKE-BASIN scenario 1

Crop	Area [km2]
Kharif - Maize	408
Kharif -Groundnut	1248
Rabi - Wheat	1392
Rabi - Sunflower	192
Cotton	792

Kharif season: 1656 km^2 +792 km^2 =2448 km^2; Rabi season: 158 km^2 + 792 km^2 = 2376 km^2

Discharge from scenario C and RS is used as input to the water allocation distribution shown in table 7.5. This is the area distribution in the command area in MIKE-BASIN.

Table 7.5 Area distribution for MIKE-BASIN scenario 2

Crop	Area [km2]
Kharif - Maize	0
Kharif -Groundnut	728
Rabi - Wheat	612
Rabi - Sunflower	84
Sugarcane	1344
Cotton	348

Kharif season: 728 km^2 +1344 km^2 =2421 km^2;Rabi season: 697 km^2 + 1344 km^2 = 2389 km^2

This MIKE-BASIN scenario includes sugarcane. The area of sugarcane is approximately 56% of the total area. It assumed that the area of other crops is reduced by 44% - maintaining total cropped command area.

Table 7.6 Results for the MIKE-BASIN scenarios in the command area

	Total annual water available from upper catchment (MCM)	**Total annual water demand for command area as a whole (MCM)**	**Total annual water deficit for command area as a whole (MCM)**	**Average crop yields per hectare in command area (kg/ha)**
Scenario B-1	792 Mm3	64 Mm3	0	Groundnut: 299 cotton : 296 wheat: 2600 maize: 546 Sunflower: 1288
Scenario C-1	601 Mm3	64 Mm3	0	Groundnut: 299 cotton : 296 wheat: 2600 maize: 546 Sunflower: 1288
Scenario RS-1	590 Mm3	64 Mm3	0.07 Mm3	Groundnut: 299 cotton : 296 wheat: 2600 maize: 546 Sunflower: 1288
Scenario C-2	601 Mm3	194 Mm3	34 Mm3	Groundnut: 81 cotton : 266 wheat: 2497 maize: Not irrigated Sunflower: 1333 Sugarcane: 17319
Scenario RS-2	590 Mm3	194 Mm3	36 Mm3	Groundnut: 81 cotton : 266 wheat: 2497 maize: Not irrigated Sunflower: 1333 Sugarcane: 17319

Table 7.6 shows the reduction in annual amount of available water reduces average crop yield in scenarios C-2 and RS-2 due to water scarcity. The average yield is reduced from scenarios 1 to scenarios 2. Despite the optimal irrigation assumption in MIKE Irrigation Module sugarcane still requires more water than other crops, leading to a deficit.

Table 7.7 shows the MIKE Irrigation Module assumptions about irrigation periods. Relative deficit varies in the different months from about 10 % to about 50%. This deficit results in reduced crop yields. The yield is reduced according to what crop stage the deficit occur, meaning how sensitive the crop is to water at that specific stage. Deficits occur in the following simulation months: Dec-01, Feb-02, May-02, Jan-03, Feb-03, Dec-03, Feb-04.

Table 7.7 Months under irrigation for different crops

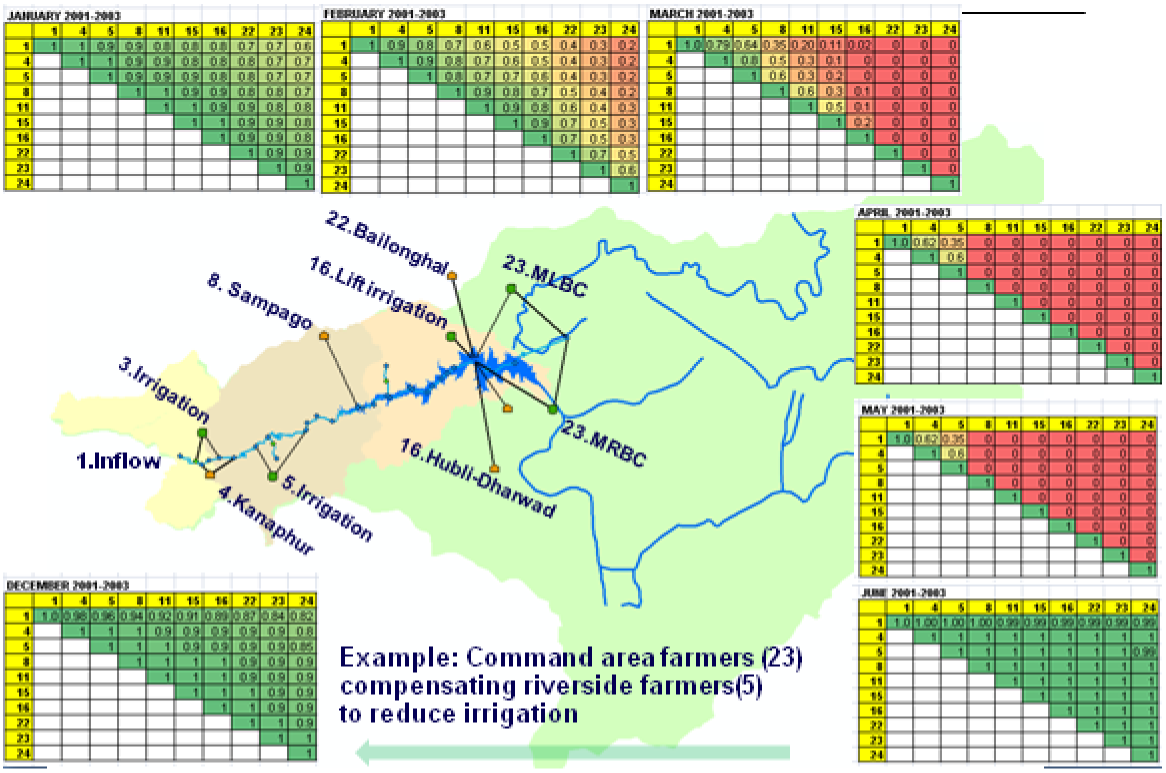
	Groundnut	**wheat**	**sunflower**	**cotton**	**maize**	**Sugarcane**
Jan		x	x	x		x
Feb		x	x	x		x
Mar		x	x	x		x
Apr		x	x	x		x
May			x	x		x
Jun	x			x	x	x
Jul	x			x	x	x
Aug	x			x	x	x
Sep	x			x	x	x
Oct	x			x		x
Nov				x		x
Dec				x		x

A weakness of the MIKE-BASIN Irrigation Module is that it doesn't provide estimates of water use per unit of yield per hectare for the different crops. This makes comparison of the model assumptions with other water allocation models difficult.

8. Economics of payments for watershed services

Given the limitations in the functionality of the water allocation model, the lack of data on the willingness of farmers to accept compensation, we can only make assessments of the feasibility of payments for watershed services under strong assumptions.

AVSWAT and MIKE-BASIN can speak to the issue of what levels of water scarcity provide the basis, in principle, for economically optimal "water trades". In basic terms upstream-downstream "water trades", i.e. downstream irrigated farmers compensating upstream farmers for water saving measures is only hydro-economically optimal when there is neither water abundance nor drought. By looking at surface water losses between upstream extraction points and downstream extraction points, we can assess how much greater agricultural yields downstream have to be than upstream yields, if water trades between farmers are to be economically attractive. When coupled to crop prices we get an estimate of how much larger WTP downstream has to be than WTA compensation upstream for surface water. The principle is illustrated in Fig. 8.1. It shows water conveyance losses due to evaporation and transmission for different months of the year at different points the length of the catchment (row and column numbers). A ratio of 1 in the table between two points means that no water is lost to evaporation and transmission. A number less than 1 indicates what portion of water measured at any point (row numbers) remains at successive water use points (column numbers). The severity of surface water lost to evaporation and transmission is also illustrated on a graded colour scale from green (none) to red (all). Take the month of February, between upstream irrigation from the river (point 5) and downstream farmers in the command area (point 23), the proportion of stream flow from point "1. Inflow" remaining at point "5. Irrigation" is 0.8 and at point "23.MLBC/MRBC" is 0.3.



JANUARY 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1	1	0.9	0.9	0.8	0.8	0.8	0.7	0.7	0.6
4		1	1	0.9	0.9	0.8	0.8	0.8	0.7	0.7
5			1	0.9	0.9	0.9	0.8	0.8	0.7	0.7
8				1	1	0.9	0.9	0.8	0.8	0.7
11					1	1	0.9	0.9	0.8	0.8
15						1	1	0.9	0.9	0.8
16							1	0.9	0.9	0.8
22								1	0.9	0.9
23									1	0.9
24										1

FEBRUARY 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1	0.9	0.8	0.7	0.6	0.5	0.5	0.4	0.3	0.2
4		1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
5			1	0.8	0.7	0.7	0.6	0.4	0.3	0.2
8				1	0.9	0.8	0.7	0.5	0.4	0.2
11					1	0.9	0.8	0.6	0.4	0.3
15						1	0.9	0.7	0.5	0.3
16							1	0.7	0.5	0.3
22								1	0.7	0.5
23									1	0.6
24										1

MARCH 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1.0	0.79	0.64	0.35	0.20	0.11	0.02	0	0	0
4		1	0.8	0.5	0.3	0.1	0	0	0	0
5			1	0.6	0.3	0.2	0	0	0	0
8				1	0.6	0.3	0.1	0	0	0
11					1	0.5	0.1	0	0	0
15						1	0.2	0	0	0
16							1	0	0	0
22								1	0	0
23									1	0
24										1

APRIL 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1.0	0.62	0.35	0	0	0	0	0	0	0
4		1	0.6	0	0	0	0	0	0	0
5			1	0	0	0	0	0	0	0
8				1	0	0	0	0	0	0
11					1	0	0	0	0	0
15						1	0	0	0	0
16							1	0	0	0
22								1	0	0
23									1	0
24										1

MAY 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1.0	0.62	0.35	0	0	0	0	0	0	0
4		1	0.6	0	0	0	0	0	0	0
5			1	0	0	0	0	0	0	0
8				1	0	0	0	0	0	0
11					1	0	0	0	0	0
15						1	0	0	0	0
16							1	0	0	0
22								1	0	0
23									1	0
24										1

JUNE 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1.0	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99
4		1	1	1	1	1	1	1	1	1
5			1	1	1	1	1	1	1	0.99
8				1	1	1	1	1	1	1
11					1	1	1	1	1	1
15						1	1	1	1	1
16							1	1	1	1
22								1	1	1
23									1	1
24										1

DECEMBER 2001-2003

	1	4	5	8	11	15	16	22	23	24
1	1.0	0.98	0.96	0.94	0.92	0.91	0.89	0.87	0.84	0.82
4		1	1	1	0.9	0.9	0.9	0.9	0.9	0.8
5			1	1	1	0.9	0.9	0.9	0.9	0.85
8				1	1	1	1	0.9	0.9	0.9
11					1	1	1	0.9	0.9	0.9
15						1	1	1	0.9	0.9
16							1	1	0.9	0.9
22								1	1	0.9
23									1	1
24										1

Example: Command area farmers (23) compensating riverside farmers(5) to reduce irrigation

Fig. 8.1. Water conveyance loss due to evaporation and transmission

Fig. 8.2 shows the ratio of remaining stream flow at point 23 to point 5 during different months of a year. Evaporation loss is found very less during the monsoon season. On the other hand, in summer evaporation losses from the stream is very high.

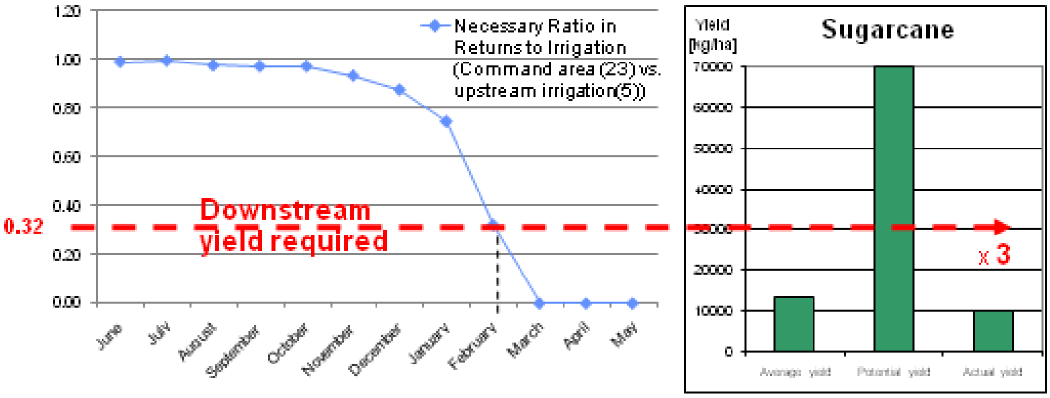
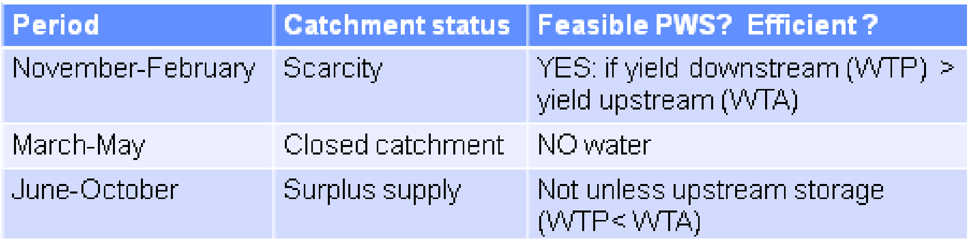


Fig. 8.3 Water conveyance loss limits the potential for efficient PWS

This ratio is used to represent the ratio of yields between the two points that would result in same economic returns for the unit volume of water, assuming farming cost to be the same. For example, the ratio of remaining streamflow of point 23(command area) to 5(irrigation above reservoir) is 0.23/0.8 =0.32 in February. Surface water would only be allocated efficiently between irrigation upstream and in the command area if returns per m3 to cropping were about 3 times higher in the command area.

For the case of sugarcane, yields of about 30 000 kg/ha would be necessary, as opposed to the current average of 10 000 kg/ha reported by farmers in the command area (Fig. 8.2). This simple economic allocation thinking assumes that cropping patterns, prices and farming costs are similar in the upstream and command area. We know this not to be the case regarding cropping patterns, although a large proportion of farmland is dedicate to sugarcane both in the upstream and command areas.

The curve in Fig.8.2 illustrates at what ratio upstream crops must be less water efficient than downstream crops for "trades" in surface water to be economically attractive from a social perspective (considering both upstream farmers and downstream farmers). In the period June-October the ratio is approximately 1 because of water abundance in the rainy season. Due to water abundance there are not likely to be any beneficiaries in the downstream willing to pay. In the period March-April, all water available in the upper catchment is lost before it reaches the command area; there is no provision of service. Only in the period December-March is there a potential for trading, under the condition that downstream WTP > upstream WT P (Fig. 8.4).



Period	Catchment status	Feasible PWS? Efficient?
November-February	Scarcity	YES: if yield downstream (WTP) > yield upstream (WTA)
March-May	Closed catchment	NO water
June-October	Surplus supply	Not unless upstream storage (WTP< WTA)

Fig. 8.4 Hydrological and economic situation in which water trades in the catchment are feasible

There are many caveats to this argument:

- If surplus water generated through water saving measures upstream could be stored and conveyed to downstream farmers using infrastructure that had lower water loss than for surface water there would be a greater potential for trades.
- Water saving measures upstream that increase groundwater recharge in an aquifer shared with command area users would be such a case. In effect, aquifers environmental service would be in water conveyance and storage at lower loss rates than could be achieved by man-made canals or pipes. However, a case must then be made for the extent of aquifers. Groundwater modelling was not possible within the scope of the project.
- Crop yields and crop distribution must be similar between the upstream providers and downstream beneficiaries. If upstream crops are low yield while downstream crops are high yield water trading will be more optimal from an economic point of view.
- Crop prices and non-water input costs must be similar. This is likely to be the case in such a small catchment as Malaprabha.

9. Summary and Conclusions

9.1 Summary

In this hydrologic analysis of the Malaprabha catchment was carried out. Long term hydro-meteorological data and stream flow observation were analysed to identify the water scarcity problem in the area in terms of scarcity of drinking water and reduced flow in the river, and the reasons for scarcity. In this study, in order to simulate the current stream flow and to study the impact of land use changes on the stream flow, particularly dry season flow, hydrologic processes taking place in the catchment were simulated by using AVSWAT. The model is calibrated with respect to the observed stream flow. It gives output in the form of water yield from each subbasins, stream flow and transmission losses at various reaches, evapotranspiration, irrigation, percolation, and groundwater recharge at each HRU in the catchment. Giving priority to the drinking water supply for the Bailhongal municipality over irrigation, the stream flow during the dry periods are compared with the demand at the intake point.

Further various scenarios were built by using the same set of calibrated parameters. The base scenario is set up to find the maximum water availability in the catchment when none of the agricultural areas are irrigated. This result is further used in the water allocation and the economic optimization model.

In order to predict the impact of current land use change in the future stream flow availability, scenarios were built by assuming gradual change from rainfed to irrigated sugarcane cultivation. In this study attempts were also made to identify the possible remediation strategy in land use, where in a gradual shift from irrigated sugarcane to the traditional rainfed cultivation and its impact on the stream flow was also studied.

Further, the result from AVSWAT is used in the MIKE-BASIN Irrigation module to simulate the crop yield, based on the current water availability. The crop yield information from MIKE-BASIN and the transmission losses at different river reaches from AVSWAT are integrated with an economic optimization model to study the feasibility of PWS based on the productivity.

9.2 Limitations of the study

- Accuracy of the of land cover classification: land cover map is extracted from LISS II imagery by using the ground truth information. However, some discrepancy still remains in the classification. In reality, the other irrigated crops and sugarcane area are more than what is shown in the land cover map.
- For simplicity in modeling mono-cropping is assumed in all agricultural areas, except the sugarcane class. However, this does not make a big difference in the result because second crop used in most of the areas are less water intensive crops like ragi, jowar etc.. Much of the irrigation in the dry season is for the sugarcane.
- Only one weather station is used for the entire catchment assuming that the station represents the weather characteristics over the entire catchment.
- Entire irrigation water is assumed to be extracted from the stream. However, in reality much of these areas are irrigated from groundwater.
- The model does not have option to simulate ground water flow from deep aquifer. Once the water is percolated into the deep aquifer, it is assumed as a loss from the system.
- The model is calibrated with respect to the stream flow alone. Simulation of soil moisture condition is not validated
- Calibration of the various model parameters was done to match the simulated stream flow with the observed one at the two gauging stations. Calibration is not performed for individual subbasins.
- Data availability: Quality of the results depends on the accuracy of the input data. Though the interpretaion of the remote sensing satellite imageries provides the spatial variation in the land use, the acquisition of time series imageries becomes expensive, making it unaffordable for local organizations. In addition to this, the expertise required to interpret the imageries also acts as another constraint.
- The main constraint for this study was the lack of an Economic model in the latest version of MIKE-BASIN. The Economic application that is under construction could not be used due to lack of input data and information that was required for the model.
- A constraint regarding the irrigation module in MIKE-BASIN model is that the module does not have functionality that can deal with rice/paddy. This is due to the differences in irrigation method. Rice is produced in an area that is covered with some cm of water. MIKE-BASIN irrigation module does only handle water under the surface – soil water.
- The Excel application currently available for MIKE-BASIN can do an analysis with regards to allocation between different kinds of water users, but not water allocation between one type of water user, such as agriculture upstream and downstream.
- Water use per unit of yield per hectare for the different crops

9.3 Advantages of the model

The following are the key advantages of the current model.

- Capability to handle spatial data
- Incorporate almost all the processes taking place in the land phase and during the flood routing
- Simple robust and user friendly
- Dynamic: Scenarios can be easily built
- Automatic estimation of the watershed area
- Generate output at different levels, which can be easily used for water allocation and economic optimization
- Automatic simulation of crop characteristics by using FAO-56 guidelines

9.4 Conclusions

From the hydrological analysis of the Malaprabha catchment the following conclusions are arrived at.

- Due to the topographic characteristics, land use and soil characteristics, the upper catchment contributes almost 80% of the monsoon flow in the catchment.
- Due to the pre-monsoon rainfall received in the area, Zone 2 contributes about 60% of the post-monsoon flow under no-irrigation condition.
- Huge irrigation in the middle and lower catchment causes reduction in the stream flow. In dry years, 2-4 months of water scarcity at the Bailhongal intake point is observed from the simulation results.
- More intense water scarcity and longer periods of scarcity can be expected with the current changing scenario. In addition, an average 50 % increase in the intensity of water scarcity may be resulted by changing 56% of the current rainfed areas to sugarcane.
- Sustainable land use practices can improve the situation. From the scenario analysis it ha been found that 10% change in the existing sugarcane areas to rainfed crops could halves water scarcity at the Bailhongal intake point. Also an average 35% reduction in the intensity of water scarcity could be achieved by converting 47% of the sugarcane areas to rainfed crops.
- Through a simple analysis of the water balance results from AVSWAT and the crop yield figures from MIKE Irrigation Module, we have argued that the hydrological and crop production conditions under which payments for watershed services would be economically feasible are quite restricted. They are:
  - ”intermediate water scarcity levels”
  - water saving and storage measures upstream are technically feasible
  - upstream farmers are willing to be compensated

- agricultural returns in Rs/acre/m3 downstream (WTP) are greater than upstream (WTA)
- institutional costs of PWS are less than difference between WTP and WTA

The last point is perhaps the most complex constraint on PWS and “water trading” at a catchment level. Institutional issues are addressed in a separate report.

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Appendix A.

Soil characteristics

	Soil class									
Parameters	**5**	**11**	**30**	**33**	**34**	**35**	**37**	**43**	**44**	**46**
No.of layers	3-A-B-C	2-A,B	2-A,B	2-A-C	2-A,B	2-A,B	2-A,B	2-A,B	2-A,B	1-A
Maximum rooting depth of soil profile	1700	900	1030	1200	1030	1030	1030	1520	1520	1650
Texture	L-C-LS	SL-SCL	SL-L	SL-SCL	SL-L	SL-L	SL-L	CL_CL	CL_CL	C
SOL_Z	270-1500-1700	150-900	120-1030	680-1200	120-1030	120-1030	120-1030	200-1520	200-1520	1500
AWC_Layer 1	0.15	0.12	0.18	0.12	0.18	0.18	0.18	0.15	0.15	0.12
AWC_Layer 2	0.12	0.135	0.15	0	0.15	0.15	0.15	0.15	0.15	
AWC_Layer 33	0.11			0.135						
SOL_BD-layer1	1.38	1.51	1.38	1.47	1.38	1.38	1.38	1.32	1.32	1.2
SOL_BD-layer2	1.23	1.139	1.36	0	1.36	1.36	1.36	1.31	1.31	
SOL_BD-layer3	1.58			1.43						
SOL_K-layer1-mm/hr	2.6	3.81	3.81	3.81	3.81	3.81	3.81	2.19	2.19	2.81
soil_K-layer2-mm/hr	2.81	2.69	2.6	0	2.6	2.6	2.6	2.19	2.19	0
soil_K-layer3-mm/hr	4.86	0	0	2.69	0	0	0	0	0	0
Organic carbon content	1.29,1.15,0.24	0.45-0.25	1.15-1.01	0.44-0.32	1.15-1.01	1.15-1.01	1.15-1.01	0.78-0.52	0.78-0.52	0.5
Clay-Layer1	23.4	14.9	21	19.8	21	21	21	31	31	55.1
Clay-Layer2	55.9	28.6	25.9	0	25.9	25.9	25.9	35	35	
Clay-layer3	10.7	0	0	24				0	0	
SILT-layer 1	40	15.5	52.2	10.4	52.2	52.2	52.2	40	40	37.7
Silt-layer2	18.8	15.4	36.8	0	36.8	36.8	36.8	35.1	35.1	
Silt layer3	7		0	9.8				0	0	
SAND-layer1	36.6	69.6	26.8	69.8	26.8	26.8	26.8	29	29	7.2
sand-layer2	25.3	56	37.3	0	37.3	37.3	37.3	29.9	29.9	
sand layer3	82.3	0	0	66.2	0	0	0	0	0	

Parameters	**47**	**48**	**50**	**60**	**61**	**63**	**65**	**66**	**68**	**69**	**78**	**82**	**84**
No.of layers	1-A	2-A,B	2-A,B	2-A-C	1-A	2-A-C	2-A-C	2-A-C	1-A	1-A	3-A-B-Rock	3-A-B(c-rock)	2-A,B
Maximum rooting depth of soil profile	1650	1520	1520	350	130	350	350	350	250	250	1590	1590	1640
Texture	C	CL_CL	CL_CL	SCL_LS	CL	SCL_LS	SCL_LS	SCL_LS	C	C	SCL_SC	SCL_SC	SCL_C
SOL_Z	1650	350-1520	200-1520	100-350	130	100-350	100-350	100-350	250	250	180-1590	180-1590	140-1640
AWC_Layer 1	0.12	0.15	0.15	0.135	0.15	0.135	0.135	0.135	0.12	0.12	0.135	0.135	0.135
AWC_Layer 2		0.15	0.15	0		0	0	0			0.13	0.13	0.13
AWC_Layer 33				0.11		0.11	0.11	0.11					
SOL_BD-layer1	1.2	1.32	1.31	0		0	0	0			1.32	1.32	1.23
SOL_BD-layer2		1.31		1.58		1.58	1.58	1.58					
SOL_BD-layer3													
SOL_K-layer1-mm/hr	2.81	2.19	2.19	0	0	0	0	0	0	0	2.54	2.54	2.81
soil_K-layer2-mm/hr	0	2.19	0	4.86	0	4.86	4.86	4.86	0	0	0	0	0
soil_K-layer3-mm/hr	0	0											
Organic carbon content	0.5	0.78-0.52	0.78-0.52	4.51-0.25	2.14	4.51-0.25	4.51-0.25	4.51-0.25	0.4	0.4	2.23-1.79	2.23-1.79	1.29-1.15
Clay-Layer1	55.1	31	31	29.6	34.3	29.6	29.6	29.6	55.5	55.5	32.2	32.2	23.4
Clay-Layer2		35	35	0		0	0	0			38.7	38.7	55.9
Clay-layer3		0	0	10.7		10.7	10.7	10.7			0	0	0
SILT-layer 1	37.7	40	40	14.3	22.5	14.3	14.3	14.3	30.9	30.9	15.3	15.3	40
Silt-layer2		35.1	35.1	0		0	0	0			16.2	16.2	18.8
Silt layer3		0	0	7		7	7	7			0	0	0
SAND-layer1	7.2	29	29	56.1	43.2	56.1	56.1	56.1	13.6	13.6	52.5	52.5	36.6
sand-layer2		29.9	29.9	0		0	0	0			45.1	45.1	25.3
sand layer3		0	0	82.3		82.3	82.3	82.3			0	0	0

Appendix B.

This section presents some estimates of water deficit to compare the irrigation water demand in the command area and the catchment's supply potential. It assists in making decisions regarding land-use change and improvements in irrigation efficiencies to parallely address the problem of water scarcity in the command area.

Runoff

Average rainfall in the Malaprabha reservoir catchment = 1050 mm

Assumed runoff coefficient for an average rainfall year = 0.27 (average of the recent 5 year period)

Reservoir catchment area = 2204 sq.km

Runoff in an average rainfall year = 625.9 MCM

Drinking water demand

Hubli-Dharwad + village drinking water demand = 53.0 MCM

Irrigation demand

Cultivable command area of the Malaprabha project

LBC = 80107 ha
RBC = 134044 ha
Total = 214251 ha

Average irrigation demand per ha. (George et al. 2008[1])

LBC= 6890 cum/ha
RBC = 2023 cum/ha
LIS = 1714 cum/ha

Average irrigation demand across the project = 3542 cum/ha

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[1] George, B., H. M Malano1, Bri. Davidson (2008) Water resource allocation modelling to harmonise supply and demand in the Malaprabha catchment, India. 13th IWRA World Water Congress. 1-4 September, Montpellier, France.

Gross irrigation demand LBC = 551.94 Mcm

RBC = 271.17 Mcm

LIS = 58.07 Mcm

Total irrigation demand from the project = 823.11 Mcm

Total water demand

Total demand = irrigation (incuding irrigation efficiency)+ drinking water

= 823 MCM + 53 MCM

= 1700 MCM

Water available in the reservoir

Reservoir storage capacity = 1250 MCM

Live storage = 870 MCM

Inflow to the reservoir = Runoff – Evaporation, assuming 10% losses due to evaporation

= 626-62.6 MCM

= 563.4 MCM = water available for allocation

Water available at the field at 50% efficiency = 281.7 MCM

This amount can only cater to approximately 79531 Ha of command area, which is just 30% of the total designated command area.

(In most Indian contexts, system-level project irrigation efficiencies are between 35-40%. A recent UNDP report has recommended a minimum of 10% improvement in the irrigation efficiency. Here we assume system efficiency to be 50% presuming operation and maintenance budgets of the Malaprabha project would target the 10% improvement)

Water deficit

Current demand = 823 MCM (irrigation command including efficiency) + 53 MCM (drinking water)

= 1700 MCM

To receive an amount equivalent to 1700 MCM from the reservoir, the required runoff coefficient is 77%, which is highly improbable.