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# Water Resources Assessment in a River Basin Using AVSWAT Model



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**PREFACE**

GIS with its data, topological, network, and cartographic modeling, map overlay, and geostatistics techniques is a very effective tool for water resources assessment (WRA). Digital elevation modeling (DEM) is useful for extracting topographic information such as slope properties, drainage basin delineation, drainage divides, and drainage networks that are required for hydrological modeling for WRA. The role of GIS and DEM in the different stages of WRA is demonstrated through a case study of rainfall–runoff simulation in Malaprabha reservoir catchment of India using Arc View Soil and Water Assessment (AVSWAT) model. GIS and DEM were useful in providing necessary input to AVSWAT model that performed fairly well in predicting runoff. The results pertaining to the parameters plant uptake compensation factor (EPCO) = 0.75, soil evaporation compensation factor (ESCO) = 0.4, and available water capacity (AWC) = 0.04, for which $R^2$ value of 0.95 is obtained during validation, are selected. In addition to investigating the water balance issues of each subbasin in Malaprabha catchment, AVSWAT was developed to predict the impact of land management practices on water displacement of sediment and agricultural chemical yields.


## 26.1 Introduction

Water as a source of life has become more important in this century due to increase in its consumption owing to the population explosion, unprecedented rise in standard of living, enormous industrial development, and technological advancements. At the global scale, between 1970 and 1990, the amount of freshwater resources available per capita decreased by a third (See page 12 in Chapter 1 of [20]). Also, water crisis is predicted to take place by mid-twenty-first century. Hence, water management continues to be a high priority issue in international agendas. The 19th special session of the UN General Assembly concluded that water would become a major limiting factor in socioeconomic development and the seriousness of the situation calls for the highest priority to be given to the freshwater problems [19]. However, the holistic integrated and environmentally sound sustainable management of our water resources is intimately linked to our ability to adequately assess them. Hence, water resources assessment (WRA) has become more essential than ever for meeting the world's water needs. WRA is defined as the determination of the sources, extent, dependability, and quality of water resources for their utilization and control. Here, water resources are defined as the water available, or capable of being made available, for use in sufficient quantity and quality at a location and over a period of time appropriate for an identifiable demand [16].

The past experience suggests that it is easier to assess the water resources of the area in a river basin or aquifer framework when compared to jurisdictional and economic regions [17]. WRA of a region involves a detailed study of the surface and subsurface water. Integration of the entire surface and subsurface data requires thousands of man-hours. However, it would increase the scope and scale of problems that can be addressed by WRA. This predicament makes the geographic information system (GIS) software a powerful tool for developing solutions in building hydrological information systems that synthesize geospatial and temporal water resources data to support hydrological analysis and modeling for WRA.

## 26.2 Background

The earliest need for WRA of the world was stressed in Mar del Plata Action Plan announced in 1977. Fifteen years later, in 1992, Rio Summit (Chapter 18 in Agenda 21 of United Nations Conference on Environment and Development) emphasized the need for the establishment of inventory of water resources, development of interactive databases, use of GIS, and sharing of appropriate knowledge and technology. Further, the World Water Assessment Programme (WWAP) was established by United Nations Water (UN Water) in 2000 for assessment of freshwater resources throughout the world. The WWAP publishes its output/recommendations in United Nations World Water Development Reports (WWDRs) that are published triennially [20,21] to enhance the WRA capacity of countries. The current interest in WRA has been emphasized by the World Water Council (WWC), the Global Water Partnership (GWP), and the World Commission on Water for the twenty-first century, to promote a World Water Vision for the year 2025.

## 26.3 Stages in Water Resources Assessment

Based on WRA: *Handbook for Review of National Capabilities* [18], following three stages are identified in the WRA:

1. The first or basic stage of WRA involves collection, processing, and inventorying hydrological, hydrometeorological, hydrogeological, physiographic, and auxiliary data on the water cycle components and water use projects for the creation of water resources information system. Depending on the characteristics of the available water resources, current and future needs of the users, the requirements of data for WRA are different for different regions and countries.
2. The second stage is to interpret the collected data in the form of technical information for the water resources information system. This stage involves assessing the state of water resources, forecasting of water-related natural disasters (such as droughts and floods), and using various techniques. The selection of a technique (such as hydrological modeling) depends on the availability of data and the objectives for WRA. Also, in this stage, further detailed investigations in meeting the requirements of water resources development projects may be carried out according to the requirement.

3. The final stage is to interpret and evaluate the data and technical information (provided by the previous stages) and convert them into knowledge, for making appropriate decisions. Some of the decisions at this stage could be on prioritizing watersheds, zoning of land within watersheds, riparian buffers, and management and mitigation of floods and droughts. Also, this stage adopts appropriate management strategies to avoid adverse environmental effects and reconcile conflicts between users for a sustained economic and social development in the region. The decisions depend on the specific task/objectives in WRA, while keeping in view the overall objective of integrated, sustainable management of water resources.

The primary objective of this chapter is to demonstrate the use of GIS and digital elevation model (DEM) in the various stages of WRA through a case study of rainfall–runoff simulation. Catchment of Malaprabha reservoir in Karnataka state of India is chosen for demonstration. It is one of the major lifelines for the arid regions of north Karnataka and possibly the largest arid region in India outside the Thar desert. Several rainfall–runoff simulation models are in use and each has its strengths and limitations, and there are no established criteria by which the superiority of any particular model can be clearly established. The Soil and Water Assessment Tool (SWAT) is selected for rainfall–runoff prediction, as this model has been widely used in hydrology and as the extensive data required for the model could be readily obtained for the study region from different sources. Details of this case study are presented in this chapter.

## 26.4 Role of GIS in Water Resources Assessment

GIS is not only a computer-based spatial database system, capable of gathering, storing, manipulating, analyzing, and disseminating geographic data, but also, in its widest definition, a data system to manage the environment for sustainable development.

GIS has been able to capture the synergy between the time series data on hydrological, hydrometeorological, and hydrogeological variables describing water properties and the geospatial data on water environment describing the water resources feature of the landscape for a better WRA. Hence, GIS can play an important role in all the three stages of WRA (Figure 26.1).

The first stage of WRA involves collection, processing, and inventorying of existing hydrological, hydrometeorological, hydrogeological, physiographic, and auxiliary data. The data required in WRA vary in space and time. Examples of data that vary in both space and time include that on

1. Variables such as temperature, wind speed, humidity of air, precipitation, runoff, evaporation, streamflows, soil moisture, and hydraulic conductivity of soil
2. Water bodies such as glaciers, rivers, lakes, oceans, and groundwater
3. Physiographical attributes such as land use and land cover

Examples of data that vary only in space include topography, geology, geomorphology, and soil of the region. The data that are collected from various sources such as conventional network of measurement devices, remote sensing (aerial surveys, satellites, and radars), DEMs, topographic maps, and satellite images can be classified into three groups, namely, historical data, real-time data, and special survey data.

GIS could be used to integrate and relate any data with a spatial component, regardless of the source of the data. The techniques in GIS useful in this stage of WRA are data creation, relating data from different sources, data representation, and handling nonspatial data. Through digitization (the most common method of data creation), geographic data are extracted from hardcopy map or survey plan and transferred into a digital medium for further use. Further, relating data from several sources in many different forms is useful. For example, relating information on soil moisture measurements obtained from tensiometers in a region to satellite images of the region might be useful for drawing inferences about soil moisture status in the region at various times of the year.

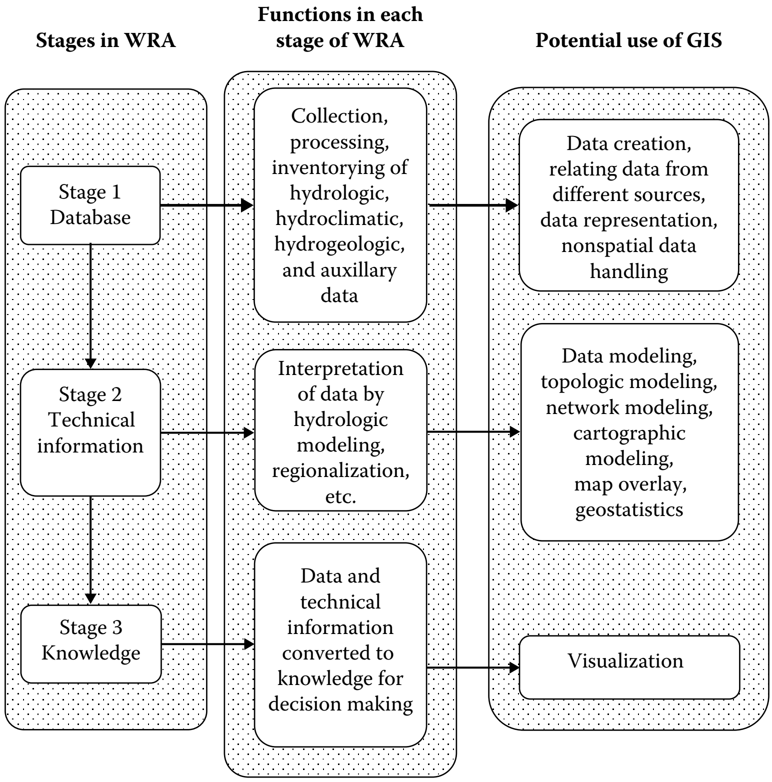


**FIGURE 26.1** Use of GIS in the components of WRA.

GIS facilitates conversion of existing digital information (such as digital satellite images generated through remote sensing or DEMs), which may not yet be in map form, into forms that can be recognized and used (e.g., maplike layer of digital information about vegetative covers, drainage network). Furthermore, real-world data objects are represented by dividing them into two abstractions: discrete objects (e.g., dam and spillway) and continuous fields (e.g., rainfall amount and elevation) to be stored as raster and vector forms. Additionally, nonspatial data can also be stored besides the spatial data represented by their spatial coordinates. For example, rainfall data can be converted to maplike layer of thematic information in GIS, based on rain gauge location data, or instead stored as attribute information to spatial data such as inventory of land use and land cover. The digital maps at different scales undergo manipulations such as projection and coordinate conversions to integrate in GIS.

The second stage of WRA involves application of techniques such as hydrological modeling and regionalization to extract technical information for the water resources information system. Availability of spatially distributed data and the ability to manipulate such data are essential to the techniques for assessing the state of water resources, forecasting of water-related natural disasters, detailed investigations for water resources development projects, etc.

The most commonly used technique is the estimation of water balance in river basins by modeling the various components of the water cycle based on a number of existing methods/models. The selection of a particular method/model depends on the available data, the characteristics of the water resources in the region, the current and future needs of the users, the finance allocated for the assessment, requirement of a stationary or changing climate, etc. The readers may refer to the various review articles [13–15,23] for a historical perspective of mathematical modeling of watershed hydrology, steps in developing watershed models, new developments and challenges, and analysis of risk and reliability in model selection.

A major impediment to progress in hydrological modeling is the inability to explicitly consider the spatial variation of model parameters [5]. This task has always been the most time consuming and therefore costly component of hydrological modeling requiring high computational power. This impediment has since been overcome to some extent by the rapid development of computer systems and creation of advanced software.

GIS with its features such as data, topological, network, and cartographic modeling, map overlay, and geostatistics is a useful tool in the second stage of WRA. The *data modeling* can be used to depict 2D and 3D characteristics of the Earth's surface, subsurface, and atmosphere from information points, for example, modeling point rainfall measurements to generate a 2D isohyetal map of a region and surface modeling of point elevation measurements to generate a 3D DEM of a region. *Topological modeling* can be used to analyze and recognize the spatial relationships that exist within digitally stored spatial data to perform complex spatial modeling. Examples of spatial relationships include adjacency (what adjoins what), containment (what encloses what), and proximity (how close something is to something else). In *network modeling*, GIS can simulate the routing of streamflow along a river. Incorporating information such as slope, speed limit, and channel dimensions is useful in representing the flow more accurately. *Cartographic modeling* refers to a process where several thematic layers of the same area are produced, processed, and analyzed. Operations on map layers can be combined into algorithms and eventually into simulation or optimization models. In *map overlay*, the two separate spatial datasets (points, lines, or polygons) are combined to create a new output vector dataset. These overlays may be a union, intersect, symmetric difference, clip, or mask. *Geostatistics* is a point-pattern analysis that produces field predictions from data points using techniques such as interpolation in order to predict the behavior of points and locations that are not directly measurable. DEMs, triangulated irregular networks, edge-finding algorithms, Thiessen polygons, kriging, spline, and trend surface analysis are all mathematical methods to produce interpolative data. Thus, GIS offers new opportunities for hydrological modeling and upon integration with hydrological models provides the capabilities to account for the spatial variability of hydrological processes by several sets of customized and user-friendly tools.

Three major integration architectures are summarized from a range of approaches that has been proposed and implemented for integrating GIS with hydrological models [1]. The first approach is a simple two-component architecture, which allows for one-way data transfer between two independent systems (e.g., a GIS and a hydrological model). It promises low cost of implementation but low usability as well. The second approach is "embedded" two-component architecture that extends capabilities of a master component by using functions of an embedded agent component. Depending on the capabilities of the model and its output requirement, GIS can be the master component (when GIS calls a model) or agent component (when model calls a GIS application). While the third approach has many-component architecture consisting of two or more master components that share common agent components such as a database management system and/or an end-user interface. This option provides a single external scheme for the integrated system, yet retains the independence of each master component. The cost of this architecture tends to be high, but it is desirable when the component systems are complex. This third type of architecture is used in the hydrological model considered for this study.

In the final stage of WRA, GIS is used to extract and organize model output data for charting and display. This is useful for better visualization of the technical information and for analyzation of results for making appropriate decisions. The outputs from the methods/models selected for the study provide information about the characteristics of the existing water resources, stress on the water resources if any, and problems due to natural, man-induced factors, mismanagement, etc. Mapping the changes in land use, land cover, and variables such as streamflow and rainfall in a region is useful to anticipate future conditions of water, to decide on a course of action, or to evaluate the results of an action or policy [3]. For example, mapping finds use in studying impact of land development on water quality and ecological resources.

Previous studies [6,7] reported incapability in representing continuous-time component in hydrological modeling as one of the major limitations of integrating GIS with hydrological models. This problem has been overcome in environmental modeling using a generic environmental modeling language integrated into a GIS, which supports spatial–temporal operators [12].

## 26.5 Role of DEM in Water Resources Assessment

A high-resolution DEM can be used as the basic spatial data source for defining the hydrography of the region. Studies have demonstrated the feasibility of extracting topographic information such as slope, drainage basin delineation, drainage divides, drainage networks, and morphometric properties of drainage basins (e.g., area and perimeter of drainage basins). These information extracted are faster to access and provide more precise and reproducible measurements than traditional manual techniques applied on topographic maps. Further, these techniques find more use in extracting information from large watersheds (greater than 10 km$^2$), where manual determination of drainage network and subwatershed features is tedious, time-consuming, error-prone, and often highly subjective process.

From the DEM (Figure 26.2), data of several features describing the hydrology of Malaprabha catchment have been derived, among which the following have been used:

- A raster dataset with the flow direction of the DEM (for each square-shaped cell of the DEM, it is assumed that the water flows toward the cell having least elevation out of its eight neighboring cells)
- A raster dataset with the flow accumulation of the DEM (each cell is assigned a value equal to the number of cells upstream of the cell; this dataset has been derived from the flow direction dataset)
- A vector dataset with drainage network (this dataset is derived based on combined information from the flow accumulation and flow direction datasets) (Figure 26.3)
- A vector dataset with probable outlets of drainage subbasins in the drainage network (Figure 26.4)
- A vector dataset with delineated drainage subbasins (this dataset is derived from the drainage network in combination with the dataset of outlets of drainage basins) (Figure 26.5)
- A vector dataset with longest streams in the delineated subbasins (Figure 26.6)

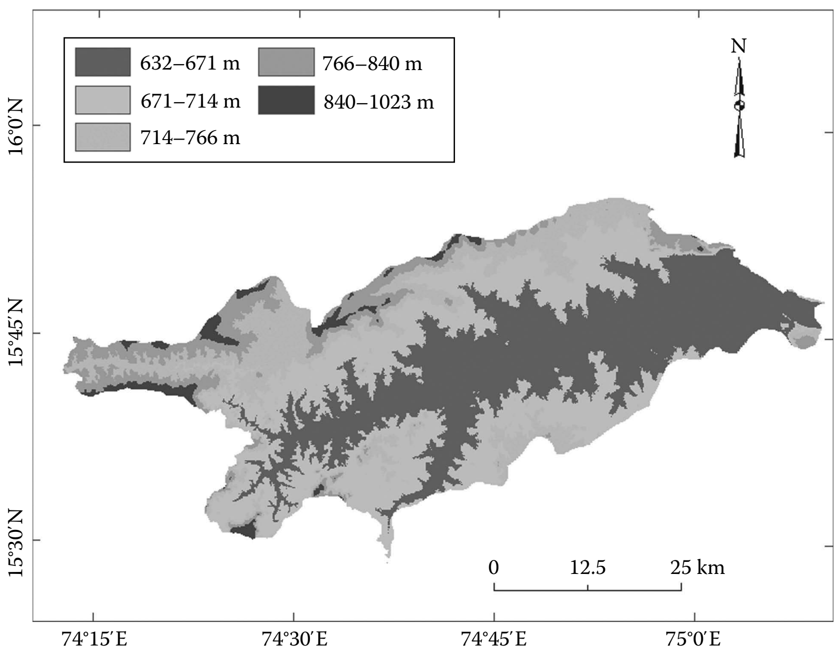


**FIGURE 26.2** DEM of the catchment of Malaprabha reservoir.

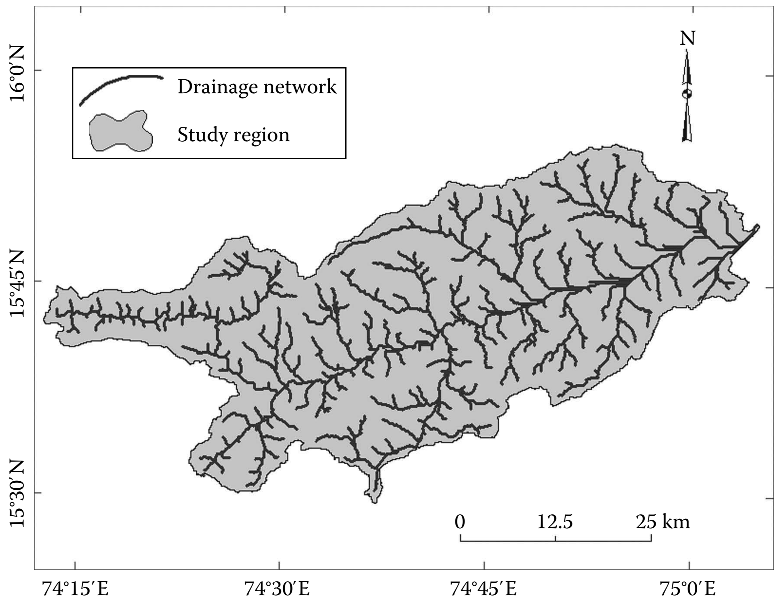


**FIGURE 26.3** Stream network in the catchment of Malaprabha reservoir obtained from AVSWAT model using DEM.

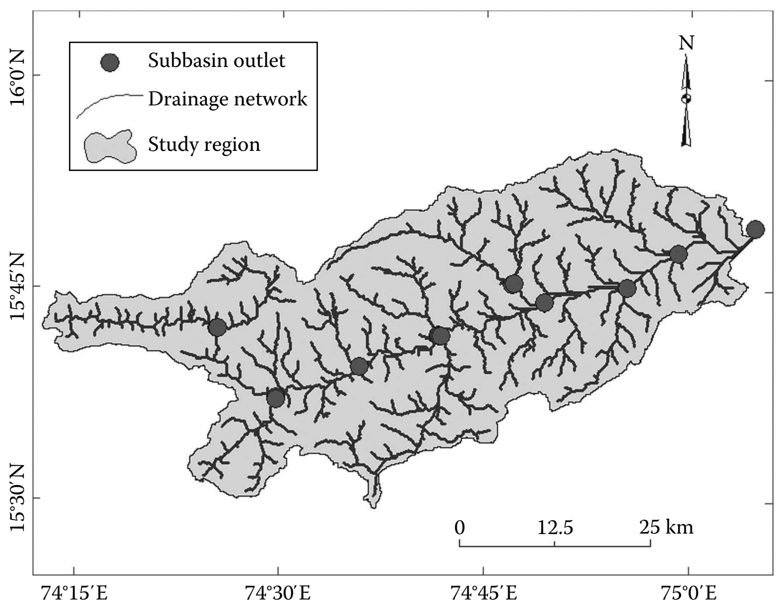


**FIGURE 26.4** Drainage subbasin outlets, which are specified in the catchment of Malaprabha reservoir to form drainage subbasins obtained from AVSWAT model.

In the present study, the available information was processed through a GIS-based model to provide, at the scale of the river basin, a comprehensive picture of the streamflow simulation. This approach makes the best use of the scattered information and makes it possible to extrapolate point data or data available at river basin level to develop a credible picture of the situation of the river basin's water use and its impact on water resources.

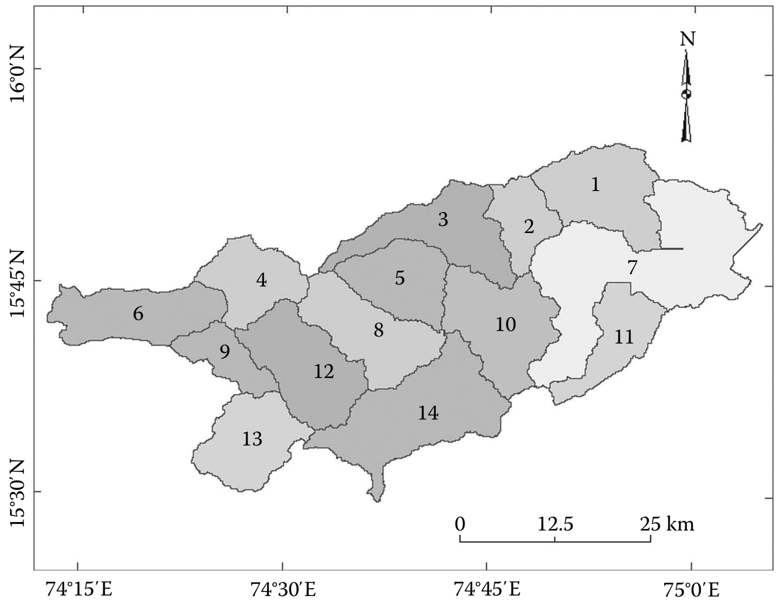


**FIGURE 26.5** Subbasins formed by AVSWAT for the selected outlets in the catchment of Malaprabha reservoir.

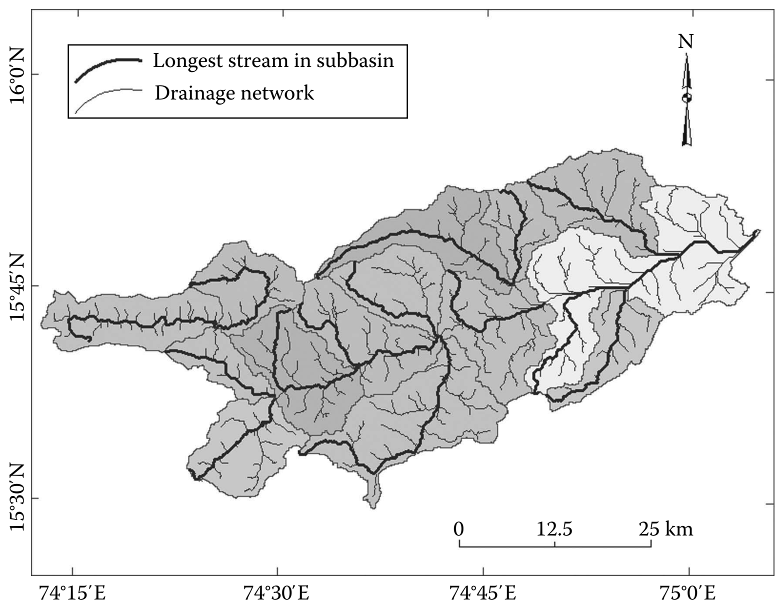


**FIGURE 26.6** Longest stream in each subbasin obtained from AVSWAT model.

## 26.6 Brief Description of SWAT and AVSWAT

SWAT is the acronym for Soil and Water Assessment Tool. It is a river basin scale model developed by Dr. Jeff Arnold for the US Department of Agriculture (USDA) Agricultural Research Service [9]. It can predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time. SWAT is a physically based, distributed, continuous-time model that operates on a daily time scale. Physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT [2].

For modeling purposes, a watershed is partitioned into a number of subbasins, which are then further subdivided into hydrological response units (HRUs). The use of subbasins in a simulation model is particularly beneficial when different areas of the watershed are dominated by land uses and soils dissimilar enough in properties to impact hydrology. Input information of each subbasin is grouped into several categories: climate, HRUs, ponds/wetlands, groundwater, and the main channel or stream draining the subbasin. The HRUs are the aggregated land areas within the subbasin that comprise of unique land cover, soil, and management combinations.

Simulation of the hydrology of a watershed is separated into two major parts in SWAT. The first part deals with the land phase of the hydrological cycle that considers amount of water, sediment, nutrient, and pesticide loadings in each subbasin. The second part deals with the routing phase that considers movement of water and sediments through the channel network to the outlet.

AVSWAT-2000 (version 1.0) [4] is an ArcView extension and a graphical user interface (GUI) of the SWAT model. The two systems, ArcView and SWAT, are dealt with as two independent master components in the integration system. The conceptual design of the integration system includes an add-on external user interface and a shared internal database to couple the two systems (Figure 26.7). The integration begins with the external user interface, where the end user initiates a new database or activates an existing one. Arc macro language (AML) scripts are activated via the interface to prepare input parameters for SWAT in the GIS environment. The data transition from GIS to the SWAT model is automated through the internal database shared by both the GIS and the hydrological model. User-friendly data entry and editing is part of the functionality of the external GUI, where users can interactively enter and modify model input files and parameters, including nonspatial parameters. The internal database stores the input data and transfers it into a SWAT compatible format. As the last step, the execution of SWAT is activated through the external user interface.

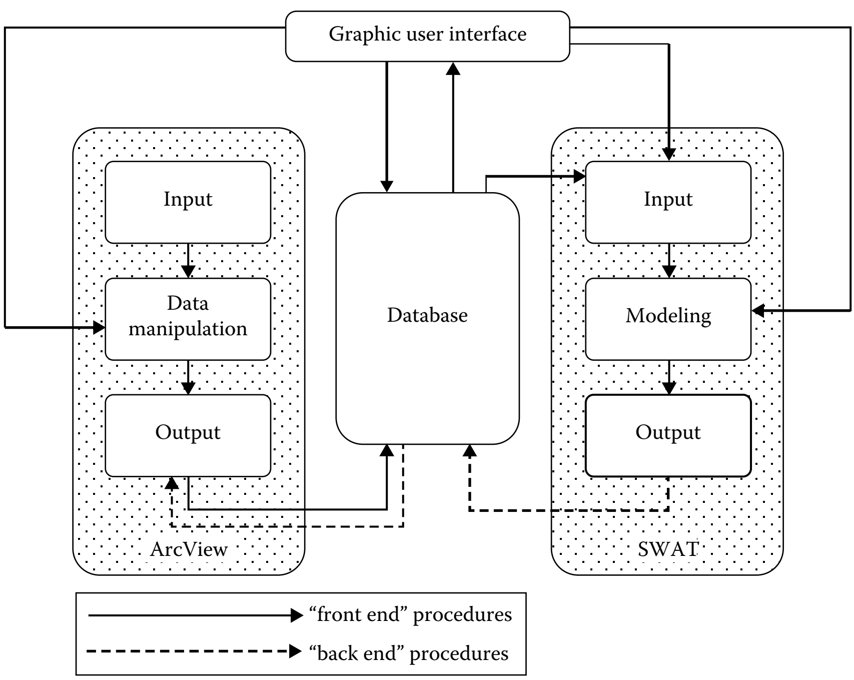


**FIGURE 26.7** Architecture of the interface system coupling ArcView and SWAT.

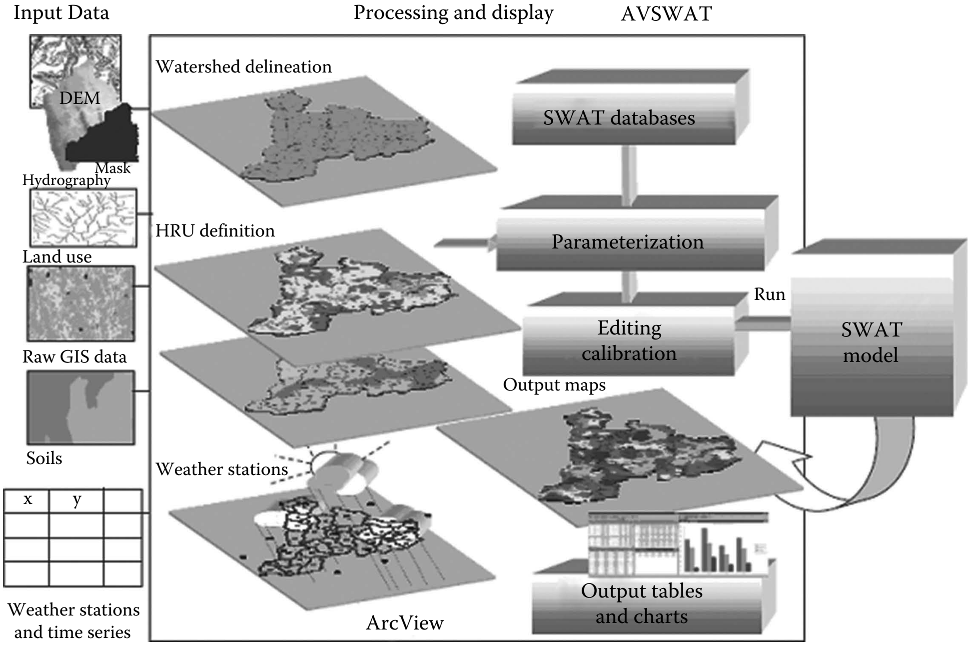


**FIGURE 26.8** Schematic of AVSWAT (From Di Luzio, M. et al., Soil and water assessment tool. ArcView GIS interface manual: Version 2000, GSWRL Report 02–03, BRC Report 02–07, Published by Texas Water Resources Institute TR-193, College Station, TX, 346 pp, 2002).

AVSWAT (Figure 26.8) is organized in a sequence of several linked tools grouped into eight modules:

1. Watershed delineation
2. Definition of HRU
3. Definition of the weather stations
4. AVSWAT databases
5. Input parameterization, editing, and scenario management
6. Model execution
7. Read and map-chart results
8. Calibration tool

The basic map inputs required for the AVSWAT include digital elevation maps, soil maps, land-use/land-cover maps, hydrography (streamlines), and time series on weather variables with their locations.

## 26.7 Description of the Study Region

The study region is the catchment of Malaprabha river, upstream of Malaprabha reservoir. It has an area of 2093.46 km$^2$ situated between latitude 15°30′N–15°56′N and longitude 74°12′E–75°8′E. It lies in the extreme western part of the Krishna river basin in India and includes parts of Belgaum, Bagalkot, and Dharwad districts of north Karnataka.

The Malaprabha river is one of the main tributaries of the river Krishna. The river originates at Kankumbi near the Chorla Ghats in the Western Ghats at an altitude of 793 m, 16 km from Jamboti village in Khanapur taluk. The Malaprabha dam was constructed by 1974 near the famous "Naviluteertha" or peacock gorge near Manoli in Parasgad taluk of Belgaum district. The Malaprabha irrigation project comprises of a masonry dam of height 145.53 m and length 40.23 m. The dam has a gross storage capacity of 37.73 (1000 million cubic feet) TMC (~1070 Mm$^3$) and live storage capacity of 29.32 TMC (~830 $Mm^3$). The area to be irrigated by right bank canal (RBC) is 202,708 ha and that by left bank canal (LBC) is 41,364 ha [22].

Analysis of temporal variation of rainfall showed that, in general, the climate of the subbasin is dry, except in monsoon months. Isohyetal map prepared for the study region showed considerable variation in spatial distribution of annual rainfall. Heavy rainfall (more than 3000 mm) is recorded at gauging stations in the upstream reaches of the Malaprabha catchment, which forms a part of the Western Ghats. In contrast, the rainfall recorded at the Malaprabha dam is around 400 mm.

The mean monthly maximum temperatures in the catchment vary from 25°C to 34°C and the average of the mean monthly maximum temperatures is 28°C. The mean monthly minimum temperature ranges from 17°C to 21°C. The day temperatures rarely fall below 25°C. The hottest months are April and May with mean maximum temperature of 34°C. December and January are the coldest months with mean minimum temperature of 17°C. On annual basis, the diurnal difference between the maximum and the minimum temperatures is 8°C–13°C.

The wind speeds are high during the monsoon season (June to September) and low during November, December, and January months. The mean monthly wind speed is 9.6 km/h during the peak monsoon (July), while in non-monsoon months, the mean monthly wind speed varies from 3 to 6 km/h.

The subbasin has a wide variety of soils such as medium black soil, deep black soil, mixed red and black soils, red sandy soil, and red loamy soil [11], which can be broadly classified into three textures, namely, clay, skeletal clay, and loam. Further, among the soils in the subbasin, the black soil is predominant.

## 26.8 Data Used in the Study

In this study, contemporaneous daily rainfall records of 11 gauging stations in the catchment of Malaprabha reservoir are considered. The rainfall data, from January 1971 to December 2000, are procured from the Directorate of Economics and Statistics (DES), Bangalore, India. The record of daily streamflows at Malaprabha dam, from January 1978 to December 2003, is collected from the files of the Water Resources Development Organization (WRDO), Bangalore. Further, the records of meteorological parameters such as daily maximum, minimum, and mean temperatures, wind velocity, and relative humidity, for the period from January 1978 to December 2000, for Gadag station are procured from the India Meteorological Department. The available information on rainfall and runoff for the study region allows comparison of the SWAT model simulated runoff with that observed at the Malaprabha dam for the period from January 1978 to December 2000. A thematic layer showing the locations of the hydrometeorological gauging stations is prepared using their spatial coordinates. Attributes such as rainfall, temperature, and wind speed in meteorological data files are assigned to each gauging station. Later, hydrometeorological data are assigned to each subbasin based on its proximity to the gauging station.

The Shuttle Radar Topography Mission (SRTM) DEM data modified for the study region are procured from the International Water Management Institute (IWMI), Hyderabad, India. The SRTM DEM presents the elevation of the land surface with a resolution of 90 m (3 arc s × 3 arc s). The SRTM obtained the elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of the Earth. SRTM consisted of X-band and C-band radar interferometry that flew onboard the space shuttle Endeavour during an 11-day mission in February of 2000. SRTM is an international project spearheaded by the National Geospatial-Intelligence Agency (NGA), the National Aeronautics and Space Administration (NASA), the Italian Space Agency (Agenzia Spaziale Italiana; ASI), and the German Aerospace Center (Deutschen Zentrum für Luft- und Raumfahrt [DLR]).

Soil, land-use, and land-cover information obtained by interpretation of satellite images and data on hydroclimatic attributes are provided as input to SWAT model.

The runoff curve numbers (CNs) considered for selected land use, land cover, and soils in the Malaprabha subbasin were adapted from [8]. The available water content, also referred to as plant available water or AWC, is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity.

The basin attributes are obtained using a given basin layer. The SWAT–ArcView interface calculates area, resolution, and geographic coordinate boundaries for the basin and for each subbasin. The length of the longest stream and the proportion of each subbasin within the basin are also estimated.

## 26.9 Application of AVSWAT Model

The main source of hydrological input to a catchment is rainfall. Therefore, assessment of its spatial and temporal variation in the study region is necessary before developing a hydrological simulation model. Average rainfall over the catchment of Malaprabha reservoir is estimated at monthly and annual time scales by the SWAT model using the records of the selected rain gauges in the study region. To check the general validity of the estimated rainfall from the SWAT model, the representative rainfall provided by SWAT and that obtained by adopting Thiessen polygon method, which is a common method for computing average rainfall over an area, are compared. GIS was used for estimation of the areas of the Thiessen polygons. The average rainfall at monthly time scale for the study region, computed using SWAT model and Thiessen polygon method, are found to be correlated to each other fairly well.

Temporal variation of average rainfall in the catchment of Malaprabha reservoir and its relationship with the streamflows recorded at the reservoir site is studied. Results show that peak flows noticed at reservoir correspond to heavy rainfall in the catchment.

The runoff from the catchment was simulated using SWAT model with ArcView interface. The ArcView interface is useful to create databases necessary for the SWAT model. First, ArcView map themes and database files, which provide necessary information about the watershed, are prepared. The ArcView map themes required for the interface include those of DEM data, land cover, land use, and soil. The database files necessary for the interface include [4] the following:

1. Location tables of subbasin outlet, watershed inlet, gauging stations of precipitation, temperature, solar radiation, wind speed, and relative humidity
2. Look-up tables of land use and soil
3. Data tables for precipitation, temperature, solar radiation, wind speed, relative humidity, point discharge (annual, monthly, and daily loadings), reservoir inflow (monthly and daily if available), and potential evapotranspiration (if available)

The DEM data were preprocessed using ArcView interface of SWAT model, to obtain stream network in the catchment of the Malaprabha reservoir (shown in Figure 26.3). For this purpose, the minimum watershed area (critical source area) was specified as 210 ha. Subsequently, the stream network was reviewed and drainage basin outlets are fixed through screen interactive option of the SWAT model (see Figure 26.4). The SWAT model was run forming 14 drainage subbasins in the Malaprabha reservoir catchment (Figure 26.5), and the physiographic characteristics of the subbasins are noted.

The land-use/land-cover and soil maps of the Malaprabha reservoir catchment (shown in Figures 26.9 and 26.10) are overlaid on each other to identify HRUs. The information about the type of land use/land cover and soil in each HRU and the number of HRUs in each drainage subbasin is documented. The SWAT model allows user to edit databases containing parameters of soils, weather stations, land cover/plant growth, fertilizer, pesticide, tillage, and urban land type.

The data tables prepared of weather variables are fed into the SWAT model and it was run. The development of the SWAT model involves calibration and validation phases. Traditionally, the first 70% of the available record is selected for training and the remaining 30% is used for validation. In the current study, the data for the period from January 1978 to December 1993 were considered for model calibration, and that for the period from January 1994 to December 2000 were considered for model validation.

The SWAT model provides amount of water in the land phase of the hydrological cycle, sediment, nutrient and pesticide loadings in each subbasin, and sediment routed through the channel network to the outlet as outputs. However, only the runoff generated by SWAT was considered for validation.

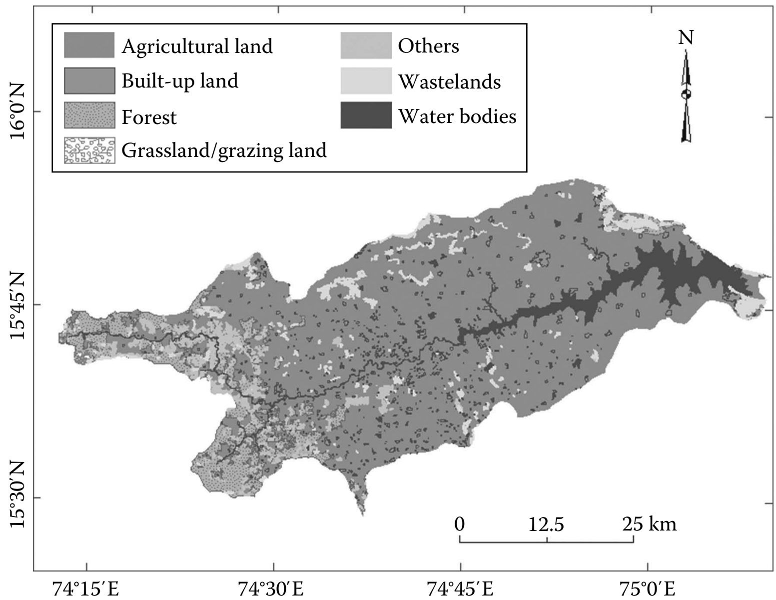


**FIGURE 26.9** Land-use/land-cover theme of the Malaprabha reservoir catchment.

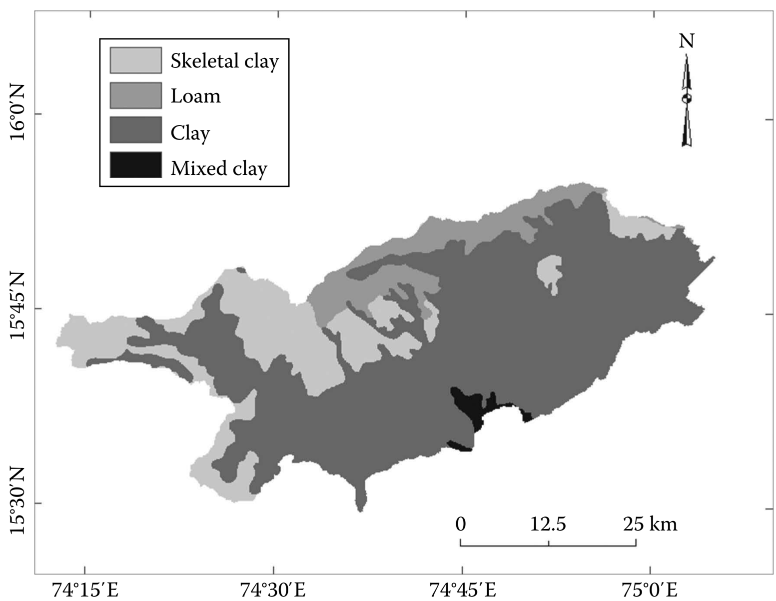


**FIGURE 26.10** Theme showing classified soils in the Malaprabha reservoir catchment.

In calibration phase, the runoff simulated by SWAT model at monthly time scale was compared with that observed at the Malaprabha reservoir. In general, the model overpredicts or underpredicts the runoff. In a few cases, the model may not simulate intermittent peak flows, possibly due to loss of information because of nonuniformity in spatial distribution of the available rain gauges in the study region.

The SWAT model estimates the water yield from an HRU for a time step, using Equation 26.1. The water leaving an HRU contributes to streamflow in the reach:

$$\text{WYLD} = \text{SURQ} + \text{LATQ} + \text{GWQ} - \text{TLOSS} - \text{Pond abstractions} \quad (26.1)$$

where surface runoff (SURQ), lateral flow (LATQ), and groundwater flow (GWQ) represent contribution to streamflow in the reach from SURQ, LATQ, and GWQ, respectively, during the time step. TLOSS refers to the amount of water lost from tributary channels during transmission. The groundwater is primarily contributed by shallow aquifers. The area-weighted values of rainfall, SURQ, GWQ, and streamflow in the reach (WYLD) for the Malaprabha catchment estimated from the corresponding values of the variables at the 14 drainage subbasins in the catchment are some of the outputs from this model.

In the present study, the SWAT model is found to overpredict the runoff. To overcome the problem, possible options include decreasing the CN and increasing AWC of soil, EPCO, and the ESCO [10].

Soil moisture depletes from various depths in the soil layer(s) to meet its evaporative demand. The parameter ESCO allows user to specify contribution from different depths of soil in meeting the soil-evaporative demand. The default setting in SWAT causes 50% of the soil-evaporative demand to be met from the top 10 mm of soil and 95% of the same to be met from the top 100 mm. When ESCO approaches 0, the SWAT model allows more water to be extracted from the lower layers of soil to meet the evaporative demand. On the other hand, as ESCO approaches 1, the model allows less variation from the default setting, indicating a situation in which evaporative demand is met primarily from the top layer of soil.

Further, plant uptakes water from its root zone to meet its transpiration requirements. The parameter EPCO allows user to specify the vertical distribution of plant water uptake within the root zone. The default setting in SWAT allows plant to uptake 50% of water demand from the upper 6% of the root zone. When EPCO approaches 1.0, the SWAT model allows more of the water uptake demand to be met by lower layers in the soil. On the other hand, as EPCO approaches 0, the model allows less variation from the default setting, indicating that plant water uptake occurs primarily within upper root zone.

With a view to examine the sensitivity of the result from the SWAT model to variation of parameters, sensitivity analysis is performed by varying each of the model parameters within its permissible range. The values of EPCO and ESCO are varied from 0.1 to 1.0 with an increment of 0.1, whereas the value of AWC is varied from −0.04 to +0.04 with an increment of 0.01. For each combination of the chosen parameters, the runoff simulated by the SWAT model is compared with that observed at the Malaprabha dam for the calibration period, in terms of model performance indicators. Results pertaining to the parameters EPCO = 0.75, ESCO = 0.4, and AWC = 0.04 are selected from the calibration phase. Even after calibration, the magnitude of error in simulating streamflows is found to be high because of consistent overprediction of runoff from the Malaprabha catchment. The overprediction of runoff by the SWAT model could be attributed to the combined effect of considerable amount of retention storage in Malaprabha catchment, which goes unaccounted for in estimating inflows into Malaprabha reservoir every water year as well as the possible underestimation of evapotranspiration in the region. Even though SWAT models these two components, investigations towards their estimation are constrained by the paucity of data. Hence, for each month, the retention storage and plausible error in estimation of evapotranspiration are lumped together as one parameter and estimated in the calibration period. Parameters thus obtained are used for the model validation. Streamflows simulated by SWAT model for the validation period after accounting for the combined effects of retention storage and evapotranspiration are shown in Figure 26.11. It can be seen from the figure that the model performs fairly well with a $R^2$ value of 0.95 during the validation period (January 1994–December 2000).

Information pertaining to temporal variation of storage in all the prominent surface water bodies existing in the subbasin (such as lakes/tanks) is necessary to arrive at a reasonable estimate for the retention storage. However, for the Malaprabha catchment, records pertaining to filling and emptying of prominent surface water bodies are not maintained. Moreover, accurate estimation of volume of surface water contributing to retention storage requires understanding interaction of surface and groundwater in the subbasin, possibly by using advanced techniques such as isotope hydrology, which is beyond the scope of the present work.

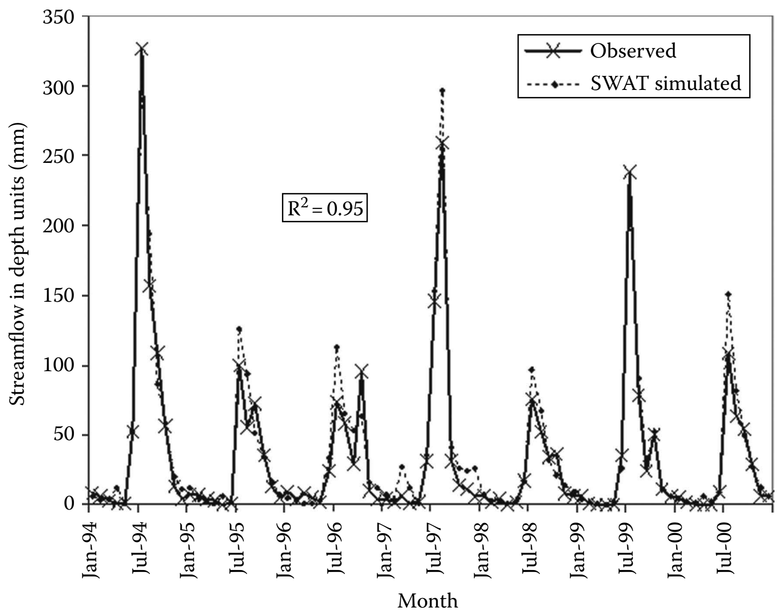


**FIGURE 26.11** Observed and simulated monthly streamflows at Malaprabha dam site for the validation period.

## 26.10 Summary and Conclusions

GIS has been used to capture the synergy between the time series data on variables describing water properties and the geospatial data on water environment for a better WRA. A high-resolution DEM can be used as the basic spatial data source in defining the hydrography of the study basin for WRA. GIS and DEM make the best use of scattered information and facilitate extrapolating point data or data available at river basin level to develop a credible picture of the situation of the water use in the river basin and its impact on water resources. Thus, GIS and DEM are useful in the first stage of WRA.

GIS with its data, topological, network, and cartographic modeling, map overlay, and geostatistics techniques is a useful tool for hydrological modeling in the second stage of WRA. DEM used for extracting topographic information such as slope properties, drainage basin delineation, drainage divides, and drainage networks is useful for hydrological modeling in the second stage of WRA.

The use of GIS and DEM in the different stages of WRA is demonstrated through a case study of rainfall–runoff simulation in Malaprabha reservoir catchment of India using SWAT model. The GIS and DEM were useful in providing necessary input to SWAT model that performed fairly well in predicting runoff. The results pertaining to the parameters EPCO = 0.75, ESCO = 0.4, and AWC = 0.04, for which $R^2$ value of 0.95 is obtained during validation, are selected.

Recently, there is growth in consensus that global climate is changing. The climate change could introduce nonstationarity in time series of hydrological and hydroclimatic variables such as streamflow and rainfall. If there is evidence of nonstationarity in data, it has to be accounted in modeling hydrology of river basin. However, longer records are necessary to prove the assertion of nonstationarity. For the Malaprabha catchment, investigations in this direction are constrained by paucity of data on hydroclimatic variables.

In this study, in addition to investigating the water balance issues of each subbasin in Malaprabha catchment, SWAT was developed to predict the impact of land management practices on water displacement of sediment, and agricultural chemical yields. This information may be used in the final stage of WRA for integrated management of water resources in the basin.

## Abbreviations

| | |
|---|---|
| AML | Arc macro language |
| ASI | Italian Space Agency |
| AVSWAT | ArcView Interface of Soil and Water Assessment Tool |
| AWC | Available water content |
| CN | Curve number |
| DEM | Digital elevation model |
| DES | Directorate of Economics and Statistics |
| DLR | German Aerospace Center |
| EPCO | Plant uptake compensation factor |
| ESCO | Soil evaporation compensation factor |
| GIS | Geographic information system |
| GUI | Graphical user interface |
| GWP | Global Water Partnership |
| GWQ | Groundwater flow |
| ha | Hectare |
| HRU | Hydrological response unit |
| IWMI | International Water Management Institute |
| LATQ | Lateral flow |
| LBC | Left bank canal |
| $Mm^3$ | Million cubic meters |
| NASA | National Aeronautics and Space Administration |
| NGA | National Geospatial-Intelligence Agency |
| NIH | National Institute of Hydrology |
| PIR | Project Identification Report |
| RBC | Right bank canal |
| SRTM | Shuttle Radar Topographic Mission |
| SURQ | Surface runoff |
| SWAT | Soil and Water Assessment Tool |
| TMC | Thousand million cubic feet |
| TLOSS | Amount of water lost from tributary channels during transmission |
| USDA | US Department of Agriculture |
| WRA | Water resources assessment |
| WRDO | Water Resources Development Organization |
| WWAP | World Water Assessment Programme |
| WWC | World Water Council |
| WWDR | World Water Development Report |
| WYLD | Streamflow in the reach |

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## References

1. Abel, D.J., Kilby, P.J., and Davis, J.R. 1994. The systems integration problem. *International Journal of Geographical Information Systems*, 8(1), 1–12.

2. Akhavan, S., Abedi-Koupai, J., Mousavi, S.F., Afyuni, M., Eslamian, S.S., and Abbaspour, K.C. 2010. Application of SWAT model to investigate nitrate leaching in Hamadan–Bahar Watershed, Iran, agriculture. *Ecosystems and Environment*, 139, 675–688.
3. Alemaw, B.F. and Chaoka, T.R. 2003. A continental scale water balance model: A GIS approach for Southern Africa. *Physics and Chemistry of the Earth. Parts A/B/C*, 28(20–27), 957–966.
4. Di Luzio, M., Srinivasan, R., Arnold, J.G., and Neitsch, S.L. 2002. Soil and water assessment tool. ArcView GIS interface manual: Version 2000. GSWRL Report 02–03, BRC Report 02–07, Published by Texas Water Resources Institute TR-193, College Station, TX, 346 pp.
5. Maidment, D.R. 1993. GIS and hydrologic modeling. In: *Environmental Modeling with GIS*, Goodchild, M.F., Parks, B.O., and Steyaert, L.T. (eds.), Oxford University Press, New York, 147 pp.
6. McDonnell, R.A. 1996. Including the spatial dimension: Using geographical information systems in hydrology. *Progress in Physical Geography*, 20(2), 159–177.
7. Meijerink, A.M.J. et al. 1994. *Introduction to the Use of Geographic Information System for Practical Hydrology*, International Hydrological Programme, UNESCO and ITC. Enschede, the Netherlands.
8. Mishra, S.K. and Singh, V.P. 2003. *Soil Conservation Service Curve Number (SCS-CN) Methodology*, Water Science and Technology Library, Vol. 42, Kluwer Academic Publishers, Dordrecht, the Netherlands, 513 pp.
9. Neitsch, S.L. et al. 2002a. Soil and water assessment tool—Theoretical documentation: Version 2000, Texas Water Resources Institute (TWRI) Report TR-191, College Station, TX.
10. Neitsch, S.L. et al. 2002b. Soil and water assessment tool—User's manual: Version 2000, Texas Water Resources Institute (TWRI) Report TR-192, College Station, TX.
11. NIH. 1989. Hydrological year book for 1988–89, Malaprabha sub-basin, Technical Report (TR-150), National Institute of Hydrology, Roorkee, India.
12. Pullar, D. 2005. Incorporating level set methods in Geographical Information Systems (GIS) for land-surface process modeling. *Advances in Geosciences*, 4, 17.
13. Singh, V.P. and Frevert, D.K. (eds.). 2002a. *Mathematical Models of Large Watershed Hydrology*, Water Resources Publications, LLC, Highlands Ranch, CO, 914 pp.
14. Singh, V.P. and Frevert, D.K. (eds.). 2002b. *Mathematical Models of Small Watershed Hydrology and Applications*, Water Resources Publications, LLC, Highlands Ranch, CO, 972 pp.
15. Singh, V.P. and Woolhiser, D.A. 2002. Mathematical modeling of watershed hydrology. *Journal of Hydrologic Engineering, ASCE*, 7(4), 270–292.
16. UNESCO/WMO. 1992. *International Glossary of Hydrology*, 2nd edn. UNESCO and WMO, Geneva, Switzerland, 413 pp.
17. UNESCO/WMO. 1997a. *Comprehensive Assessment of the Freshwater Resources of the World*. Report by the UN, UN Development Programme, UN Environment Programme, FAO, UNESCO, WMO, World Bank, WHO, UN Industrial Development Organization and Stockholm Environment Institute. World Meteorological Organization, Geneva, Switzerland.
18. UNESCO/WMO. 1997b. *Water Resources Assessment–Handbook for Review of National Capabilities*, Geneva, Switzerland, 153 pp.
19. United Nations General Assembly. 1997. *Programme for the Further Implementation of Agenda 21*, United Nations General Assembly Special Session, United Nations, New York.
20. World Water Development Report. 2003. *The United Nations World Water Development Report 1: Water for People, Water for Life*. UNESCO Publishing/Berghahn Books, Oxford, U.K., 576 pp.
21. World Water Development Report. 2006. *The United Nations World Water Development Report 2: Water—A Shared Responsibility*. UNESCO Publishing/Berghahn Books, Oxford, U.K., 600 pp.
22. WRDO. 1986. Malaprabha project–project identification report, Irrigation Department, Bangalore, India.
23. Xu, C.Y. and Singh, V.P. 2004. Review on regional water resources assessment models under stationary and changing climate. *Water Resource Management*, 18(6), 591–612.