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Full Length Research Paper

Scenario generation using geographical information system (GIS) based hydrological modelling for a multijurisdictional Indian River basin

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Lack of information about the futuristic scenarios of possible water allocations acts as a deterrent in resolving the conflicts pertaining to transboundary watercourses. It is increasingly being felt that technology, in the form of simulation modelling, has a very significant role to play in this context. For water resources engineering problem solving, geographical information system (GIS) offers a cognitive spatial representation of complex hydrologic and hydraulic systems. Of specific interest to decision makers is the capability of GIS to visually display information for interpretation of water resource model inputs and outputs, which enables users to take a more dynamic approach with data input, modification, scenario development, and evaluation (Martin et al., 2005). In the present study, GIS based hydrological modelling has been utilized for the purpose of assessment of the total amount of water available in the study area, as well as prediction of the impact of changes in the land management practices on the water availability in the study area, and consequently the amount of water allocated to each of the riparian states. The hydrological model used for the study is SWAT (soil and water assessment tool). The results of the study show that water yield of the basin is inversely proportional to the amount of forest cover. The study demonstrates that simulation modelling can play a very significant role in water resources management by generating a series of scenarios or options for the stakeholders, so as to enable them to take sound rational decisions.

Key words: Geographical information system (GIS), hydrological modelling, soil and water assessment tool (SWAT), scenario generation.

INTRODUCTION

In the present study, geographical information system (GIS) based hydrological modelling has been used to simulate the hydrological regime of Cauvery river basin in India. The hydrological model used for the study is SWAT (soil and water assessment tool) (Arnold et al., 1995). The impact of changes in the land management practices on the water availability in the basin has been modelled. SWAT is the acronym for soil and water assessment tool, a river basin or watershed scale model developed by Dr. Jeff Arnold for the USDA agricultural research services (ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watershed with varying soils, land use and management conditions over long periods of time. SWAT is a continuous time model, that is, a long-term yield model having the capability of scenario generation, so as to equip the policy makers with a wider range of options, which makes it the ideal tool to be used for such a study (Arnold et al., 1995, 1998; Neitsch et al., 2002).

DESCRIPTION OF THE STUDY AREA

The Cauvery is the fourth largest river in the peninsular of southern India, after Godavari, Krishna, and the Mahanadi. The Cauvery rises at Talakaveri on the

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Brahmagiri Range of hills (12° 25' N, 74° 34'E) in the Western Ghats in the Coorg District of Karnataka, at an elevation of 1,341 m above mean sea-level. In its course of 802 km from the Western Ghats to the Bay of Bengal, the main river flows for 381 km in Karnataka, 357 km in Tamil Nadu, and provides the boundary between the two states for the rest. One of its important tributaries in Karnataka, the Kabini, originates in Kerala; and drainage from Kerala contributes to the Bhavani and the Amaravathy, two of the river's tributaries in Tamil Nadu. Sub-branches of the river irrigate the Karaikal area in Pondicherry before entering the sea.

The Cauvery is thus an interstate river, with all four basin states- Karnataka, Tamil Nadu, Kerala, and Pondicherry- having an interest in the sharing of its waters, although Karnataka in the upper and Tamil Nadu in the lower reaches are by far the principal co-riparians (Guhan, 1993). The climate of Cauvery river basin may be described as essentially a tropical monsoon type, which is a product of the interplay of the two opposing air masses of the South-West and North-East Monsoons. The following four distinct seasons occur in the basin (CFFC, 1972):

1. Cold weather period (January – February);
2. Hot Weather period (March – May);
3. South – West Monsoon period (June – September);
4. North – East Monsoon period (October – December).

The general agricultural practice in the basin broadly has three categories of cultivation, namely (i) wet land irrigated from the rivers and tanks; (ii) garden lands irrigated from pump sets and wells and (iii) rain-fed dry land cultivation. In the wet lands, paddy is the most important crop, whereas ragi, jowar and other millets constitute the important rainfed crops (CFFC, 1972).

MATERIALS AND METHODS

The SWAT model requires data on terrain, land use, soil, weather and man-made structures like reservoirs etc for assessment of water resource availability at the desired locations of the drainage basin. To create a SWAT dataset, the interface needs to access Arc View map themes and database files, which provide topographical, land use/land cover, soil class and climatic information about the watershed. Maps and database files have been prepared prior to making the simulation runs.

Contours

A survey of Indian topographic sheets on a scale of 1:250,000 have been used. Spatial data has been created on the GIS platform using Geomedia Explorer. The polyconic projection system has been used. Two line type feature classes were defined, for digitization of contours and stream network. The contours have been digitized for the purpose of digital elevation model (DEM) generation and subsequently, watershed delineation.

Stream network

Stream network is an optional Arc View map theme which needs to be provided as a shape file. In case it is not provided by the user, the interface generates it using the DEM. In the present case, a polyline shape file of stream network has been obtained from the digitized drainage network. This shape file has been superimposed on the DEM. The stream delineation shape file has been used in the present case because it was felt that in some areas, the relief was so low that the DEM map grid was unable to accurately predict the location of the streams.

Land use data

The input data pertaining to land use/land cover can be input in the shape file as well as grid format. In the present case, the Cauvery basin land use data has been input as a shape file which was obtained after digitizing the land use maps obtained from the Cauvery authorities on a GIS (Geomedia Explorer) platform. This shape file was later converted into the grid format. The categories specified in the land cover/land use map are reclassified into the SWAT land cover/plant types. In case a United States Geological Survey (USGS) land use/land cover map is used, the interface converts it into SWAT land cover/plant types using an inbuilt table that identifies the different SWAT land cover/plant types used to model the various USGS land uses.

Since the USGS maps have not been used in the present case, there were two options available for reclassifying the input map land uses into SWAT land uses. The first option was to type in the 4 letter SWAT land cover/plant type code for each category when the land use map was loaded in the interface, while the second option was to create a look up table identifying the 4 letter SWAT code for different categories. The first option has been used for reclassification and the reclassified land use categories of the Cauvery basin have been shown in Figure 1.

Soil class data

The input data pertaining to land use/land cover can be input in the shape file as well as grid format. In the present case, the Cauvery basin soil data has been input as a shape file which was obtained after digitizing the soil maps obtained from the Cauvery authorities on a GIS (Geomedia Explorer) platform. This shape file was later converted into the grid format. Since the inbuilt AVSWAT database contains information pertaining to the US soils only, the data pertaining to the soil types present in the Cauvery basin has been entered in the user soils database. There are no differences between US and indian soil? The US classification is either well adapted or not (Neitsch et al., 2002). The "Name" specified for each soil in the user soils database is the same as its name in the input soil category map. The soil class categories of the Cauvery basin are shown in Figure 2.

Climatic data

The model requires climatic data pertaining to the precipitation, maximum and minimum temperature, solar radiation, wind speed and relative humidity. Since hydrological processes operate on a daily time step, daily values of these variables are needed to accurately predict the hydrological behaviour of the basin. The model has an inbuilt weather generator which can be used for predicting the daily values of all these variables, provided certain long term weather statistics are available. This feature of the model makes it very useful for ungauged watersheds.

However, Gholami (1999) has shown that the outputs of the

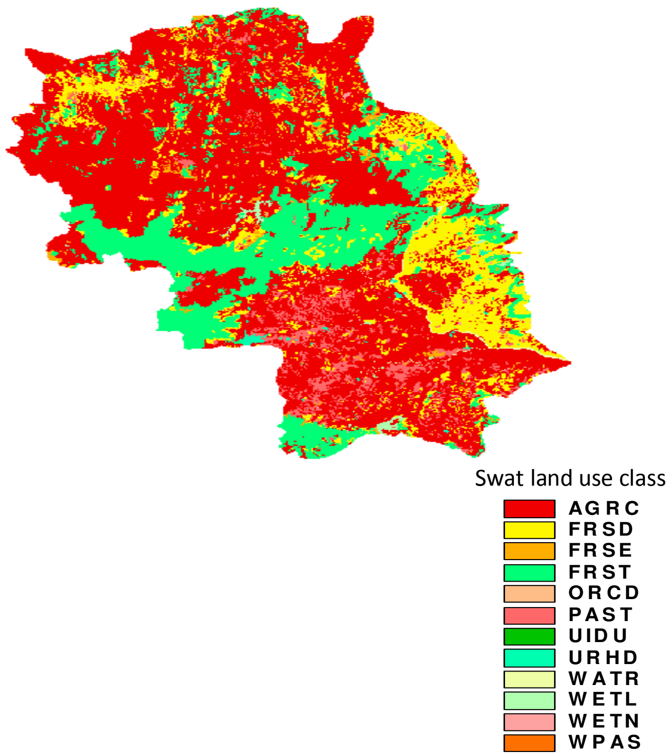

Figure 1. Reclassified land uses for the Cauvery river basin.

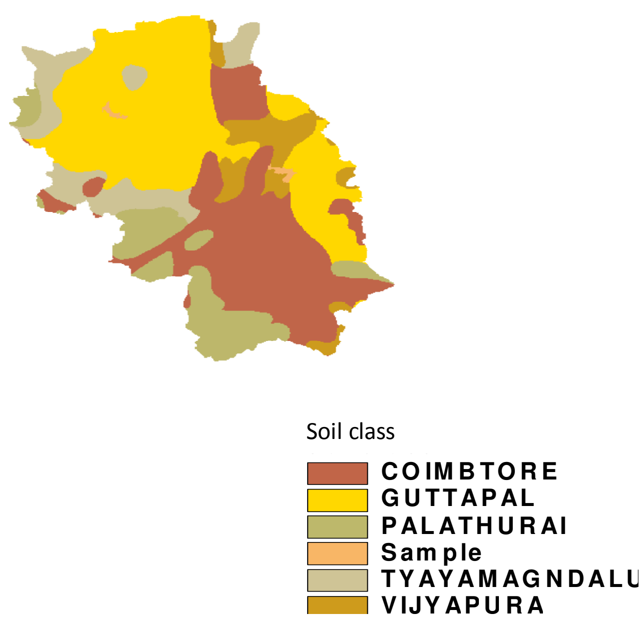

Figure 2. Reclassified soil classes for the Cauvery river basin.

model get closer to the reality if daily observed values are used along with the long term data. The long term (30 year average) data has been provided in the user weather stations database pertaining to input variables like precipitation, maximum temperature, minimum temperature, solar radiation, wind speed and relative humidity. Recently, the Indian Meteorological Department has provided the rainfall data for the whole of India considering a grid with a cell size of 1°×1° (Rajeevan et al., 2006) and the same has been used for the present study. For values of other climatic variables like maximum temperature, minimum temperature and solar radiation, daily values for 3 climatic stations has been used along with the long term averages for the same. The daily values of wind speed and relative humidity have been simulated by the inbuilt weather generator of the model.

Reservoir data

Impoundment structures modify the movement of water in the channel network by lowering the peak flow and volume of flood discharges. SWAT is able to model three types of impoundments. The first type is a small structure with one spillway. Releases occur only when the storage volume of the structure is exceeded and the excess volume is released within one day. The second type of impoundment is a small, uncontrolled reservoir with a principal and emergency spillway. Water is released at a specified rate when the volume of the reservoir exceeds the principal spillway volume. Volume exceeding the emergency spillway storage is released within one day. The third type of impoundment is a managed reservoir. Water may be released from the managed reservoir based on measured outflow or target reservoir volumes. The third type of impoundment has been used in the present study.

A total of nine reservoirs have been simulated in the present study. These are Hemavathy, Harangi, KRS, Kabini, Marconahalli, Suvarnavathy, Mettur, Bhavani and Amravathy. These are the major reservoirs in the basin and the data for these are available, that is the reason for their inclusion in the study. All these have been input as large managed reservoirs with known monthly outflow values. The reservoirs have been input on the main channel network after the watershed delineation (described subsequently) is over. Monthly outflow values for all these reservoirs have been input as separate tables containing monthly outflow data from the time the reservoir became operational.

PREPROCESSING

The following steps have been used in preprocessing:

DEM Generation

Several interpolation methods can be used for generating the unavailable data in GIS which include regression analysis, theissen polygon and inverse distance weighted methods. The method of interpolation used for the present study is the inverse distance weighted (IDW) method. The DEM is shown in Figure 3.

Watershed delineation

Four grid data matrices that are prerequisite to automatic delineation of watershed in the same sequence are:

1. DEM,
2. Flow direction,
3. Flow accumulation, and
4. Stream link.

HRU Generation

Each unique combination of land use and soil class constitutes a "Hydrologic Response Unit" or HRU. Subdividing each sub watershed into unique land use and soil class combination enables the model to reflect the differences in evapotranspiration and other hydrologic conditions for different land covers/crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases the accuracy of the water yield predictions and provides a much better physical description of the water balance. In the present study, the entire basin has been subdivided into 42 sub-basins. There are two options of determining the HRU distribution. In case a single HRU is to be generated for each sub-basin, the HRU is determined by the dominant land use class and soil type within each sub-basin. However, in case multiple HRUs are required within each sub-basin, a two step procedure is followed.

Firstly, land uses are chosen. Once the land uses to be modeled are determined, the different soils for each land use are chosen. One HRU is created for each unique land use/soil class combination. In the present case, since more accuracy is desired, multiple HRUs are chosen within each sub-basin. The threshold levels of land use as well as soil types have been fixed as 5%. The threshold level is used to eliminate minor land uses/soil types in each sub-basin. In the first stage land uses that cover a percentage of the sub-basin area less than the threshold level are eliminated and the area of the remaining land uses is reapportioned, so that 100% of the land area in the sub-basin is modeled. In the second stage minor soil types within each land use area are eliminated and area of the remaining soil types is reapportioned. After fixing the threshold levels, a total of 231 HRUs were obtained.

MODEL CALIBRATION

The daily values of discharges up to Musiri (outlet) have been taken from Cauvery basin authorities for the purpose of model calibration and validation. The model has been validated over a 10 year period from 1980 to 1989 and it was observed that the performance of the model was highly satisfactory. The percentage error in annual average flows over a 10 year period have been estimated as 8.1%, if data from the Central Water Commission (CWC) is used, and 10.8% if data from the Water Resources Development Organisation (WRDO) is used. As a further check, observed and simulated monthly discharges were compared for a two year period and the results have been plotted as shown in Figure 4.

The Nash Sutcliffe coefficient was observed to be 0.934 and the value of coefficient of determination was calculated as 0.9362. This shows that the model has captured the system well and hence there is no need to calibrate the model. The results have been found to be in agreement with Gosain and Rao (2003), wherein it has been stated that “the SWAT model has been used in various Indian catchments of varied sizes and it has been observed that the model performs very well without much calibration.”

SCENARIO GENERATION USING HYDROLOGICAL MODELLING

Generation of futuristic scenarios is one of the most important applications of hydrological modelling. Scenario generation helps the decision makers to analyse the potential impacts of their actions. The well known hydrological principle of "Think globally, act locally” can only be applied if sophisticated tools and techniques such as simulation modelling are available. In the present case, a variety of land use changes are simulated and the impact on the hydrological characteristics of the basin are analysed. The aim of the exercise is to generate a series of scenarios or options for the stakeholders, so as to enable them to take sound rational decisions.

The stakeholders, if they so desire, can use simulation modelling for some other sets of land use changes which are more acceptable to them. Hence, the attempt is to empower the stakeholders by providing them with the freedom of choice. Moreover, the impacts of futuristic climate changes on the hydrological regime can be effectively captured through the use of modelling techniques and the remedial actions can be taken well in time. In the present scenario, the (approximate) land uses within the Cauvery basin are:

1. Agriculture = 60%
2. Forests = 35%
3. Others = 5%

Futuristic scenarios have been generated for three categories of

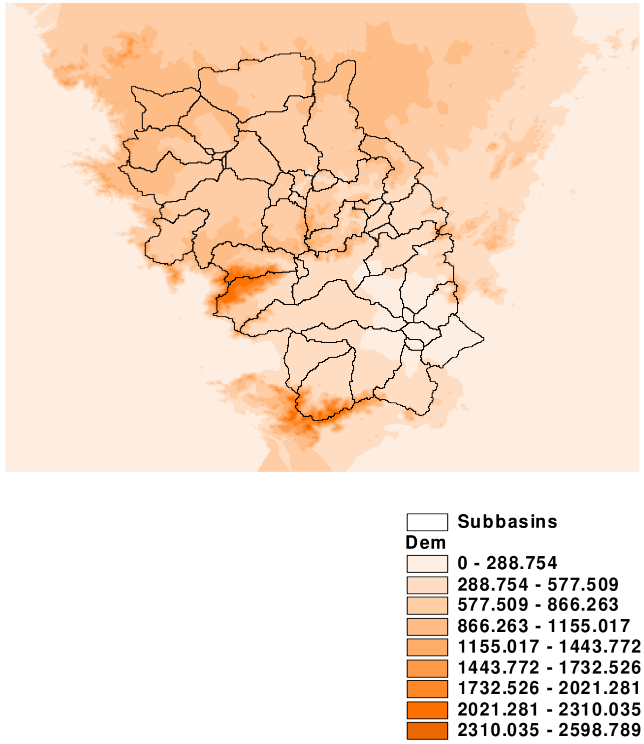

Figure 3. Layout of Cauvery basin and DEM showing elevations in metres.

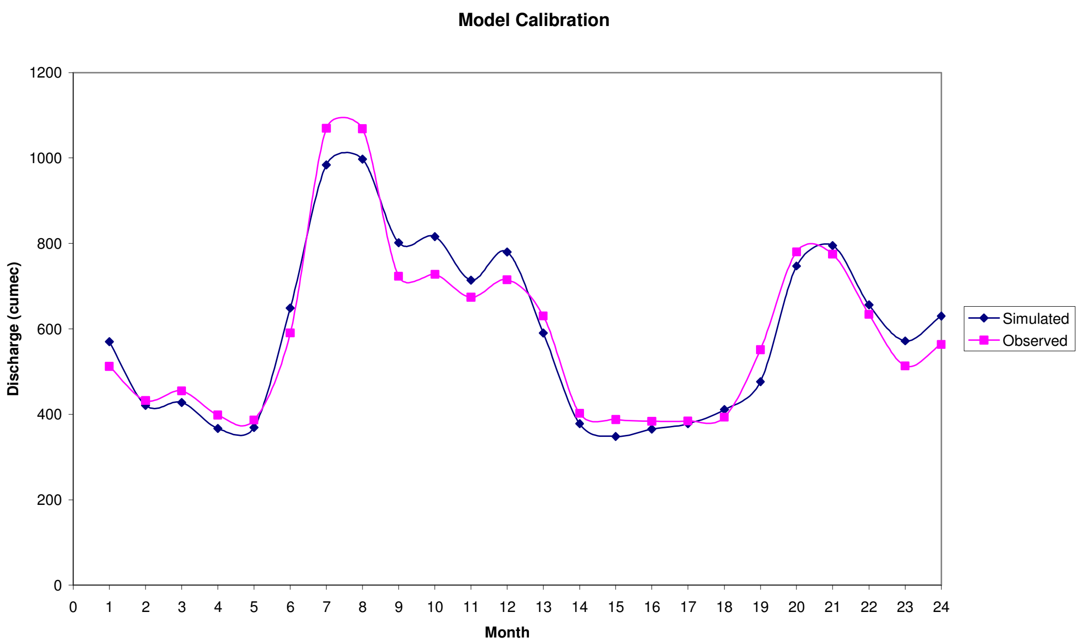

Figure 4. Comparison of average monthly flows over a 2 year period.

land use changes. Table 1 shows four categories of land uses, S_1 to S_4 in which S_4 is the present land use scenario. Hydrological modelling was carried out on GIS (Arc View) platform to analyse the aforementioned categories of land use changes. The resultant variation of water yields of the basin are shown in Table 2. Since it is often argued that water allocations should be on the basis of 75% dependable flows, the same have also been calculated and plotted. Units are in TMC (1 TMC is equal to one thousand million cubic

Table 1. List of land use scenarios.

I	Scenario	%AGRC	%FRST
1	S_1	75	20
2	S_2	70	25
3	S_3	65	30
4	S_4	60	35
5	S_5	55	40
6	S_6	50	45
7	S_7	45	50

Table 2. Variation of average flows.

Agriculture / Forest	45	50	55	60	65	70	75
20							833(S_{11})
25						814(S_{21})	
30					807(S_{31})		
35				795(S_{41})			
40			781(S_{51})				
45		778(S_{61})					
50	757(S_{71})						

Table 3. Variation of 75% dependable flows.

Agriculture / Forest	45	50	55	60	65	70	75
20							597(S_{12})
25						587(S_{22})	
30					584(S_{32})		
35				574(S_{42})			
40			563(S_{52})				
45		562(S_{62})					
50	559(S_{72})						

feet). These values have been plotted in Tables 2 and 3 and Figures 5 and 6.

RESULTS AND DISCUSSION

An analysis of Figures 5 and 6 shows clearly that as the percentage of forests decreases, the water yield increases in the basin. The loss of forest cover reduces interception of raindrops (increasing drop impact energy and soil detachment), reduces evapotranspiration, increasing the amount of water available for infiltration, soil storage, and runoff (Hibbert, 1967; Calder et al., 2009). Therefore, soil moisture capacity is reached with less rainfall, and any excess can produce surface runoff, or Hortonian flow, and increase peakflows and streamflow volumes (Bosch et al., 1982). Hibbert (1967) reported the results for thirty-nine studies of the effect of altering forest cover on water yield. Taken collectively, these studies reveal that forest reduction increases water yield. Studies have also shown that afforestation (re-establishment of forest cover) results in a decrease in water yield, proportionally to the growth rate of the stand (Jason and Matlock, 2009). Note that these findings are for short term period and indeed, precipitation in long term may be negatively affected by loss of forest cover (Hibbert, 1967).

Conclusions

GIS based hydrological modelling has been used to assess the impacts of climate change on the hydrological regime of Cauvery river basin in India. SWAT has been

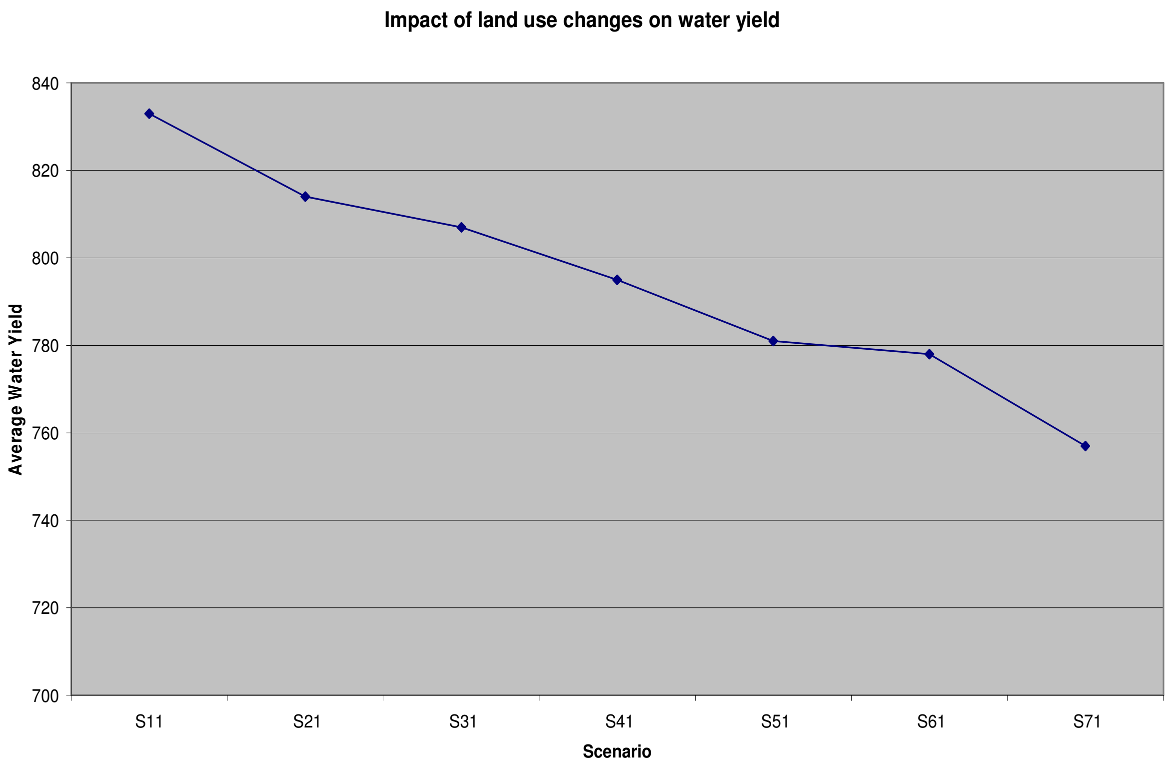

Figure 5. Variation of average water yield in Cauvery under various land use scenarios.

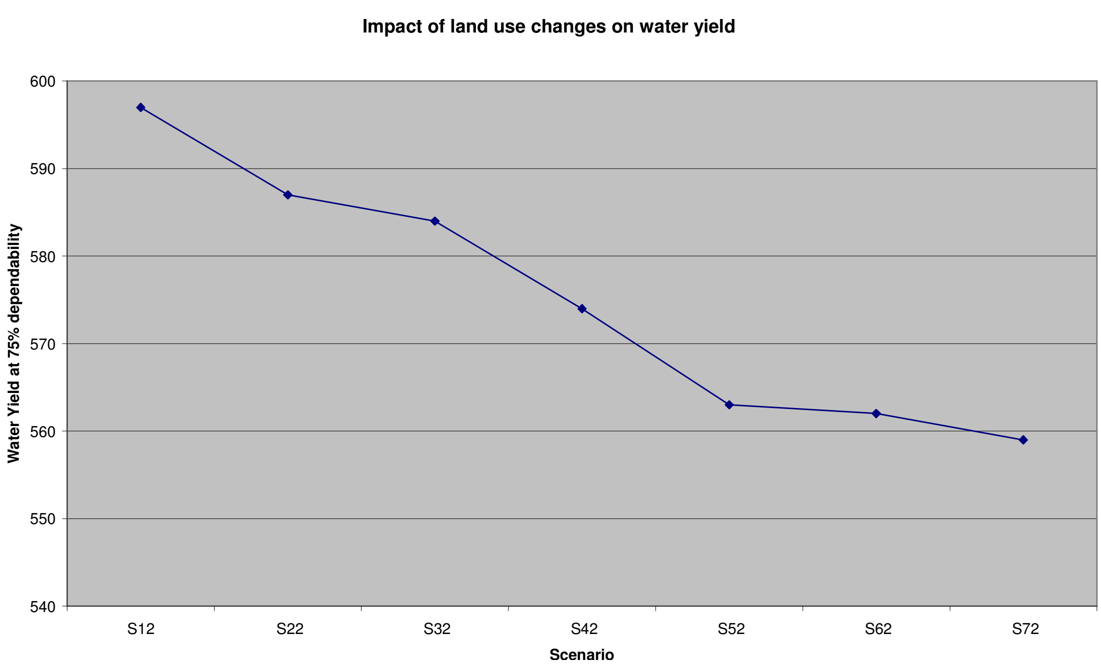

Figure 6. Variation of 75% dependable water yield in Cauvery under various land use scenarios.

utilized for the purpose of assessment of the total amount of water available in the Cauvery basin along with the prediction of the impact of changes in the land management practices on the water availability in the basin. The results indicate that contrary to popular beliefs, as the percentage of forests decreases, water yield increases in the basin. Finally, the study demonstrates that simulation modeling can play a very significant role in water resources management by generating a series of scenarios or options for the stakeholders, so as to enable them to take sound rational decisions.

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