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Full Length Research Paper

Coupling law and technology for water allocations among riparian states

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The problem of sharing the waters of trans-boundary watercourses has traditionally been viewed as one lying exclusively within the domain of legal doctrines. However, lack of information about the sustainable futuristic scenarios of possible water allocations acts as a deterrent in resolving the conflicts pertaining to trans-boundary watercourses. It is increasingly being felt that technology, in the form of simulation modeling, has a very significant role to play in this context. However, law and technology so far stand isolated in their respective spheres. This study is an attempt to use technology to bridge the information gap that usually persists for law enforcing agencies. The legal doctrines consist of a broad series of guidelines. The present work is an attempt to support a legal doctrine by devising a set of quantifiable formulae for water allocations among the riparian states by taking the case study of an Indian interstate river basin. The potential role of Geographic Information Systems (GIS) based hydrological modeling in bringing about an effective resolution of the problems pertaining to the sharing of interstate rivers has been demonstrated. The hydrological model used for the study is Soil and Water Assessment Tool (SWAT). The study shows that simulation modeling can play a very significant role in conflict resolution by generating a series of scenarios or options for the stakeholders, so as to enable them to take sound rational decisions.

Key words: Legal doctrines, scenario generation, simulation modeling, trans-boundary watercourses, water allocations.

INTRODUCTION

The problem of sharing the waters of trans-boundary watercourses has traditionally been viewed as one lying exclusively within the domain of legal doctrines. Most of the laws pertaining to the conflict resolution among the riparian states have a certain underlying philosophy which, in most of the cases, falls under one of the five legal principles (Salman and Uprety, 2002; Singh and Gosain, 2004):

1. Principle of absolute territorial sovereignty (Harmon doctrine), which gives plenary powers to upstream riparian states.
2. Principle of absolute territorial integrity, favouring the downstream riparian states.
3. Principle of prior appropriation, which protects existing uses
4. Principle of no significant harm to co-riparian states
5. Principle of reasonable and equitable use (to determine the reasonable and equitable share of each watercourse state, a list of relevant factors may be taken from the UN Convention on the Law of Non Navigational uses of trans-boundary Watercourses (1997) (Article-6), which will be explain further. Both the Helsinki Rules (1966) as well as the UN Convention on the Law of Non Navigational Uses of International Watercourses (1997) have adopted this principle as the most significant means of resolving the conflicts pertaining to trans-boundary watercourses (Singh and Gosain, 2004).

METHODOLOGY

The aim of the present study is to suggest a mechanism for resolving conflicts pertaining to the trans-boundary watercourses in

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a holistic manner, integrating the legal and technological aspects, by taking case study of a multi-jurisdictional river basin in India. A set of quantifiable formulae have been devised for water allocations among the riparian states on the basis of the principle of reasonable and equitable use. The Delphi technique has been used for assigning to the various components of the water allocation formulae. The sample set for the Delphi technique consisted of about 50 professionals and academicians from diverse organi-zations and locations, working in the arena of water resources and environmental engineering. Geographic Information Systems (GIS) based hydrological modeling has been utilised for estimating the total water yield in the selected river basin. The hydrological model used for the present study is Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1995; 1998; Neitsch et al., 2002) on a GIS (Arc View) platform. SWAT has been 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 make it the ideal tool to be used for such a study. Futuristic scenarios have been generated for various land use changes. The water allocation formulae have been utilised in conjunction with the total water availability scenarios as obtained from hydrological modeling so as to determine the total volume of water to be allocated to each of the riparian states for the existing set of land use conditions as well as for each of the proposed land use changes.

Formulation of the legal doctrine

To determine the reasonable and equitable share of each watercourse state, a list of relevant factors may be taken from the UN Convention on the Law of Non Navigational Uses of Trans-boundary Watercourses (1997) (Article-6):

1. Geographic, hydrographic, hydrological, climatic, ecological and other factors of a natural character;
2. The social and economic needs of the watercourse states concerned;
3. The population dependent on the watercourse in each watercourse state;
4. The effects of the use or uses of the watercourses in one watercourse state on other watercourse states;
5. Existing and potential uses of the watercourse;
6. Conservation, protection, development and economy of use of the water resources of the watercourse and the costs of measures taken to that effect;
7. The availability of alternatives, of comparable value, to a particular planned or existing use.

The following axioms can be framed on the basis of the broad principles enunciated in the sixth article of the UN Convention (1997):

1. States having more population dependent on the shared watercourse should get more water
2. States having more area in the basin are entitled to get more water
3. States contributing more depth of rainfall in the basin should get greater share of water
4. Existing water uses should be respected i.e., states using more water presently should get more water
5. States which have higher per capita incomes should be allocated less water
6. States having higher literacy levels should be allocated less water
7. States having higher life expectancy at birth should get less water.

In the present study, 2 cases have been considered:

Case I considers all the aforementioned factors whereas Case II considers factors 1 to 4 only. Hence, factors of literacy, life expectancy and per capita incomes have not been included in Case II. Scenario generation has been carried out for both these cases.

Water allocation component

In order to allocate waters among the riparian states, a quantifiable entity needs to be defined. This entity has been termed as Water Allocation Component (WAC). WAC is a unique numerical value assigned to each of the riparian states on the basis of a set of equations. In these equations each and every factor which is relevant for water allocations are included in a suitable weighing factor. WAC can be calculated for each of the riparian states on the basis of Equations 1 and 2 for Case I and Case II respectively.

Case I

$$WAC_{1i} = \frac{F_1A_i + F_2P_i + F_3R_i + F_4EU_i}{F_5PCI_i + F_6L_i + F_7LE_i} \quad (1)$$

Case II

$$WAC_{2i} = F_1A_i + F_2P_i + F_3R_i + F_4EU_i \quad (2)$$

Where i is the index representing the riparian state, WAC_{1i} stands for Water Allocation Component for the i^{th} riparian state for Case I, WAC_{2i} stands for Water Allocation Component for the i^{th} riparian state for Case II, A_i is the fraction of the watercourse area in the i^{th} riparian state, P_i is the total population dependent on the watercourse in the i^{th} riparian state expressed as a fraction of the total population inhabiting the river basin, R_i is the fraction of the total rainfall depth that falls on the i^{th} riparian state, EU_i is the existing volume of water that is being used by the i^{th} riparian state expressed as a fraction of total volume of water being presently used in the basin, PCI_i is the per capita income of the i^{th} riparian state expressed as a fraction of the total per capita income of the watershed community, L_i is the literacy level of the i^{th} riparian state expressed as a ratio of the %literacy in the state and sum of % literacy levels in all the riparian states, LE_i is the life expectancy at birth (in years) of the i^{th} riparian state expressed as a ratio of sum of life expectancies at birth (in years) for all the riparian states.

The value of variables A_i, P_i, R_i, EU_i, PCI_i, L_i, LE_i vary from 0 to 1. In the present study, since there are three states involved, i can take a value from 1 to 3, for Karnataka, Tamil Nadu and Kerala respectively.

Moreover,

$$\sum_{i=1}^{n} A_i = \sum_{i=1}^{n} P_i = \sum_{i=1}^{n} R = \sum_{i=1}^{n} EU_i = \sum_{i=1}^{n} PCI_i = \sum_{i=1}^{n} L_i = \sum_{i=1}^{n} LE_i = 1 \quad (3)$$

where n= No of riparian states

Each of these entities would have a distinct value for each of the riparian states.

F_1, F_2, F_3, F_4, F_5, F_6 and F_7 are the weighting factors to be assigned to A_i, P_i, R_i, EU_i, PCI_i, L_i and LE_i respectively. The determination of F_1 to F_7 has been done using Delphi technique.

Table 1A. Positive factors for water allocations.

S/N	Factor	Weightage (0-10)
1	Area of watercourse in the riparian state	
2	Population dependent upon the watercourse in the riparian state	
3	Rainfall occurring in the portion of watercourse in the riparian state	
4	Existing volume of water used by the riparian state	
*		

Table 1B. Positive factors for water allocations.

S/N	Factor	Weightage (0-10)
1	Per capita income of the riparian state	
2	Literacy level in the riparian state	
3	Life expectancy in the riparian state	
*		

Normalised water allocation component

Once the WAC have been determined for each of the riparian states, they are normalised for the two cases as shown in Equations 4 and 5.

$$NWAC_{1i} = \frac{WAC_{1i}}{\sum_{i=1}^{N} WAC_{1i}} \quad (4)$$

$$NWAC_{2i} = \frac{WAC_{2i}}{\sum_{i=1}^{N} WAC_{2i}} \quad (5)$$

Where I is the index representing the riparian state, $NWAC_{1i}$ is Normalised Water Allocation Component for i^{th} riparian state for Case I, $NWAC_{2i}$ is Normalised Water Allocation Component for i^{th} riparian state for Case II.

The normalised water allocation components for each of the riparian states shall, thus, lie between 0 and 1.

Determination of weighting factors using Delphi technique

In order to assign the weighting factors to various factors required for calculation of WAC, Delphi technique has been used. Delphi technique has been developed to elicit the opinion of the experts for the purpose of policy formulation. It was pioneered by the RAND Corporation, and involves an anonymous panel of experts (that is a panel member does not know who the other panel members are) responding to a given problem. The response set is collated and returned to the panel members for review. The members can either update their response in the light of the responses of other panel members, or provide reasons for holding on to their present opinions. The process is repeated until consensus is achieved (Kumar, 2005). Delphi technique has been used very widely in diverse areas ranging from budget allocations to societal changes. Delphi has worked well when trying to prioritize national funding for projects among different states with conflicting goals, or if the scale of the decision-making problem is very large. Taiwan used the method to prioritize their entire Information Technology industry, and they conclude: "Finally, these decisions reflect the experts' world views, life experiences, cognitive feelings and perceptions. Thus, these results are based on the participants' subjective assessments that may also be influenced by data. Decision-making in itself is subjective. However, the use of experts in a systematic manner will yield a satisfactory solution to socio-technical problems. Some examples of the subject areas in which Delphi studies have been undertaken include: economic trends and societal change, issues in the agriculture, educational developments, regulatory processes, medical developments, determining future issues in grievance arbitration, developing family therapy models, determining future need for affirmative action programs, determining policy options and evaluating budget allocations (Kumar, 2005).

In the present study, Delphi technique has been utilized for the assignment of weightage to each of the aforementioned factors for determining the share of the riparian states that is calculation of F_1, F_2, F_3, F_4, F_5, F_6 and F_7. The weighting factors have been assigned using expertise of 41 professionals and academicians from diverse organizations and locations, working in the arena of water resources and environmental engineering. Even though the sample size is not very large, care was taken to ensure the inclusion of samples from as diverse a background as possible. Moreover, the aim of the exercise is to suggest a methodology for assigning numerical values to highly subjective elements. Following questionnaire was used to collect the response of the experts.

Questionnaire used for Delphi technique

Based upon Article-6 of the UN Convention, what factors should be used for distribution of waters of an interstate among the basin states and what weighting factors should be assigned to each of them. In Tables 1A and B, kindly fill in the impact factors giving values from 0 to 10.

0 - Factor is not important for water sharing
10- Factor is very important for water sharing
* - Any other objectively measurable factor that you deem fit for water allocations on the basis of Article 6 of the UN Convention.

Sign:
Name:
Department:
Place:

Table 2. Means and variations of factors F_1 to F_7.

Item	Mean	Std. Deviation (SD)	Mean+2*SD	Mean-2*SD
Area	5.56	2.4	10.36	0.76
Population	7.78	2.23	12.24	3.32
Rainfall	6.2	2.47	11.14	1.26
Existing use	6.27	2.4	11.07	1.47
Per capita income	5.68	2.46	10.6	0.76
Literacy	4.05	2.65	9.35	-1.25
Longevity	3.07	2.87	8.81	-2.67

Table 3. Values of factors for all the riparian states.

Item	Notation	Karnataka	Tamil Nadu	Kerala
Area	A	0.42	0.54	0.04
Population	P	0.29	0.64	0.07
Rainfall	R	0.32	0.36	0.32
Existing Use	EU	0.19	0.80	0.01
Per Capita Income	PCI	0.31	0.35	0.34
Literacy	L	0.29	0.32	0.39
Longevity	LE	0.31	0.33	0.36

The means and variations of the responses have been shown in Table 2.

Since, all the average values in Table 2 lie between the limits of Mean+ 2*SD and Mean- 2*SD, there is no need of the second round and hence, the values of the factors F_1 to F_7 are 5.56, 7.78, 6.2, 6.27, 5.68, 4.05 and 3.07, respectively.

Estimation of WAC and NWAC values

After putting the values of F_1 to F_7 as determined using Delphi technique, the WAC can be calculated for each of the riparian states using the following equations:

Case I

$$WAC_{1i} = \frac{5.56\,A_i + 7.78\,P_i + 6.20\,R_i + 6.27\,EU_i}{5.68\,PCI_i + 4.05\,L_i + 3.07\,LE_i} \quad (6)$$

Case II

$$WAC_{2i} = 5.56\,A_i + 7.78\,P_i + 6.20\,R_i + 6.27\,EU_i \quad (7)$$

Description of the study area

The Cauvery is the fourth largest river in peninsular southern India, after Godavari, Krishna, and the Mahanadi. The Cauvery rises at Talakaveri on the 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-riparian states. Since the share of Pondicherry has more or less been agreed by all the riparian states as 7 Thousand Million Cubic (TMC) feet, the same has been assumed in the present study and the subsequent analysis has been carried out to determine the water allocations of the other three riparian statesonly namely, Karnataka, Tamil Nadu and Kerala. The Cauvery is known as the 'Dakshina Ganga'and is one of the seven sacred rivers of India. In both Karnataka and Tamil Nadu, it is the subject of myth and legend and has been celebrated in music, poetry, literature, and folklore. A number of ancient temples along the river testify its religious and cultural significance (Guhan, 1993). Table 3 shows the values of A_i, P_i, R_i, EU_i, PCI_i, L_i and LE_i as determined for all the riparian states in the Cauvery basin.

Putting the values obtained from Table 3 in Equations 6 and 7, the values of WAC and normal water allocation components for Karnataka, Tamil Nadu and Kerala have been computed as given in Table 4.

It can easily be seen that the normalised water allocation components are nothing but the percentages of the total water available in the basin which are to be allocated to the respective riparian states. Moreover, it can be verified that the sum of normalised water allocation components of all the riparian states is

1. A comparison of the two cases shows that in Case II share of Karnataka gets reduced, whereas that of Tamil Nadu and Kerala is increased. This is because of the fact that Kerala is ahead of other riparian states in the social and economic factors like literacy, life

Table 4. Values of water allocation components and normalised water allocation components for all the riparian states.

State	Case I		Case II	
	WAC	NWAC	WAC	NWAC
Karnataka	2.00	0.33	7.77	0.30
Tamil Nadu	3.54	0.58	15.23	0.59
Kerala	0.61	0.09	2.80	0.11

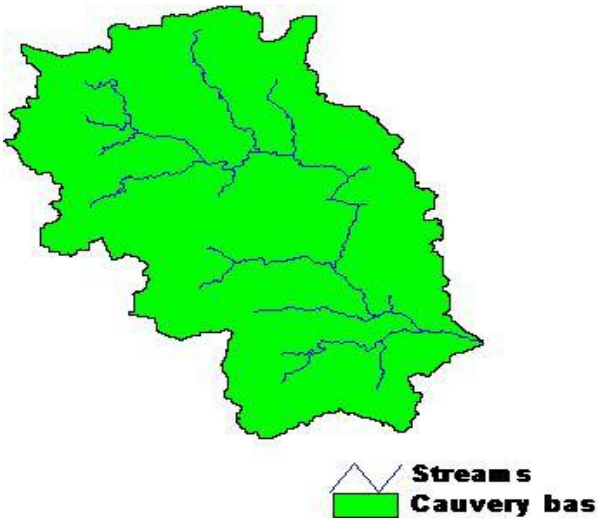

Figure 1. A layout of Cauvery basin along with the digitized stream network.

expectancy and per capita income. Hence if the social and economic needs of the watercourse states are considered (as in Case I), Kerala's share gets reduced.

Water allocations

The total amount of water to be allocated to the i^{th} riparian state can be calculated as:

$$[WA]_i = [NWAC]_i \,.\, [Q_{total}] \quad (8)$$

Where; WA_i= Amount of water to be allocated to the i^{th} riparian state, Q_{total}= Total water available in the entire river basin.

ROLE OF HYDROLOGICAL MODELING

A hydrological model plays an important role of generating scenarios such as the impact of change in land management practices on water utilizations. But before using the hydrological model, it has to be first validated for the baseline data. 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 Arc View interface requires data on the following entities, details of which for the present study are given thus.

Contours

Survey of India topographic sheets on a scale of 1: 250,000 have been used. Spatial data has been created using the digitization process. The polyconic projection system has been used. The digitized contours have been used for the creation of Digital Elevation Model (DEM).

Stream network

A polyline shape file of stream network has been obtained from the digitized drainage network. The digitized stream has been used in the present case for "burn in" option 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. The delineated Cauvery basin along with the digitized stream network has been shown in Figure 1.

Land use data

In case of the land use/ land cover data, the user has the option of providing the input data as a shape file or a grid. 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. 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 using the SWAT global database. The reclassified land use categories of the Cauvery basin have been shown in Figure 2.

Soil data

In case of the soil data, the user has the option of providing the input data as a shape file or a grid. 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. The soil class categories of the Cauvery basin have been shown in Figure 3.

Climatic data

The model requires climatic data of the precipitation, maximum temperature, 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 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 model get closer to the reality if daily observed values are used along with the long term data. Recently, 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 generated using the long term statistics for the same.

Reservoir data

Impoundment structures modify the movement of water in the channel network by lowering the peak flow and volume of flood

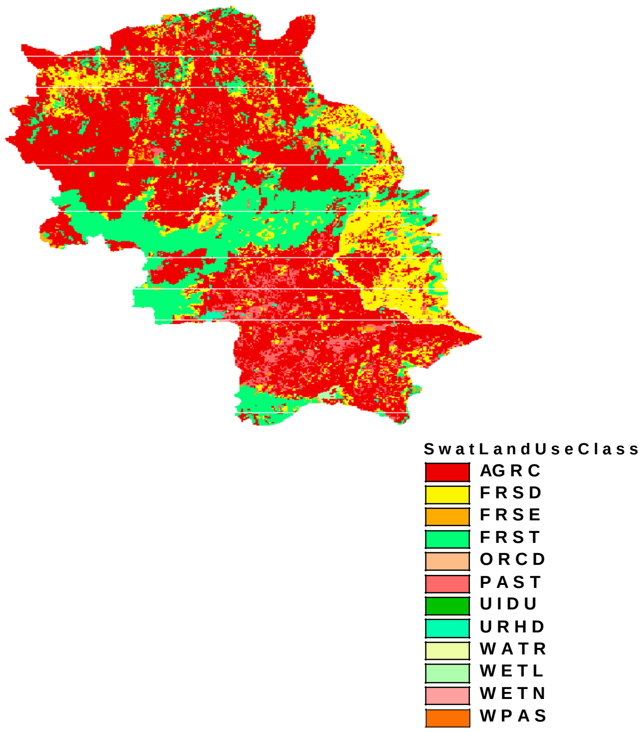

Figure 2. Reclassified land uses for the Cauvery river basin.

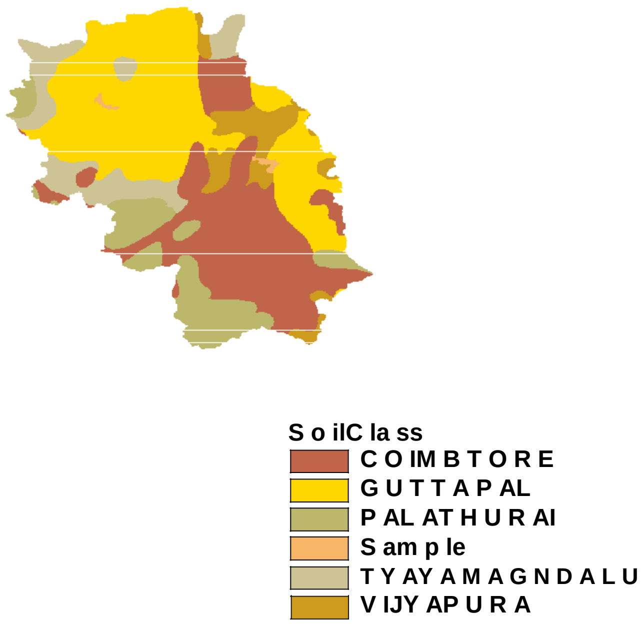

Figure 3. Reclassified soil classes for the Cauvery river basin.

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.

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 has been available. All these have been incorporated as large managed reservoirs with known monthly outflow values. Monthly outflow values for all these reservoirs have been input from the time the reservoir became operational.

Preprocessing

Following steps have been used in preprocessing:

DEM generation

The method of interpolation used for the present study is the Inverse Distance Weighted (IDW) method. The DEM has been shown in Figure 4.

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
4. Stream link

Hydrologic response unit (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 combinations 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. One HRU is created for each unique land use/ soil class combination. The threshold levels of land use as well as soil types have been fixed as 5%. The threshold level is used to ignore minor land uses/ soil types in each sub-basin. In the first stage land uses that cover a percentage of the sub-basins 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-basins is modeled. In the second stage minor soil types within each land use area are eliminated and area of the

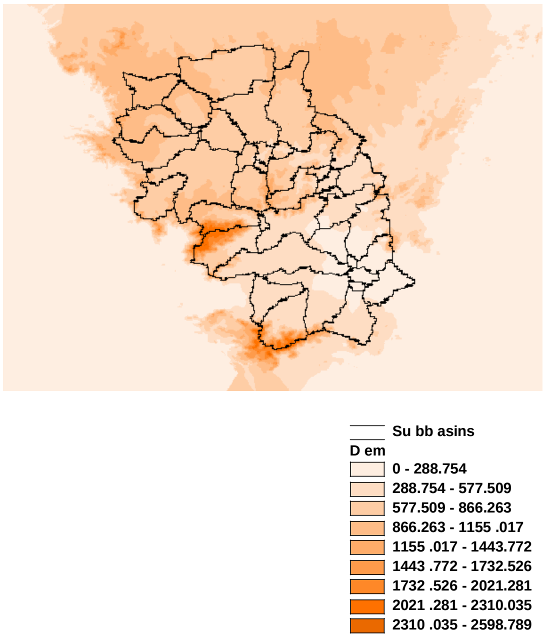

Figure 4. Layout of Cauvery basin and DEM showing elevations in metres.

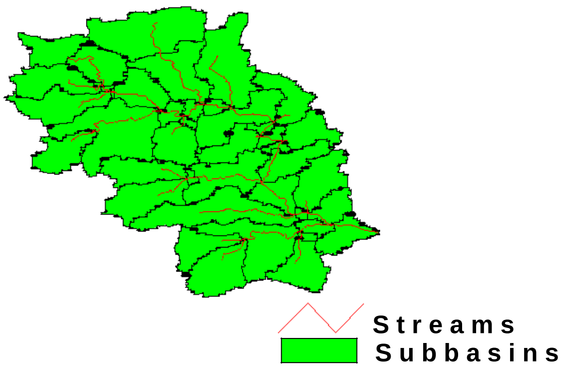

Figure 5. Delineated Cauvery basin and its subbasins along with the generated stream network.

remaining soil types is reapportioned. After fixing the threshold levels, a total of 231 HRUs have been obtained (Figure 5).

Model calibration

The daily values of discharges up to Musiri (outlet) have been used for the 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 without carrying out any calibration process. The percentage errors in annual average flows over a 10 year period have been estimated as 8.1%. Comparison of observed and simulated monthly discharges for a two year period has been plotted as shown in Figure 6.

The Nash Sutcliffe Coefficient was observed to be 0.934 (Nash and Sutcliffe, 1970) and the value of coefficient of determination was calculated as 0.9362. This shows that the model has captured the system well.

The observation has 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 SWAT

Generation of futuristic scenarios is one of the most important applications of hydrological modeling. Scenario generation helps the decision makers to analyze the potential impacts of man made interventions. The well known hydrological principle of "Think globally, act locally" can only be applied if sophisticated tools and techniques such as simulation modeling are available. In the present case, a variety of land use changes are simu-lated and the impact on the hydrological characteristics of the basin is analyzed. 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 modeling 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 modeling techniques and the remedial actions can be taken well in time (Chen, 2003; Luitjen et al 2003; Rajasekaram et al, 2003). The present land use within the Cauvery basin is (CFFC, 1972)

Agriculture = 60%
Forests = 35%
Others = 5%

Futuristic scenarios have been generated for three categories of land use changes. Table 5 shows four cate-gories of land uses, S_1 to S_4 in which S_1 is the present land use scenario, whereas S_2 to S_4 are the proposed land use change scenarios.

Hydrological modeling was carried out to analyze the aforementioned categories of land use changes. The resultant variation of water yields of the basin are shown in Table 6. 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 in Table 6. Units are in TMC and figures in parentheses are in cubic km. It may be observed from Tables 6 and 7 that as the percentage of forests decreases, the water yield

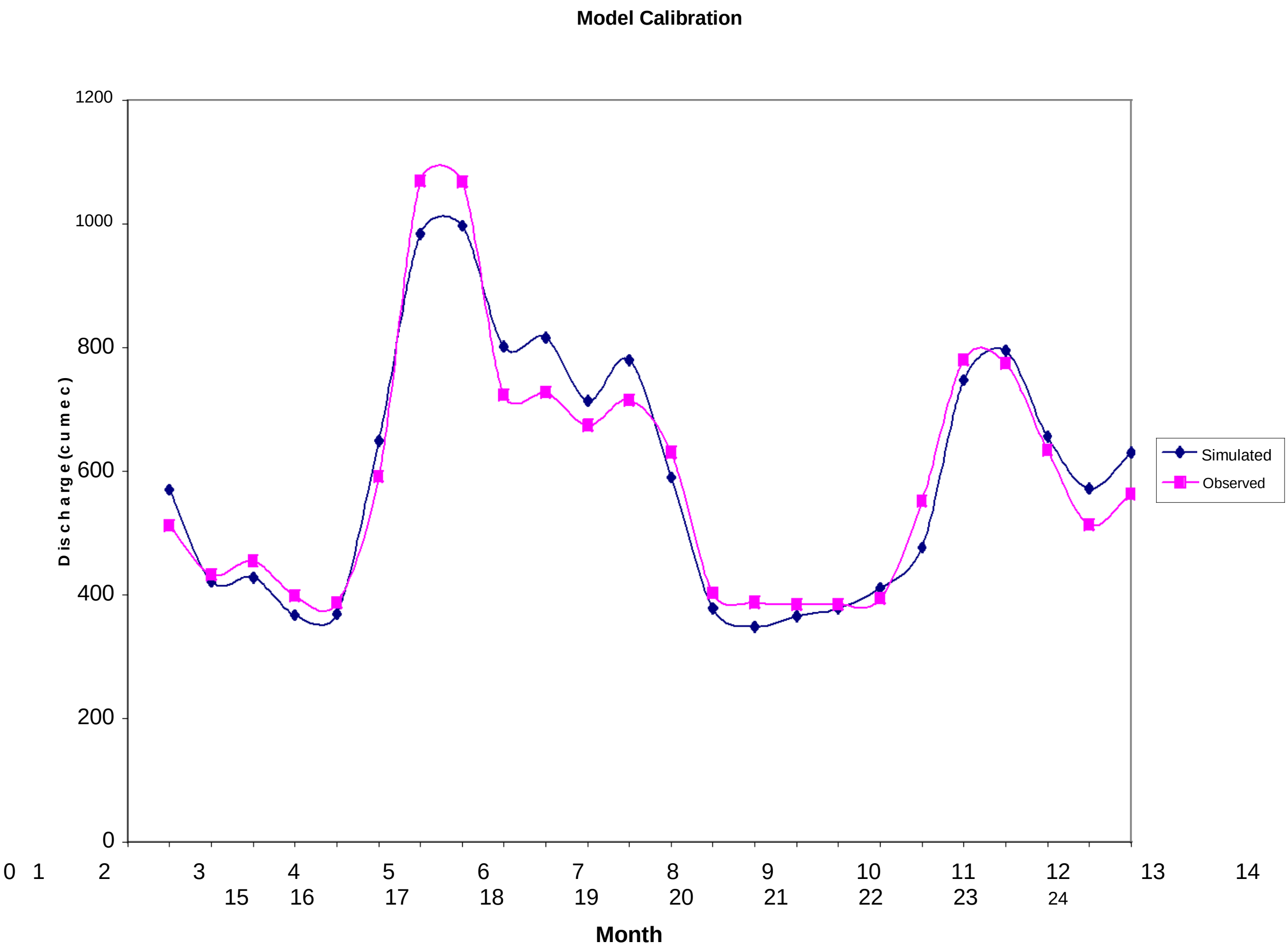

Figure 6. Comparison of average monthly flows over a 2 year period.

Table 5. List of land use scenarios.

i	Scenario	%AGRC	%FRST
1	S_1	60	35
2	S_2	65	30
3	S_3	70	25
4	S_4	75	20

j=1 for average flows; and 2 for 75% dependable flows.

increases in the basin.

Use of scenario generation for various legal doctrines

Once the total amount of water available in the basin has been calculated, it can be apportioned among the various riparian states using different legal doctrines. Such an allocation has been shown in Tables 8 and 9 for Case I and Case II, respectively. Case I considers factors of population, area, rainfall, existing use, literacy, life expectancy and per capita income, whereas Case II considers the factors of population, area, rainfall and existing use only. The following are the notations used for each legal doctrine, X_{ij} in Table 5.

H= Harmon Doctrine; I= Principle of Absolute Territorial Integrity; P= Principle of Prior Appropriation; S= Principle of No Significant Harm; E= Principle of Reasonable and Equitable Use.

In order to allocate waters on the basis of Harmon doctrine, Karnataka's demand being the upper riparian is fixed and the other allocations are done on the basis of the respective shares using the formula devised for respective shares in previous sections. Similarly, for absolute territorial integrity, Tamil Nadu's demand is fixed, and other allocations are done as per respective shares in the devised formula. Allocations using the principle of prior appropriation are done on the basis of existing uses only. Existing uses also form the basis of allocations as per the principle of no significant harm,

Table 6. Water yield for various combinations of land use.

Forest \ Agriculture	60	65	70	75
35	716 (20.3) (S_{11})			
30		720 (20.4) (S_{21})		
25			725 (20.5) (S_{31})	
20				739 (20.9) (S_{41})

Table 7. The 75% dependable water yield.

Forest \ Agriculture	60	65	70	75
35	388 (11.0) (S_{12})			
30		396 (11.2) (S_{22})		
25			397 (11.3) (S_{32})	
20				409 (11.6) (S_{42})

Table 8. Shares of riparian states under various legal doctrines: Case I.

	Average flows (TMC)					75% Dependable flows (TMC)			
	Total	Karnataka	Tamil Nadu	Kerala		Total	Karnataka	Tamil Nadu	Kerala
				Harmon doctrine					
H_{11}	716	465	218.37	32.63	H_{12}	388	465	0	0
H_{21}	720	465	221.85	33.15	H_{22}	396	465	0	0
H_{31}	725	465	226.2	33.8	H_{32}	397	465	0	0
H_{41}	739	465	238.38	35.62	H_{42}	409	465	0	0
				Principle of absolute territorial integrity					
I_{11}	716	118.5	566	31.5	I_{12}	388	0	566	0
I_{21}	720	121.66	566	32.34	I_{22}	396	0	566	0
I_{31}	725	125.61	566	33.39	I_{32}	397	0	566	0
I_{41}	739	136.67	566	36.33	I_{42}	409	0	566	0
				Principle of prior appropriation					
P_{11}	716	136.04	572.8	7.16	P_{12}	388	73.72	310.4	3.88
P_{21}	720	136.8	576	7.2	P_{22}	396	75.24	316.8	3.96
P_{31}	725	137.75	580	7.25	P_{32}	397	75.43	317.6	3.97
P_{41}	739	140.41	591.2	7.39	P_{42}	409	77.71	327.2	4.09
				Principle of no significant harm					
S_{11}	716	136.04	572.8	7.16	S_{12}	388	73.72	310.4	3.88
S_{21}	720	136.8	576	7.2	S_{22}	396	75.24	316.8	3.96
S_{31}	725	137.75	580	7.25	S_{32}	397	75.43	317.6	3.97
S_{41}	739	140.41	591.2	7.39	S_{42}	409	77.71	327.2	4.09
				Principle of reasonable and equitable use					
E_{11}	716	236.28	415.28	64.44	E_{12}	388	128.04	225.04	34.92
E_{21}	720	237.6	417.6	64.8	E_{22}	396	130.68	229.68	35.64
E_{31}	725	239.25	420.5	65.25	E_{32}	397	131.01	230.26	35.73
E_{41}	739	243.87	428.62	66.51	E_{42}	409	134.97	237.22	36.81

Table 9. Shares of riparian states under various legal doctrines: Case II.

	Average flows (TMC)					75% Dependable flows (TMC)			
	Total	Karnataka	Tamil Nadu	Kerala		Total	Karnataka	Tamil Nadu	Kerala
				Harmon doctrine					
H_{11}	716	465	210.84	40.16	H_{12}	388	465	0	0
H_{21}	720	465	214.2	40.8	H_{22}	396	465	0	0
H_{31}	725	465	218.4	41.6	H_{32}	397	465	0	0
H_{41}	739	465	230.16	43.84	H_{42}	409	465	0	0
				Principle of absolute territorial integrity					
I_{11}	716	109.5	566	40.5	I_{12}	388	0	566	0
I_{21}	720	112.42	566	41.58	I_{22}	396	0	566	0
I_{31}	725	116.07	566	42.93	I_{32}	397	0	566	0
I_{41}	739	126.29	566	46.71	I_{42}	409	0	566	0
				Principle of prior appropriation					
P_{11}	716	136.04	572.8	7.16	P_{12}	388	73.72	310.4	3.88
P_{21}	720	136.8	576	7.2	P_{22}	396	75.24	316.8	3.96
P_{31}	725	137.75	580	7.25	P_{32}	397	75.43	317.6	3.97
P_{41}	739	140.41	591.2	7.39	P_{42}	409	77.71	327.2	4.09
				Principle of no significant harm					
S_{11}	716	136.04	572.8	7.16	S_{12}	388	73.72	310.4	3.88
S_{21}	720	136.8	576	7.2	S_{22}	396	75.24	316.8	3.96
S_{31}	725	137.75	580	7.25	S_{32}	397	75.43	317.6	3.97
S_{41}	739	140.41	591.2	7.39	S_{42}	409	77.71	327.2	4.09
				Principle of reasonable and equitable use					
E_{11}	716	214.8	422.44	78.76	E_{12}	388	116.4	228.92	42.68
E_{21}	720	216	424.8	79.2	E_{22}	396	118.8	233.64	43.56
E_{31}	725	217.5	427.75	79.75	E_{32}	397	119.1	234.23	43.67
E_{41}	739	221.7	436.01	81.29	E_{42}	409	122.7	241.31	44.99

which is presently being used as another version of prior appropriation principle (Singh and Gosain, 2004). Lastly, allocations as per the principle of reasonable and equitable utilization have been done on the basis of the equations devised in previous sections for Case I and Case II. Some of these results for both cases have been plotted in Figures 7 to 9.

Conclusions

This study is an attempt to use technology to bridge the information gap that usually persists for law enforcing agencies. The results indicate that reality is contrary to popular beliefs when science is used, such as seen in the present case that when the percentage of forests decreases, water yield increases in the basin. In case of Karnataka, water allocation is maximum for the Harmon doctrine and minimum for the principle of absolute territorial integrity or prior appropriation principle. It is to be expected since Tamil Nadu is the lower riparian state and has been the traditional user of the Cauvery waters. The water share of Karnataka for the principle of reasonable and equitable use lies between these two extremities for all the scenarios. This illustrates that principle of reasonable and equitable use has a logical basis and gives due weightage to all relevant factors. On the contrary, water share of Tamil Nadu is maximum for the prior appropriation principle and minimum for the Harmon doctrine. Again, in this case also, the water share as obtained from the principle of reasonable and equitable use lies between the two extremities for all scenarios. This again proves the usefulness of the principle of reasonable and equitable use as the most balanced and "all encompassing" principle, not giving undue weightage to any one factor, but including all the relevant factors in its realm. In case of Kerala, the minimum water is allocated for the principle of prior

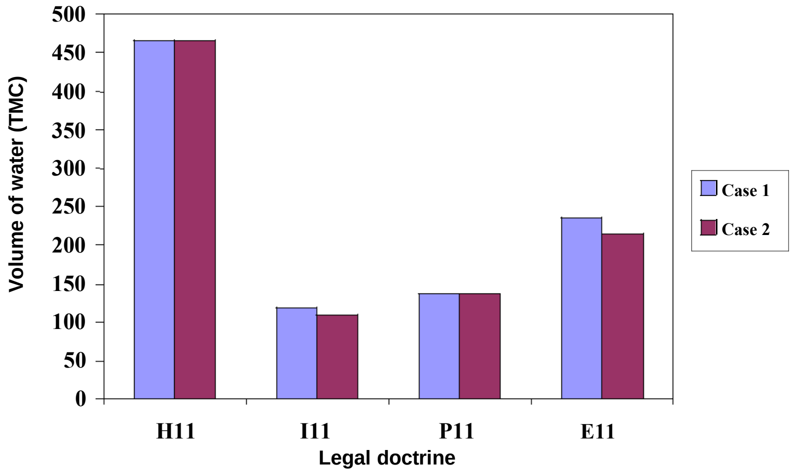

Figure 7A. Karnataka's allocations for average flows and S_1 scenario.

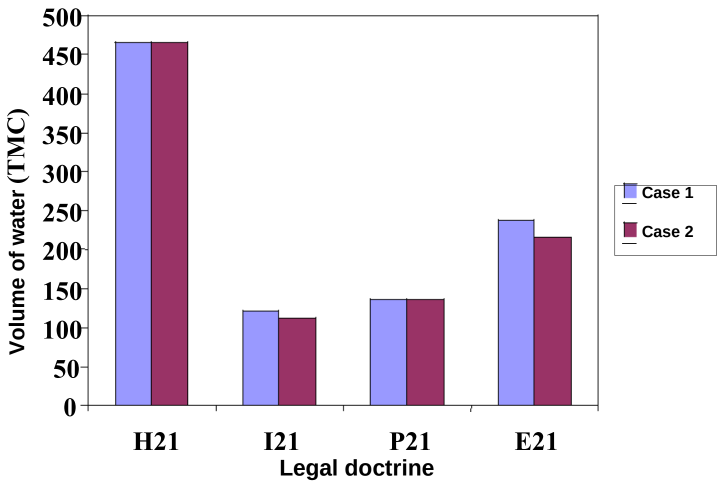

Figure 7B. Karnataka's allocations for average flows and S_2 scenario.

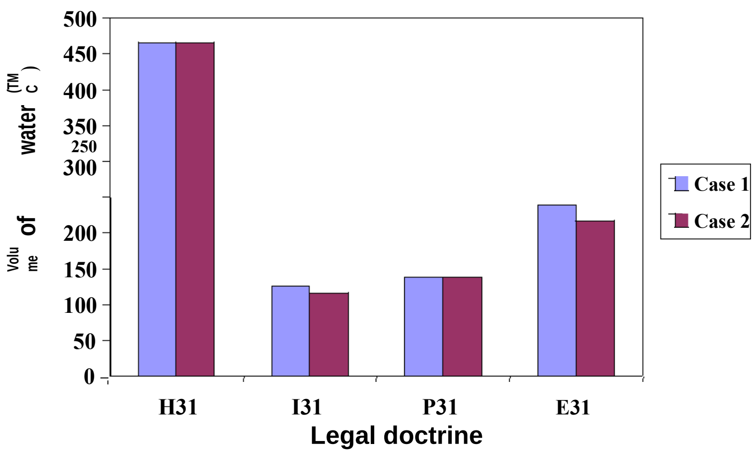

Figure 7C. Karnataka's allocations for average flows and S_3 scenario.

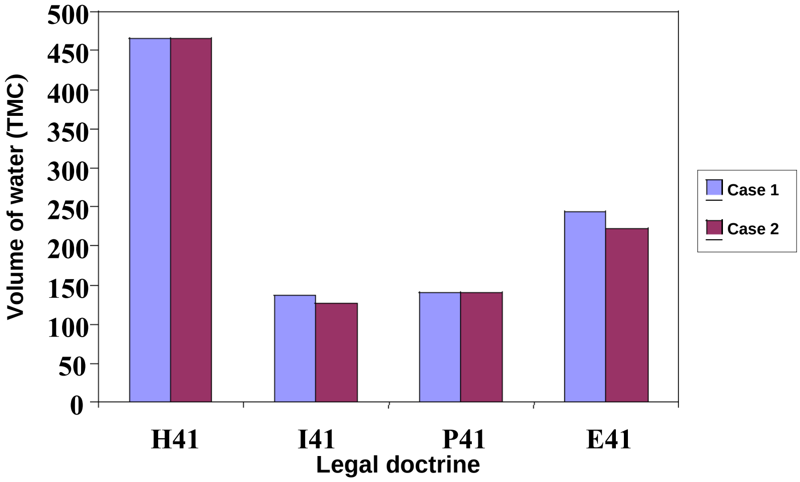

Figure 7D. Karnataka's allocations for average flows and S_4 scenario.

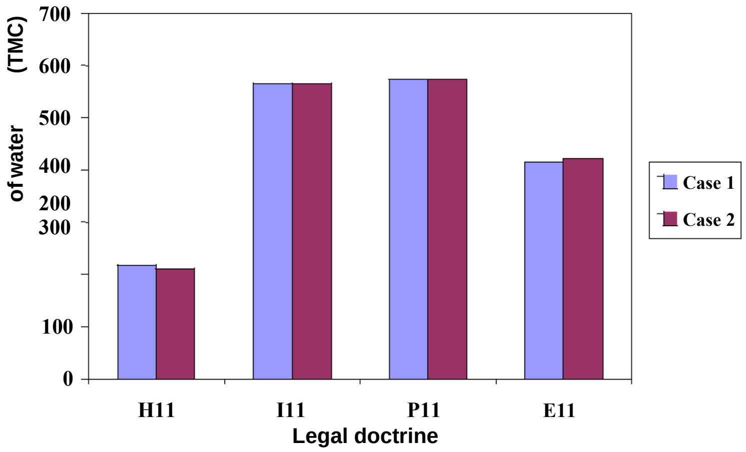

Figure 8A. Tamil Nadu's allocations for average flows and S_1 scenario.

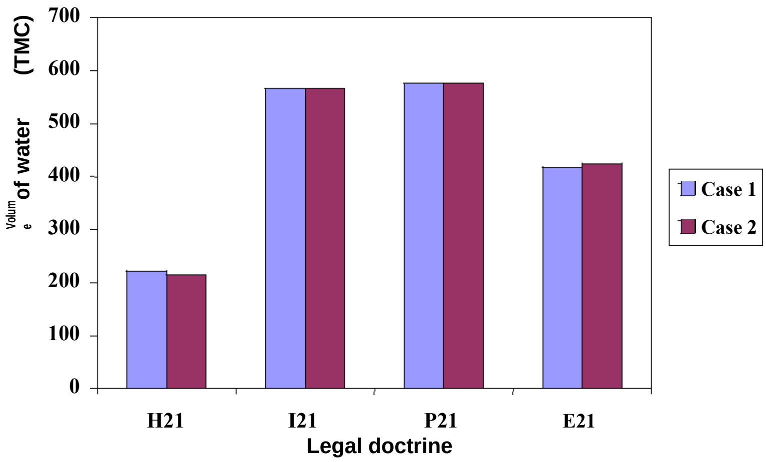

Figure 8B. Tamil Nadu's allocations for average flows and S_2 scenario.

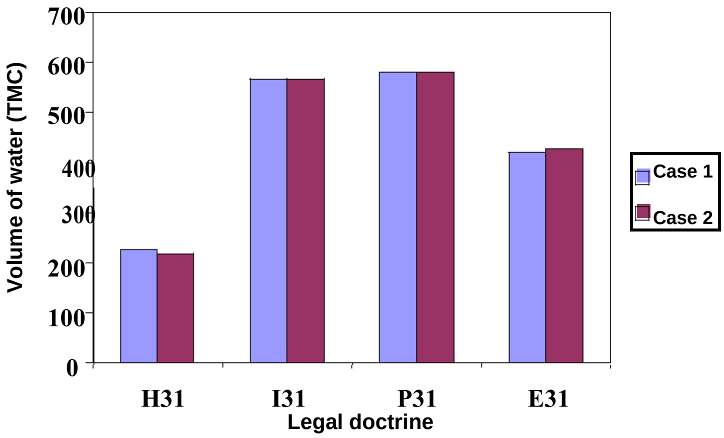

Figure 8C. Tamil Nadu's allocations for average flows and S_3 scenario.

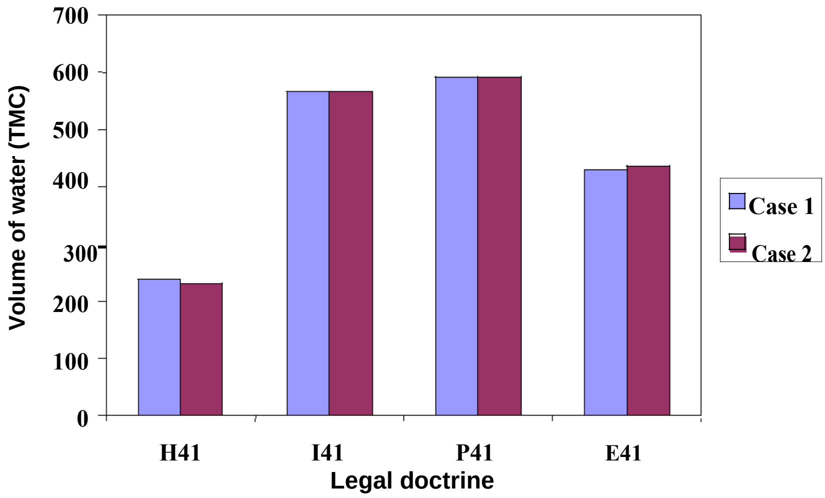

Figure 8D. Tamil Nadu's allocations for average flows and S_4 scenario.

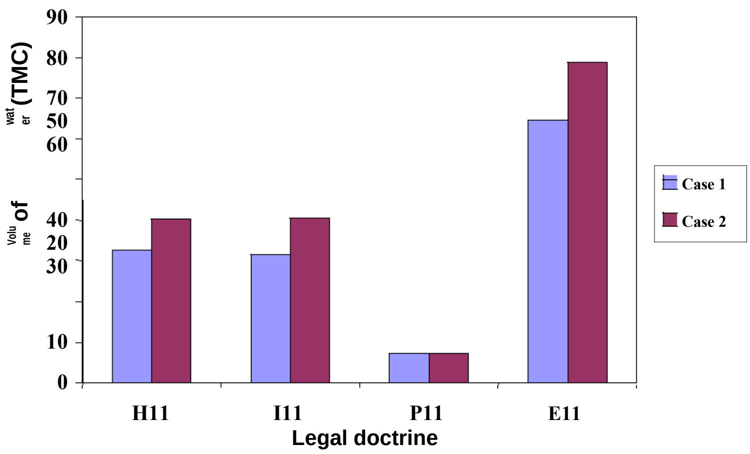

Figure 9A. Kerala's allocations for average flows and S_1 scenario.

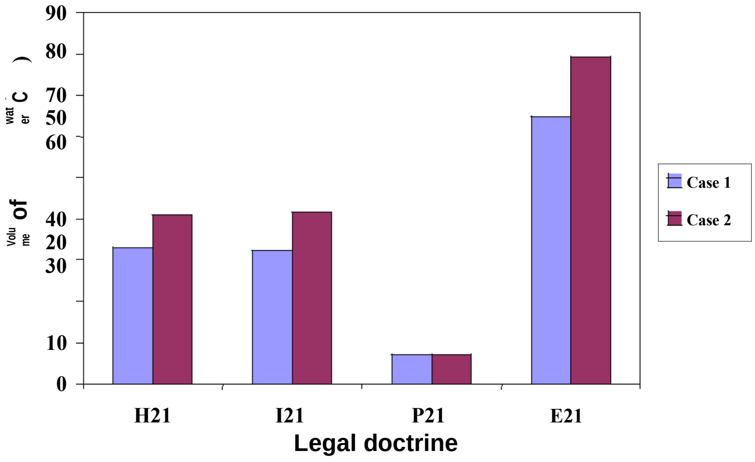

Figure 9B. Kerala's allocations for average flows and S_2 scenario.

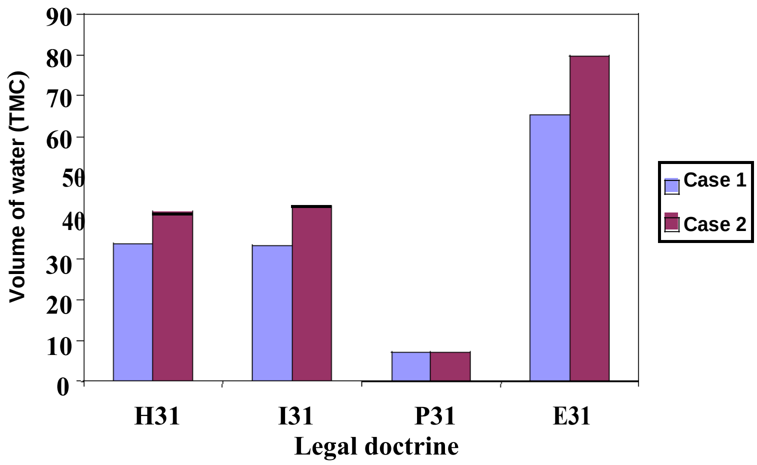

Figure 9C. Kerala's allocations for average flows and S_3 scenario.

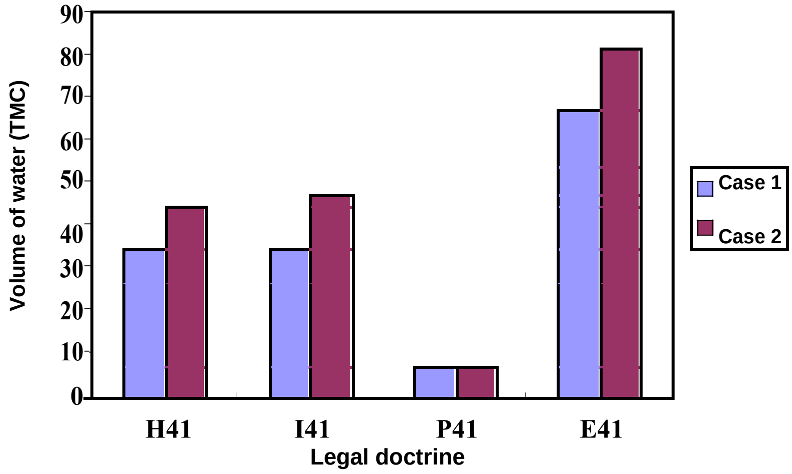

Figure 9D. Kerala's allocations for average flows and S_4 scenario.

appropriation as Kerala has been a late starter in using the Cauvery waters. Interestingly, in this case, principle of reasonable and equitable use yields maximum water share. This proves that the principle of reasonable and equitable use makes sure that the late starters in water use are not penalized eternally. Comparing Case I and Case II plots, it is observed that Kerala's share is more in Case II whereas Karnataka's share is more in Case I. This is because Kerala is ahead of other riparians in the social and economic factors like literacy, life expectancy and per capita income. Hence, if the social and economic needs of the watercourse states are considered (as in Case I), Kerala's share gets reduced.

Finally, the study demonstrates that simulation modeling can play a very significant role in conflict resolution 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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REFERENCES

Arnold JG, Williams JR, Maidment DR (1995). "Continuous-time water and sediment-routing model for large basins." J. Hydraulic Eng., 121(2): 171-183.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998). "Large Area Hydrologic Modeling and Assessment Part I: Model Development." J. Am. Water Resour. Assoc., 34(1): 73-89.

CFFC (1972). "Report of the Cauvery Fact Finding Committee." Ministry of Irrigation and Power, Government of India, New Delhi.

Chen HH (2003). "A Study on how Changes in Land Use Impact Water Resources in Taiwan." Water Int., 28(4): 422-425.

Gholami SA (1999). "Distributed Watershed Modeling of a Mountainous Catchment" PhD dissertation, Department of Civil Engineering, IIT Delhi.

Guhan S (1993). "The Cauvery River Dispute; Towards Conciliation." Frontline Publication, Madras.

Kumar D (2005). "Formulation and demonstration of a technique to quantify leachate pollution potential of municipal landfills" PhD dissertation, Department of Civil Engineering, IIT Delhi.

Luitjen JC, Knapp EB, Sanz SI, Jones JW (2003). "A Role for GIS based Simulation for Empowering Local Stakeholders in Water Resources Negotiations in Developing Countries: Case Studies for two Rural Hillside Watersheds in Honduras and Columbia." Water Policy, 5: 213-236.

Nash JE, Sutcliffe JV (1970). "River Flow Forecasting through Conceptual Models Part - I, A discussion of Principles." J. Hydrol., 10: 282-290.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR, King KW (2002). "Soil and Water Assessment Tool Theoretical Documentation." Version 2000.

Rajasekaram V, Simonovic SP, Nandalal KDW (2003). "Computer Support for Implementation of a Systemic Approach to Water Conflict Resolution." Water Int., 28(4): 454-466.

Rajeevan M, Bhate J, Kale JD, Lal B (2006). "High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells." Curr. Sci., 91(3): 296-306.

Salman SMA, Uprety K (2002). "Conflict and Cooperation on South Asia's International Rivers." Law, Justice and Development Series, World Bank, Washington DC.

Singh A, Gosain AK (2004). "Conflict Resolution in transboundary watercourses: An Indian Perspective" Land Use and Water Resour. Res., 4(2): 1-2.5.