

An optimization model and policy analysis of water allocation for a river basin

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Abstract The problem of inter-sectoral water allocation is investigated for the utilizable water in the Cauvery river basin in the state of Karnataka, India. This paper aims to maximize the total benefit of available and utilizable water while trying to ensure a certain basic water right for every individual. It also aims to meet irrigation requirements as put forward by government (central or state) in drought contingency plan. In this context, a novel nonlinear optimization model is developed which utilizes hydro-agro-economic data collected from multiple sources. This optimization model allocates the available water among different competing sectors which includes municipality, industries and agriculture. Furthermore, the sensitivity analysis evaluates the economic impact of different parameters of competing demands such as water availability, population and basic water right (quantity). The results of this study reveal that the basic water right for essential needs can be ensured with integrated management of available surface water resources. This novel optimization model and policy analysis can be readily applied to other river basins across the globe.

Keywords Basic water right · Contingency plan · Inter-sectoral water allocation · Optimization model · Cauvery river basin

Introduction

Increasing population and rapid economic development in the state of Karnataka, India have led to an increase in demand of water resource in the Cauvery river basin. This increased demand has been observed across all sectors, including municipal, industrial, agriculture, hydro-power, thermal-power, and recreation. Out of these, municipal, industrial and agricultural sector have been considered in this paper. In addition to that “The National Food Security Act” (GOI 2013a) is intended to ensure food security for the existing population in India. To attain this goal, the food grain production by 2025 will have to be increased by approximately 76% of the 2001 figure (NWP 2012). The required increase in food production will place severe stress on the water resources. In this context water allocation to arid regions will be a big challenge where one sixth of the total area is drought prone (NWP 2012). In such scarce situation, it is necessary to ensure basic right for drinking, sanitation, and farmers’ agricultural requirements. Human rights based development (UNICEF 2004) also endorses the policy of “right to water” and “right to food”. Optimal allocation of water to these competing demand sectors is a big challenge for water managers and policymakers. Hence, it is necessary to have an allocation vector that maximizes the utility (market and non-market valuation both) of available water resource (surface or/and ground water). The water resource allocation should incorporate a policy and institutional framework for distributing water in any region. Such policy framework is generally provided by international organizations, such as the United Nations or by a national level government organization. An example is the National Water Policy-2012 (NWP 2012) formulated by Ministry of Water Resource, Govt. of India. The policy framework is a

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collection of some guidelines for allocating water (or water rights) among different sectors. These guidelines consider issues related to human satisfaction, environment, socio-economics, and hydrology (UNICEF 2004). In this work we consider human satisfaction, which refers to the quantity of water that is necessary for the daily needs of an individual (Abdul 2008). Furthermore, farmers' livelihood can be ensured by setting the water quantity to a certain minimum area of cultivation.

The water resource allocation problem has been observed to be of an interdisciplinary nature. It requires modeling techniques that can study the water allocation as integrated with hydrology, agronomic, economic, and institutional components (Natasha 1996). In this study, we develop a mathematical programming model which incorporates domestic, agricultural and industrial utility of water. The model obtains optimal inter-sectoral allocation by maximizing total utility of water available at river basin while meeting the constraints of basic water rights of individuals and farmers. This paper is structured as follows: “[Literature review](#)” gives a detailed review about the mathematical modeling of the inter-sectoral water allocation in a river basin, along with case studies. Followed by “[Study area: Cauvery river basin](#)” which provides details about the study area, and “[Optimization model](#)” which explains the optimization model for water allocation and discusses the different hydro-economic components of the optimization model. This is followed by “[Results and discussions](#)”. In “[Policy analysis](#)”, the different allocation policies are compared in terms of the quantity of water allocated and the associated benefits. A sensitivity analysis is carried out to study the impact of the population and water scarcity on the water allocation and is discussed in “[Sensitivity analysis: increasing population and water scarcity](#)”.

Literature review

Historical evidence of human civilization has been found mostly around the river banks (e.g., Indus Valley, China, and Egypt). In addition, at present the rivers are major source of surface water and it is important to have effective and efficient water resource management at river basin. In the context of water allocation at any river basin, it is necessary to have sufficient knowledge and ability to integrate economics, engineering, ecology, and social and legal aspects in an analytical framework. For example, Booker (1995) studied the hydrological and economic impacts of drought using an optimization model that also included policy issues. The optimization approach has the ability to include the hydrological,

operational aspects, and also the socio-economic policy issues for water-resource management. This type of mathematical programming approach has been termed as hydro-economic modeling (Noel and Howitt 1982). We want to underpin the literature on hydro-economic modeling in light of the basic water right and water allocation policy for maximizing the utility of water resource at any river basin.

This literature review has importance in relation to two aspects: (A) hydro-economic modeling and the basic framework for optimal inter-sectoral allocation, and (B) case studies in different river basins and the approaches applied in these studies.

- A. In the context of hydro-economic modeling and its components, Booker and Young (1994) proposed a nonlinear optimization model to estimate the impacts of alternative market institutions in Colorado River basin. This model depended solely on the market-based valuation of water to study the increasing beneficial uses of the water resource. Later, McKinney et al. (1999) presented an optimization model that integrated economics, hydrology and agronomic components. Later, the inter-sectoral water allocation among different users, such as agriculture, municipal, industrial, and environment were considered in the analysis of many scholars (Juan et al. 2001a, b; Babel et al. 2005; Letcher et al. 2006; Tilmant and Kelman 2007; Tilmant et al. 2008). The most cited work is that of Rosegrant et al. (2000), who proposed an integrated hydro-economic modeling framework that took into account the interactions among farmer input choice, agricultural productivity, non-agricultural water demand, and resource degradation towards estimating the social and economic benefits. The model assumed a linear relationship between crop yields and seasonally applied non-saline water. It also included a series of institutional rules, including the minimum required water supply to a demand site, the minimum and maximum crop production, the flow requirement through a river for environmental and ecological purposes, and maximum allowed salinity in the water system. Ximing et al. (2003) used the same model to address the questions on the measurement of the irrigation system efficiency in a river basin. In the literature, a holistic (integrated) approach has been reported to be appropriate for studying the impact of any water resource policy framework on an economic system (Julien et al. 2009). Therefore, the study of different water policies for water allocation is a major focus of the current research.

B. To review the literature from the perspective of river basins, and case studies dealing with different issues of water allocation, are addressed here. The model proposed by Rosegrant et al. (2000) and Ximing et al. (2003) which considered the interactions between water allocation, farmer input choice, agricultural productivity, non-agricultural water demand, and resource degradation, was applied on Maipo, Chile. McKinney et al. (1999) focused on the Syr-Darya river basin of Central Asia applying a non-linear multi-period network model of the river basin with the objective of maximizing the total water use benefit from irrigation, hydro-power generation, and ecological water use. Graveline et al. (2014) carried out a simulation on hydro-economic variables in Gallego, Spain, in a study on global change and policy options that affect the catchment water scarcity and their economic implications in the agricultural sector. The well-known river basin of Murray–Darling, Australia, was studied using a simulation model to observe the impact of variability and changes in water availability on environment and irrigation, as well as on the value of irrigated agricultural production (Kirby et al. 2012). Similarly, many other case studies have applied hydro-economic modeling in different river basins, such as Mekong in Southeast Asia (Ringler 2001), George catchment in Australia (Kragt et al. 2011), Middle Guadiana basin in Spain (Blanco-Gutierrez et al. 2013); and Illinois River in United States (Debnath et al. 2015). Vedula and Nagesh Kumar (1996) partially studied the Cauvery river basin in Karnataka region, India; they applied hydro-economic models to one of the tributaries of the Cauvery river to study a single reservoir operations policy on irrigation that included the concept of evapotranspiration of crops. However, no extensive study incorporating major issues, such as the basic water right for individuals or contingency plan for farmers has been done on the upper Cauvery river basin in Karnataka region, India.

In the present research, an optimization model for inter-sectoral water allocation subject to basic water rights is carried out with the Cauvery river basin as study area. The following section the contribution of the study in relation to the above discussed aspects.

Research contribution

The model used by Rosegrant et al. (2000) and Tilmant et al. (2008) addressed the minimum water quantity for certain sectoral (e.g., irrigation) demands. In the past, the literature did not see the problem of inter-sectoral water

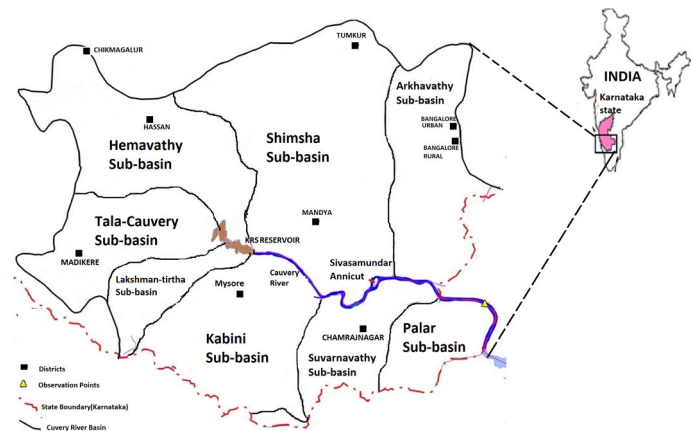
allocation under a new framework that gives basic water rights security to the municipal and agricultural sectors. The minimum allocation of water to any sector was unable to capture the notion of a basic water right for human livelihood or an agriculture contingency plan to ensure the livelihood of farmers. When such minimum allocation is derived from a purview of an institutional directive, it includes a “basic water right” constraint in the model. It is necessary to study the implication of such constraint in light of the decreasing per capita available water with the increasing population. In previous literature, no study addressed the above issues in the upper Cauvery river basin with the approach of integrated hydro-economic modeling. The basic contribution of the present research is in addressing the following issues in the case of the upper Cauvery river basin:

- The development of an optimization model for inter-sectoral water allocation in the Cauvery river basin:
 - An economic assessment that considers the value of water used for different purposes and the net benefits derived from allocating water to each identified sector over time.
 - A study of different policy scenarios for the optimal inter-sector allocation of water.
- A study of the economic impact of different parameters of competing demands:
 - An analysis of the optimal allocation of water among competing demands under a new framework that ensures basic water rights.

Study area: Cauvery river basin

The Cauvery river is one of the major inter-state rivers in South India. It originates from the Western Ghats in the Coorg district of the Indian state of Karnataka at an elevation of 1341 meters and drains into the Bay of Bengal in the neighboring state of Tamil Nadu. This river has a total drainage area of 81,155 km² (GOI 2013b). It is about 800 km (GOI 2013b) long, with 320 km in Karnataka and 416 km in Tamilnadu (GOI 2013b).

The major reservoirs along the course of the river in Karnataka are Hemavathy, Krishnaraja Sagar, and Kabini. Harangi, Hemavathi, Lakshman-Thirtha, and Kabini are the major sub-basins, which form the upper Cauvery river basin (see Fig. 1). These four sub-basins constitute the total catchment area for the Harangi, Hemavathy, Krishnaraja Sagar (KRS), and Kabini reservoirs. All the sub-

Fig. 1 The Cauvery river basin

basins in the upper Cauvery river basin are mainly fed by rainfall; the high discharge period is during the monsoon from June to September, whereas the lean period is from October to May. The major reservoir projects (Hemavathy, Harangi, KRS, and Kabini) mainly benefit the districts of Hassan, Mandya, Mysore, and Chamrajnagar. These districts are agriculture dominated, and their irrigation requirements create more demand for available surface water compared with the other districts in the basin. There are also many medium reservoir projects namely Nugu, Yagachi, Iggalur, Marconahalli, Taraka, Suvarnavathy, Arka-vathy, Votehole, Gundal, Uduthorehalla, Kanva, Chicklihole, Byramangala, Mangala, and an annicut in Sivasamundar. These projects benefit nine districts: Kodagu, Hassan, Mandya, Mysore, Chamrajnagar, Tumkur, Bangalore-urban, Bangalore-rural, and Ramanagara, Fig. 1 presents these geographical locations. The Ramanagara district is not shown in the figure due to the unavailability of data in the origination image from CWC.¹ The total water drain Cauvery river under the Karnataka state is 370 TMC (Thousands Million Cubic ft.), out of which that stored in the reservoirs is 7146.1540 MCM (Million Cubic Meters). The agriculturists in the Cauvery river basin cultivate four major crops: paddy, ragi, maize, and sugarcane (GOI 2013c). The increasing population of the Bangalore and Mysore districts due to the rapid economic development of the IT and other economic sectors has put an enormous amount of stress on the available surface and ground water. The increasing demand for urban domestic and non-domestic consumption has created a challenging situation in managing the available water resources. The population of Bangalore (rural and urban) and Mysore accounts for 60% of the total population living in the upper Cauvery basin (based on census data of India, 2011) (GOI 2015c). The per-capita water demand is 173 lpcd (Liters per

capita per day), whereas the supplied water is 138 lpcd; the available water that reaches consumers after leakage losses is 83 lpcd, according to the Bangalore Water Supply and Sewerage Board (BWSSB) (Anon 2011). Similarly, Mysore municipal water supply board has set a required supply for domestic usage of 135 lpcd.

Modeling

A river basin consists of a number of supply nodes S (reservoirs) and demand nodes D (districts). These nodes are connected by links such as canals and pipes. The nodes and links of a river basin can be represented by a network (See Fig. 2). Let $G(N, A)$ be the directed network representing a river basin, where $N = \{S, D\}$ is the set of nodes, and $A = N \times N$ is the set of links (arch) connecting any two nodes. The water users (demand nodes) are grouped into sectors (stakeholders) defined by $D = \{I, M, J\}$. A particular sector (e.g., agriculture) may demand water at several demand nodes (districts), and a demand node may be associated with a number of water use sectors such as agriculture, municipal (or domestic) or industrial (or non-domestic) (See Fig. 2).

Let Ω be the set of feasible water allocation vectors and \mathbf{x} is a specific allocation vector $\mathbf{x} \in \Omega$. The $\mathcal{B}(\mathbf{x})$ is the benefit derived by the productive use of the allocated water across all the sectors in all the demand nodes. The objective of the water allocation optimization problem is to maximize the utility, as given by Eq. (1):

$$\text{Max}_{\mathbf{x} \in \Omega} [\mathcal{B}(\mathbf{x})]. \quad (1)$$

To maximize the total utility of water in a river basin it is necessary to maximize each sector's utility function. Hence, we derive the benefit function for each of the water use sectors. The associated benefit maximization will also subject to some set of constraints that are going to address the basic water right issues.

¹ Center water Commission (CWC) comes under Ministry of Water Resource, Government of India.

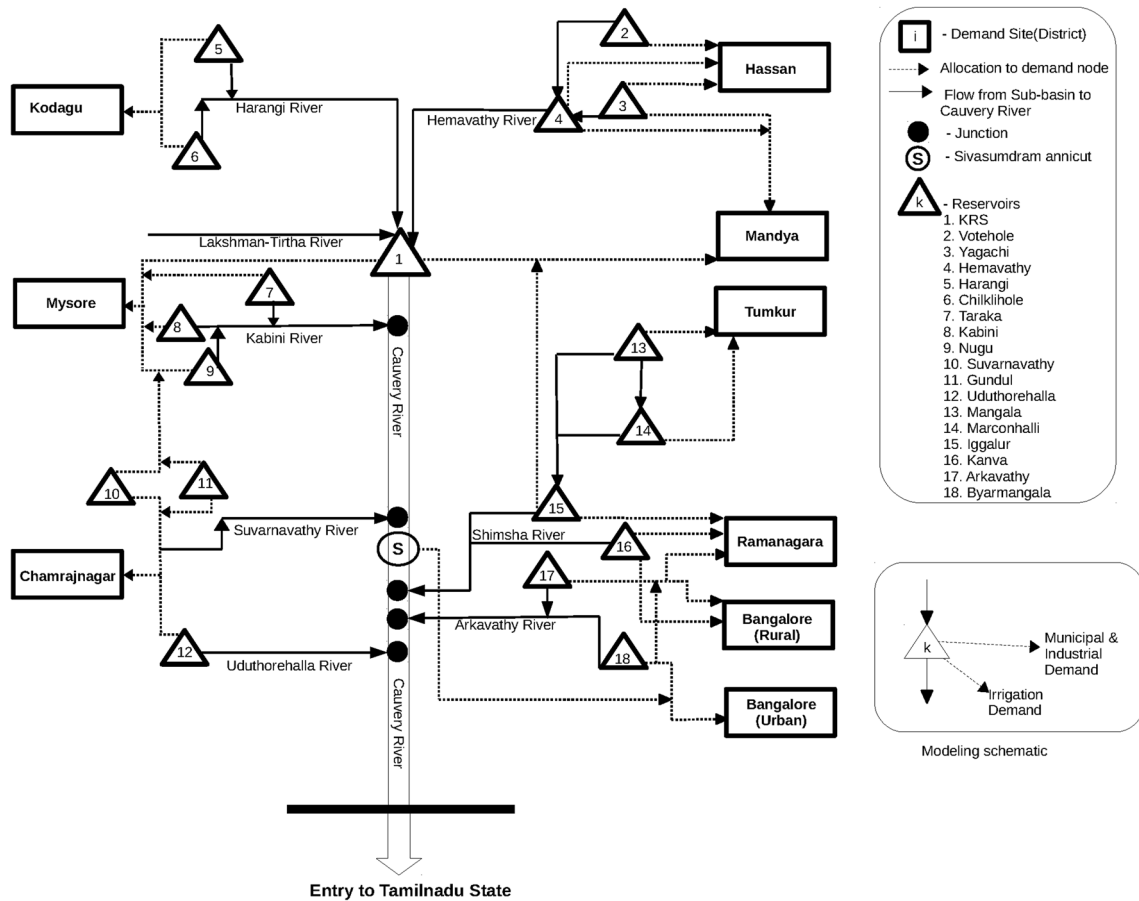


Fig. 2 Node-link network model

Optimization model

Mathematical notations for mathematical programming model,

Sets	
N	All nodes in network, $N = \{D, S\}$
D	Set of demand type $D = \{I, M, J\}$
S	Set of supply nodes $S = \{R, B\}$
I	Irrigation (agricultural) demand nodes
J	Industrial demand nodes
M	Municipal demand nodes
B	Supply nodes don't store the water (annicut etc.)
R	Reservoir nodes
K	Crop-type, $K = \{\text{paddy (rice), sugarcane, maize, ragi}\}$

Index

n, n'	Nodes at river reaches
s	Supply node
d	Demand node
r	Reservoirs
b	Simple node
i	Demand node of irrigation
j	Demand node of industry
m	Demand node of municipal
k	Type of crop

Variables	
Q_{sik}	Quantity of water allocated/delivered from any supply node s to a demand node i for crop type (area) k
Q_{sj}	Quantity of water allocated/delivered from any supply node s to a demand node j
Q_{sm}	Quantity water allocated/delivered from any supply node s to a demand node m for municipal usage
$(Q_e)_{mn'}$	Quantity of water loss due to evaporation, leakage etc. while flowing from any node n to node n'
$Q_{nn'}$	Quantity of water flowing from any node n to node n'
A_{ik}	Irrigated area of land for crop type k at demand node i in thousands hectare
Parameters	
$(Q_e)_m$	Quantity of water required for essential municipal usage at a municipal node m
Q_e	Quantity of water required for essential usage for individual (liter per capita per day)
C_{si}	Cost of supply, per unit of water from node s to a node i
$(C_p)_{ik}$	Aggregate cost fixed, irrigation technology, labor cost etc. of agriculture at node i of crop type k (₹/hectare)
A_i	Total land area for agriculture at irrigation node i
Y_{ik}	Crop yield (tons per hectare) of crop type k at demand node i
q_{ik}	Quantity of water required for unit hectare cultivation of crop k
T_m	Population of municipal m
p_k	Selling price of crop k per ton
Q_n	Storage or availability of water at node n

Net benefit from agricultural water use

It is defined by an aggregate production function of crops at a given demand node. We take the approach of subtracting the total cost of production from the total value of the crop cultivated to derive the net benefit. This approach for estimating the benefit from agricultural water use is standard in literature (Griffin 2006) and we have adopted it due to the availability of data from the Department of Agriculture, Government of India (see Eq. 2). In this approach the net value of the crop cultivated will have to incorporate water quantity required and its cost, cost of labor used in cultivation, crop yield, and the market value of the harvested crop (minimum support price announced by Government of India). Since, the water requirements and the value of the crop vary by the crop, it is important to identify the area under cultivation for a specific crop. The cumulative production over the three crop seasons in a year is to be considered for obtaining the net economic benefit. The net benefit from agricultural water use is represented by (B_{Agri}),

$$B_{Agri} = \sum_S \sum_I \sum_K \left\{ \overbrace{\left(\frac{Q_{sik}}{q_k} \right) \cdot (p_k \cdot Y_{ik})}^{\text{Total benefit}} - \overbrace{\left(\frac{Q_{sik}}{q_k} \right) (C_p)_{ik} - Q_{sik} \cdot C_{si}}^{\text{Total cost}} \right\} \\ = \sum_S \sum_I \sum_K \left\{ \left(\frac{Q_{sik}}{q_k} \right) \cdot [p_k \cdot Y_{ik} - (C_p)_{ik}] - Q_{sik} \cdot C_{si} \right\} \quad (2)$$

In Eq. (2), p_k is minimum support price (MSP) (₹/kg) for crop k , and Y_{ik} is yield (kg/Ha) of crop k at district node i . The product of p_k and y_{ik} is revenue generated by cultivation of crop k in per unit area. The $(C_p)_{ik}$ gives the cost of cultivation (₹/Ha) of crop k at a given demand node (district) i that includes the cost of labor, fertilizers, etc. The Q_{sik} is allocated water to district node i from supply node s for crop k . The product of $Q_{sik} \cdot C_{si}$ is the total cost (₹/m³) of water supplied to the node i .

Let, the minimum water required for cultivating a specific crop k is (q_k) (m³/Ha). If Q_{sik} is the quantity of water allocated from the supply node s to demand node i , then $\left(\frac{Q_{sik}}{q_k} \right)$ represents the area that could be cultivated by crop k .

The crop water requirements (see Chandrakanth (2009)), average yield (see CONTIN 2015), cost of production, and minimum support price (MSP)² for the produce used in the analysis. Using this information the net benefit that can be derived by supplying 1 m³ of water to a specific crop can be computed.

Net benefit of municipal and industry (non-domestic)

The approach of inverse demand function is used to estimate the utility associated with municipal and industrial water usage. Typically, the municipal and industrial water demand curve has been defined in literature by a negative slope and concave near the origin (Diaz et al. 2000; Griffin 2006) (see Fig. 3).

A power function or an exponential decaying function will exhibit this characteristic. Using the exponential decay model the marginal benefit function (MNB) from domestic and industrial water usage can then be represented by (Divakar et al. 2011) as shown in Eq. (3),

$$MNB = a \cdot e^{\left(\frac{Q}{b} \right)} \quad a > 0, b < 0, \quad (3)$$

where, Q is quantity of water consumed, and a and b are constants that define the nature of the negative exponential demand curve. The demand function in Eq. (3) is downward sloping and intersect the price axis indicating that consumption ceases for a high enough price. The

² Computed on the basis of the data available related to MSP, cost of cultivation, and yield for the year of 2010–11.

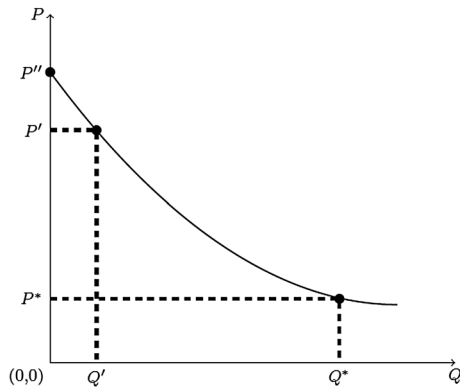


Fig. 3 Demand for municipal and industrial water usage

parameters of this function can be estimated by specifying two points on the curve. Given the two points on the curve (P^*, Q^*) and $(P'', 0)$ the parameters a and b are given by:

$$a = P'',$$

$$b = Q^* / \ln(P''/P^*). \tag{4}$$

Then the net benefit derived by consuming Q' quantity of water can be determined by integrating the marginal net benefit function as in Eq. (3):

$$B = \int_0^{Q'} a \cdot e^{\left(\frac{Q}{b}\right)} dQ$$

$$= a \cdot b \left(1 - e^{\left(\frac{Q'}{b}\right)}\right). \tag{5}$$

Objective function

The objective of the water allocation problem is to maximize the total net benefit by consumption across all the sectors (Eq. 1). The objective function given in Eq. (1) can now be expanded by incorporating the benefits from agriculture (Eq. 2), municipal (Eq. 5) and also non-domestic consumption can be obtained from the Eq. (5). The expanded form of objective function is given by Eq. (6):

$$\text{Max} [B_{\text{Agri}} + B_{\text{Munis}} + B_{\text{Nondom}}], \tag{6}$$

Where,

$$B_{\text{Agri}} = \sum_S \sum_I \sum_K \left\{ \left(\frac{Q_{sik}}{q_{ik}}\right) \cdot [p_k \cdot Y_{ik} - (CP)_{ik}] - Q_{sik} \cdot C_{sik} \right\}, \tag{7}$$

$$B_{\text{Munis}} = \sum_S \sum_M a_1 \cdot b_1 \left(1 - e^{\left(\frac{Q_{sm}}{b_1}\right)}\right), \tag{8}$$

$$B_{\text{Nondom}} = \sum_S \sum_J a_2 \cdot b_2 \left(1 - e^{\left(\frac{Q_{sj}}{b_2}\right)}\right). \tag{9}$$

The water allocation that maximizes the above given total net benefit function, needs to be identified along with the main objective that satisfies the basic water rights. Such an allocation need to satisfy the following constraints that will define the feasible region within which the above objective may be achieved.

Constraints

Flow balance constraints

The water flow in a river basin is modeled with the help of the node-link network (see Fig. 2). And, in any node-link network the total input and output flow should be equal. Hence for a given node $n \in S$ on the review flow network, let $U(n)$ be the set of nodes that are immediately upstream of n . Similarly, let $D(n)$ be the set of nodes that are immediately downstream of n . Then, for flow balance:

$$\sum_{n' \in U(n)} Q_{n'n} = \sum_{n'' \in D(n)} Q_{nn''} + \sum_{i \in I(n)} \sum_{k \in K} Q_{nik} + \sum_{m \in M(n)} Q_{nm} + \sum_{j \in J(n)} Q_{nj}. \tag{10}$$

Equation (10) must be satisfied. Here, $I(n)$, $M(n)$, and $J(n)$ represent the set of agricultural, municipal, and industrial demand nodes, respectively, supplied from node n . The water supplied to the demand nodes either for irrigation purposes or municipal and industrial is typically not fully available for productive use. A significant portion of it is lost due to seepage, leakage, and unauthorized use. Hence, the water allocated for use in a demand node (Q_{nik} , Q_{nm} , Q_{nj} in the above expression) need to adjusted for these loses while estimating the net benefit derived from its use.

The water fed to these demand sites will have to be less than the available water storage capacity of the reservoirs. Hence for a supply node $n \in S$,

$$\sum_{i \in I(n)} \sum_{k \in K} Q_{nik} + \sum_{m \in M(n)} Q_{nm} + \sum_{j \in J(n)} Q_{nj} \leq Q_n^{\text{max}} \sum_{n' \in U(n)} Q_{n'n}, \tag{11}$$

where Q_n^{max} is the reservoir capacity (utilizable water). The node representing a annicut is an exception to this constraint as the storage capacity at the site could be much lower than the water pumped from the site to meet some demand. For example, the Sivasamudram annicut is the water drawing point for the Bangalore municipal water supply board (BWSSB) which draws around 900 MLD of water from here. Hence, for the annicut node the flow constraint in general would be,

$$\sum_{i \in I(n)} \sum_{k \in K} Q_{nik} + \sum_{m \in M(n)} Q_{nm} + \sum_{j \in J(n)} Q_{nj} \leq \sum_{n' \in U(n)} Q_{n'n}, \tag{12}$$

with the absence of the Q_n^{\max} term indicating the absence of any storage capacity at that node.

Area constraints

The net irrigated area is defined to be the area under any form of irrigation at least once in a year. A portion or all of this area could be under cultivation for more than once in a year, provided there is water available for this purpose. In the area of our study, there are three cropping seasons namely rabi, kharif, and summer. The planning horizon for the model is taken to be one year and hence the water allocated for irrigation should not exceed the requirements for the three seasons for the net irrigated area. This gives the maximum irrigable area in a year. For a given agricultural demand node $i \in I$, let A_i be the total irrigable area in a year. Then constraint is given by Eq. (13) as:

$$\sum_S \sum_K \frac{Q_{sik}}{q_k} \leq A_i, \quad \forall i \in I. \quad (13)$$

Basic water right

International human right conventions recognize the basic human right to be able to access safe, sufficient, acceptable, and affordable water as the right to water is indispensable to be able to lead life. UN resolution 64/292 calls upon states to meet these goals. The National Water Policy of India reflects these goals, though these rights are not legislated. The National Rural Drinking Water Programme (GOI 2015b) has suggested the approach of setting lpcd standards as a means of measuring availability of water reflecting the human right goals. As stated in Sect. “Research contribution”, the main objective of this research is to evaluate the impact of such a goal if it were to be legislated and made mandatory to meet these lpcd goals in the upper Cauvery basin. This objective enters the model simply as a constraint on the total water allocated for municipal consumption.

Let Q_e be the lpcd standard for municipal consumption. Then, for a given municipal demand node $m \in M$ the minimum total municipal water requirement would be $T_m Q_e$. If Q_{sm} is the allocation from supply node s to municipal demand node (m) for municipal consumption, then:

$$\sum_S Q_{sm} \geq T_m Q_e \quad \forall m \in M. \quad (14)$$

This constraint enforces the requirement that the allocated water to any municipal demand node should be greater than the total water demanded under the basic water right.

Contingency area constraint

The contingency plan developed by the Department of Agriculture and Cooperation, Govt. of India (GOI 2015a) can be viewed as the basic water right requirements for the agriculture sector. Under a drought scenario, the contingency plan gives guidelines of cropping patterns to ensure a minimum area for cultivation for each crop in every district. This plan suggests a lower bound for the irrigable area in the optimization model. Let, A_{ik}^* be the minimum area to be irrigated in an agricultural demand node $i \in I$ for crop $k \in K$. Then to meet the contingency plan the constraint:

$$\sum_S \frac{Q_{sik}}{q_k} \geq A_{ik}^* \quad \forall i \in I, k \in K, \quad (15)$$

should be satisfied. This constraint can also be viewed as guaranteeing a certain minimum livelihood for the farmers.

In the situation when more than the area specified by the contingency plan can be irrigated the hydro-economic optimization model would tend to give more preference to the crop with the highest return. It is highly probable that all the excess water is diverted to such a crop. Hence to avoid such a situation, we enforce crop specific area constraint such that the proportion of irrigated area for a particular crop does not deviate significantly from the proportion of the crop in the contingency plan. This constraint is motivated to provide an upper bound on the irrigated area for given crop k in relation to all the other crops. This is an extension to the constraint derived from the contingency plan. This will avoid a skewed irrigated area for crops such as sugarcane. This constraint can be expressed as:

$$\frac{\sum_S \sum_I \frac{Q_{sik}}{q_k}}{\sum_S \sum_I \sum_K \frac{Q_{sik}}{q_k}} \leq \delta \frac{\sum_I A_{ik}^*}{\sum_I \sum_K A_{ik}^*}, \quad \forall k \in K, \quad (16)$$

where $\delta \in \mathbb{R}^+$ is a parameter that specifies the amount of flexibility in adhering to the constraint on the cropping area.

Parameters of interest

- The Bangalore urban area is provided water and sewage services by the Bangalore Water and Sewage Services Board (BWSSB). The household water consumer is charged an average price of approximately 21 ₹/m³ and the non-domestic consumer is charged an average price of approximately 48 ₹/m³ (BWSSB 2015). The annual bulk quantity supplied by BWSSB for domestic usage is 229.95MCM, and for non-domestic it is around 65MCM (BWSSB 2013). The water supply in Bangalore is rationed by way of limiting the time period for which water is pumped through the network. A typical consumer augments the BWSSB supply with additional

sources such as on-site bore-wells and tanked water supply services provided by private operators. The bore-wells are not metered and hence the consumer will only face the fixed cost of setting up the wells. The water-tanker service providers charge around 85 ₹/m³ for domestic usage and 170 ₹/m³ non-domestic usage (The Hindu 2015). We take this price point to indicate the choke price beyond which the demand falls to zero. With these data points the parameters of the demand curve for domestic consumer is estimated as:

$$\begin{aligned} a_1 &= P'' = 85, \\ b_1 &= Q^* / \ln(P''/P^*) = 229.95 \times 10^6 / \ln(85/21) \\ &= 164469823.5, \end{aligned}$$

and the non-domestic consumer as:

$$\begin{aligned} a_2 &= P'' = 170, \\ b_2 &= Q^* / \ln(P''/P^*) = 65 \times 10^6 / \ln(170/48) \\ &= 51399756.68. \end{aligned}$$

- For the basic water right constraint in “Basic water right”, Based on extensive survey of water use across the world (Peter et al. 1996), recommends a 50 lpcd standard to meet the drinking water, hygiene, sanitation services, and food preparation requirements. In our analysis, we have set the 170 lpcd standard as the basic water right which also reflects the demand quantity of 173 lpcd estimated by BWSSB (Anon 2011).
- The gross total utilizable water available in all the reservoirs is 7146.15MCM and after accounting for the reservoir evaporation losses the total net available water is 6074.23MCM (see page no. 715 of Jain et al. (2007)).

Computational details

The non-linear optimization model that we have discussed in “Optimization model” was translated into an AMPL computational model (A Mathematical Programming Language). The application of model to the upper Cauvery river basin results in a total of 193 variables, 23 equality constraints, and 61 inequality constraints. The model was solved using the interior point optimization algorithm implemented in the IPOPT version 3.11.4 solver (COIN-OR 2015). The obtained results are also checked with COIN-OR solver Couenne (Convex Over and Under ENvelopes for Nonlinear Estimation) is a branch and bound algorithm. Since the objective function is non-linear we employed the multiple random starting point strategy to identify the global optimal solution. We selected the best solution from 200 iterations with random starting points. These results were also verified with another solver (COIN-OR solver Couenne).

Scenario: different water-allocation policies

The basic objective of this section is to study the impact of mandating basic water right for domestic and agriculture use (see “Research contribution”) while maximizing the total net benefit of the available water. The basic water right for municipal usage and minimum water for cultivation has been defined as right to water for human sustenance and food security. The basic water right for municipal use is fixed at 170 lpcd (see “Optimization model”) in our analysis. The minimum water right for agricultural use is defined by the contingency plan (see “Optimization model”). The contingency plan stipulates the minimum area of cultivation of a particular crop during the drought period in the upper Cauvery basin.

The national water policy 2012 (NWP 2012) motivates the evaluation of the following policy scenarios. The first scenario of free market allocation is considered to act as the base case to understand the total benefit that can be derived in the absence of any water allocation constraints. In this case the water is allocated solely based on the benefit derived by the use. No external priority considerations are enforced in the base scenario. In the next, high priority municipal allocation scenario where water is allocated to other users (industrial and agricultural) only after meeting all the demands placed by the municipal users. Alternatively, the high priority agricultural allocation scenario allocates water to the municipal and industrial users only after meeting the entire demand of the agricultural users. The final case of least priority non-domestic allocation, the industrial water users are allocated only after satisfying the entire demand of the agricultural and municipal water users.

In above context, the given mathematical model in “Objective function” Eq. (6) gives maximization of total benefit obtained from different inter-sectoral water allocation subject to constraints given by Eqs. (10, 11, 12, 13, 14, 15, 16). It also includes the constraints of basic water rights (see “Basic water right” and “Contingency area constraint”). In the context of a policy analysis on inter-sectoral water allocation, we use the model given in Eq. (17) that is a restructure of Eq. (6). It is a maximization of total benefit for the three sectors, namely municipal water use, industrial water use, and agricultural water use:

$$Z_{\text{total}} = \alpha \mathcal{B}_{\text{Agri}} + \beta \mathcal{B}_{\text{Munis}} + \gamma \mathcal{B}_{\text{Nondom}}. \quad (17)$$

These policy scenarios are implemented in the model (Eq. 17) as follows,

1. *Free market allocation (FMA)* This allocation policy does not assign any differential priority to any of the sectors, i.e., Domestic, agriculture or Non-Domestic. In Eq. (17) we set $\alpha = \beta = \gamma = 1$. The free market-based allocation implicitly allows for maximizing the

total utility derived from the optimal allocation to the different sectors.

2. *High priority municipal allocation (HPMA)* In this scenario water is allocated to non-domestic users and agriculture users only after the demand of the domestic sector is entirely met. In this policy we choose a sufficiently large number for β (the multiplier for the municipal benefit term in Eq. (17)) such that $\beta \gg (\alpha = \gamma)$.
3. *High priority agricultural allocation (HPAA)* The National water policy (2012) document gives the second highest priority to agricultural water use after municipal use. If we set $\alpha \gg (\beta = \gamma)$ in Eq. (17), the model will give the highest priority to agricultural use and water will be allocated to other users only after satisfying the entire needs of this sector.
4. *Least priority non-domestic allocation (LPNA)* It is the most conservative policy of the four scenarios under consideration. The parameters of the benefit function are such that the maximum water use utility is derived from non-domestic water use. But this policy gives the

least priority to this sector by fixing $\beta \gg \alpha \gg \gamma$ in Eq. (17). In this case the highest priority is given to municipal users, followed by the agricultural users, and finally the non-domestic users.

It is important to note that in all the above discussed four scenarios the water requirement for the basic water right of municipal consumption and contingency plan of the agriculture sector acts as a lower bound. This would imply that appropriate utility based allocation will be done by the model only after these basic rights are satisfied.

Results and discussions

Policy analysis

In the previous section we have mentioned different policy scenarios. Table 1 documents the trade-offs between the three sectors (domestic, non-domestic, and agriculture) with four different policy scenarios. The overall

Table 1 Base case water allocation: different policy scenario

Parameters	FMA	HPMA	HPAA	LPNA	Label
a1	85.00	85.00	85.00	85.00	
b1	164,469,823.50	164,469,823.50	164,469,823.5	164,469,823.5	
a2	170.00	170.00	170.00	170.00	
b2	51,399,756.68	51,399,756.68	51,399,756.68	51,399,756.68	
Essential water for municipal (per person) (in lpcd)	170.00	170.00	170.00	170.00	
Total population (in 1000)	22,532.72	22,532.72	22,532.72	22,532.72	
Total available water (in MCM)	7146.15	7146.15	7146.15	7146.15	
Net water available (in MCM)	6074.23	6074.23	6074.23	6074.23	
Total revenue of water allocation (in million ₹)	282,026.20	282,026.20	210,818.44	231,996.09	*
Total revenue agriculture (in million ₹)	51,185.05	51,185.05	62,264.59	57,226.87	
Total revenue municipal (in million ₹)	174,769.22	174,769.23	148,553.85	174,769.22	
Total revenue industry (in million ₹)	56,071.94	56,071.94	0.02	0.02	
Total water allocated for agriculture (in MCM)	2766.21	2766.21	3244.90	3013.59	
Agriculture proportion (% of total water Al located)	38.71	38.71	45.41	42.17	∅
Water required for agriculture contingency plan (in MCM)	1044.68	1044.68	1044.68	1044.68	
Total area irrigated (1000 Ha)	1627.23	1627.23	1892.22	1827.86	∞
Maximum irrigable area (1000 Ha)	2031.94	2031.94	2031.94	2031.94	±
Minimum area required irrigation (1000 Ha)	231.02	231.02	231.02	231.02	
Total water allocated for municipal (1000 Ha)	1644.89	1644.89	1398.16	1644.89	
Municipal proportion (% of total water)	27.08	27.08	23.02	27.08	
Total essential municipal supply of surface water (in MCM)	1398.16	1398.16	1398.16	1398.16	
Total water allocated for industry (in MCM)	263.87	263.87	0.00	0.00	
Proportion of industrial water (% of total water)	4.34	4.34	0.00	0.00	≤
Water allocated for agriculture against required (%)	264.79	264.79	310.61	288.47	Æ
Water allocated for municipal against required (%)	117.65	117.65	100.00	117.65	≠

The sum of proportion of water allocated to agriculture, municipal consumption, and industrial use is less than one as a significant quantity of water is lost due to seepage loss in canals and pipe transit

performance of the four policy scenarios, namely FMA, HPMA, HPAA, LPNA in the presence of basic water rights is presented. Essentially, the table represents the allocated water to sectors and their benefit (revenue in ₹) as an output using the optimization model (see Eqs. 6, 7, 8, 9, 10, 13, 14, 15). The optimal water allocation and the resultant net utility derived indicates that the policy scenarios of FMA and HPMA provide the maximum net benefit. The total net benefit (row labeled *) of FMA is equal to that of HPMA and they are greater than HPAA, LPNA by 45.13% and 27.28%, respectively.

The tabulated results show that the different policies are benefiting different sectors. The FMA and HPMA policy gives nearly 17% more water to domestic consumption (row labeled ≠) than the requirement set by the basic water right constraint (200 lpcd as against the 170 lpcd requirement). On the other hand, the agriculture sector gets more water allocation in the HPAA and LPNA policy scenarios. Though the FMA and HPMA provides 174% more water (row labeled Æ) than that mandated by the contingency plan, the HPAA policy scenario that gives priority to agriculture allocates an additional 47% to the agriculture sector. In terms of the proportion of total available water the HPAA policy scenario allocates about 53.42% as compared with around 45.54% by the FMA and HPMA (row labeled Ø). In terms of the total land area that could be irrigated using the allocated water, the HPAA policy scenario provides for around 36.7% of the maximum irrigable area, while under the FMA and HPMA this reduces to around 31.3% (rows labeled ∞ and ±). As one would expect, the non-domestic sector gets the least priority with FMA and HPMA only allocating about 4.3% of the total available water, while there is no allocation under the HPAA and LPNA policy scenarios (row labeled ≤). In pure economic terms the utility of water consumption in the non-domestic sector is higher than that of the municipal consumption, which in turn is higher than that of the agricultural sector. In the FMA policy scenario, the available water is first allocated to the non-domestic sector up to its upper bound, followed by the allocation to the domestic sector again up to its maximum permissible limit. The remaining water is then allocated to the agriculture sector. This behavior can be inferred from the water allocation numbers in Table 1.

Some of the key findings that can be inferred from the Table 1 are as follows.

- The maximum allocation of 4.3% of the total available water to non-domestic sector is made by the FMA and HPMA policy scenarios.
- HPAA policy ensures that the maximum possible irrigable area (around 36.7%) to be supplied with water. The remaining area is left un-irrigated due to the

constraint on the basic water right for municipal consumption. Note that the completely optional allocation for non-domestic use is not made under this scenario.

- The HPAA and LPNA allocates more water to the agriculture sector than the other two FMA and HPMA policy scenarios.
- FMA derives the maximum total utility from the available water.
- The per-capita allocation for municipal sector is only 170 lpcd under HPAA, while it reaches the upper bound (200 lpcd) in the FMA, HPMA and LPNA policy scenarios.

Next, we discuss the results from the sensitivity analysis that analyzes the change in the allocations under various changing circumstances such as increase in population, decrease in water availability in the mandated basic water rights.

Sensitivity analysis: increasing population and water scarcity

Here in this section, we study the impact of decreasing availability of water. This can be either due to increasing population or decrease in the availability of water for productive use as explained below,

1. The increasing population will put huge demand on the existing water resource. Hence, the per-capita water availability will decrease leading to scarcity. It is also called as socio-economic drought.
2. The other reason for scarcity is due to the inherent variability in the river water flow due to the meteorological factors. This may cause a decrease in the available per-capita water resource. It is also called the hydrological drought.

This is essentially a two-dimensional study of scarcity and its impact on inter-sectoral water allocation. The no-drought scenario (hydrological or socio-economical) is one in which all the reservoirs are assumed to be filled to their utilizable capacities. As in the previous policy analysis scenarios we consider 170 lpcd to be the basic water right quantity (essential water for basic needs) Anon (2011).³ The scarcity that is discussed above has been incorporated in sensitivity analysis by increasing the population from 0 to 30% in steps of 3% and decreasing the available water resource from 0 to 30% in steps of 3%. The decrease in the available water is implemented across all the reservoirs uniformly. Also, the contingency plan is equally adjusted by the same proportion to reflect the increasing population.

³ 174 lpcd is per capita water demand as per BWSSB in the report.

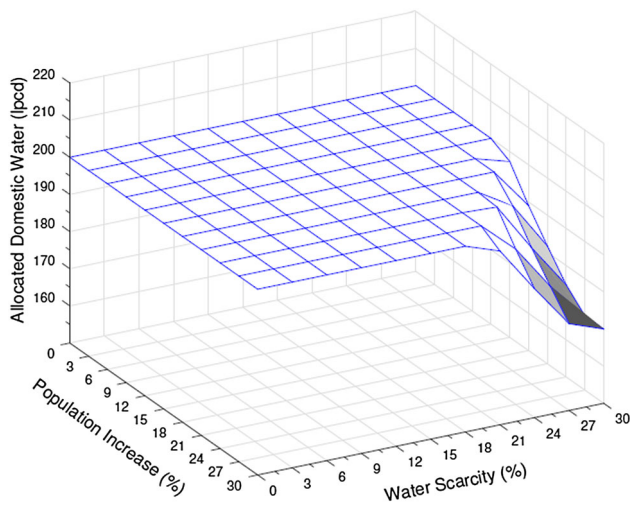


Fig. 4 Satisfaction to domestic usage (% to basic water right)

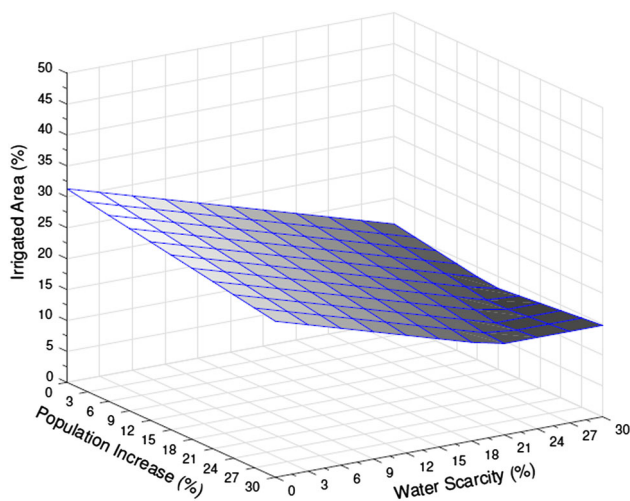


Fig. 5 Irrigated area (% to maximum area)

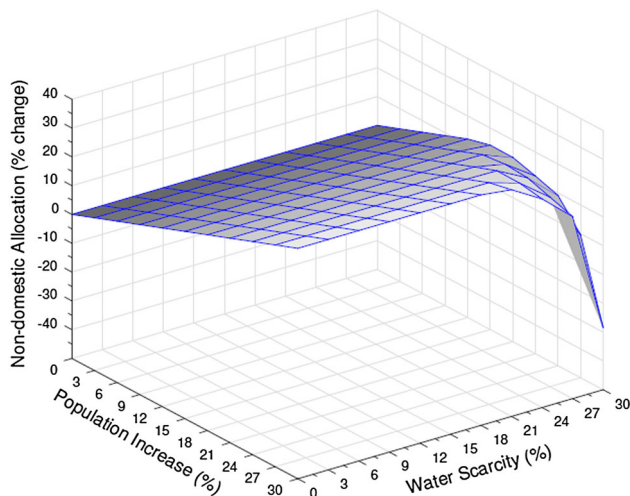


Fig. 6 Water allocated to non-domestic usage (% change)

The results are presented with the help of surface plots in Figs. 4, 5 and 6.

As mentioned earlier the sensitivity analyses are performed with respect to the FMA policy. The FMA policy allocates 200 lpcd to municipal consumption against a requirement of minimum 170 lpcd. An increase in the population by itself or decrease in the available water alone does not affect the water allocated for municipal use and it remains at 200 lpcd as seen in Fig. 4. However, when the population increases and water availability decreases simultaneously, the water allocated for municipal use decreases at high levels of population increase and water scarcity. At very high levels of water scarcity and population increase the municipal allocation decreases to the lower bound of 170 lpcd. The above analysis becomes very relevant due to the following reasons.

- The nine districts of Karnataka in the upper Cauvery river basin have had an average decadal (2001–2011) population growth of about 10.83% with the Bangalore Urban district recording a maximum growth rate 46.68% and the Kodagu district recording the least growth rate of 1.13%.⁴ In the next decade (2012–2022) it has been forecasted that the population of Karnataka will grow by about 17.7%.
- The average annual inflow into the KRS reservoir from Harangi, Hemavati and Lakshmanthirtha sub-basins has been measured to be about 4175 MCM with a standard deviation of 1629 MCM.⁵ The coefficient of variation is around 0.39 indicating that the chance of occurrence of hydrological scarcity may not be insignificant.

The above discussions indicate that population increase of about 15% and hydrological scarcity of around 15–20% are highly probable scenarios in the upper Cauvery river basin. The sensitivity analysis shows that in such scenarios the water allocation to municipal use tends to decrease. This also has an impact on the agriculture sector significantly. Figure 5 shows that the irrigated area (%) decreases from a peak of around 31%. This decrease can be attributed to the increased municipal needs. The reduction in agricultural satisfaction levels is continuous until it hits a trough corresponding to the contingency plan. This trough in the agricultural satisfaction is mirrored in the decrease in the per-capita water allocated for municipal consumption shown in Fig. 4. In this discussion, we have highlighted that in such scarce situation what should be the allocation

⁴ Source: Projected Population of Karnataka 2012–2021, Directorate of Economics and Statistics, Bangalore, 2013, page 8, <http://des.kar.nic.in/docs/Projected%20Population%202012-2021.pdf>. Accessed on 17/6/2015.

⁵ The estimates are based on the flow measurements made by Central Water Commission at KM Vadi, Kudige, and MH Halli measurement points that are up-stream to KRS over the period from 1980 to 2011.

pattern while keeping the pivotal discussion of basic water rights for individual and contingency for agriculture.

Since the industrial water use bound is represented as a percentage (10% for Mysore and Bangalore rest district has upper bound of 5%) of water allocated for municipal use (see Table 1, row labeled \leq), we see an increase (% change) in the water allocated for industrial use as the population increases (see Fig. 6). However, at high levels of scarcity (socio-economic and hydrological) the water allocated for industry drops significantly. This is due to the fact that both the municipal and agricultural water allocation has to meet their lower bounds (i.e., basic water rights) and the industry sector which does not have such a bound gets the least.

Conclusion

We have developed a non-linear optimization model to allocate water for inter-sectoral demand in the Cauvery river basin with the constraints of basic water right. Four different policy scenarios based on preferential sectoral demands are considered for analysis. In our results and analysis the FMA (Free Market Allocation) policy gives an allocative efficiency to the available surface water. Nevertheless, this optimization model does not compromise with the right to water for domestic and agricultural demands. It ensures a set quantity of basic water right to every individual and agriculture.

Also, we have observed that crop benefit is not a lone instrument that is sufficient to make agriculture a competitive sector. It is found that our model is giving an allocative efficiency (i.e., economic utility maximization) but to make agriculture sector more competitive it is needed to achieve an improved per drop output.

We have shown in the sensitivity analysis that a legislation can be enacted to ensure right to water in upper Cauvery river basin. The basic water right with a quantity of 170 lpcd can be ensured even in 50% drought situation. This drought can be caused either due to population increase or due to less than normal precipitation.

References

- Abdul S (2008) Water poverty in urban India: a study of major cities. UGC-summer programme, UGC-Academic Staff College, Jamia Millia Islamia, New Delhi
- Anon (Anonymous) (2011) 71-City water-excreta survey, 2005–06. Centre for Science and Environment, New Delhi
- Babel MS, Gupta AD, Nayak DK (2005) A model for optimal allocation of water to competing demands. *Water Resour Manag* 19(6):693–712
- Blanco-Gutierrez I, Varela-Ortega C, Purkey DR (2013) Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: a hydro-economic modeling approach. *J Environ Manag* 128:144–160
- Booker JF (1995) Hydrologic and economic impacts of drought under alternative policy responses. *Water Resour Bull* 31(5):889907
- Booker JF, Young RA (1994) Modeling intrastate and interstate markets for Colorado River water resources. *J Environ Econ Manag* 26:66–87
- BWSSB (2013) Bangalore water supply & sewerage board, Bangalore notification-I the Bangalore water supply (amendment) regulations, 2012
- BWSSB (2015). <http://www.bwssb.org/sites/default/files/bwssb-new-tariff.pdf>. Accessed 25 Dec 2014
- Chandrakanth MG (2009) Karnataka state water sector reform: current status, emerging issues and needed strategies. IWMI-Tata Water Policy Program, International Water Management Institute (IWMI)
- COIN-OR (2015). <https://projects.coin-or.org/Ipopt>. Accessed 8 June 2015
- CONTIN (2015) Contingency plan given by department of agriculture and cooperation ministry of agriculture, Government of India. <http://agricoop.nic.in/acp.html>. Accessed 25 Dec 2015
- Debnath D, Boyer T, Stoecker A, Sanders L (2015) Nonlinear reservoir optimization model with stochastic inflows: case study of lake tenkiller. *J Water Resour Plan Manag* 141(1): 04014046
- Diaz GE, Brown TC, Sveinsson OG (2000) Aquaris: a modeling system for river basin water allocation. Tech. rep., General Technical Report RM-GTR-299, US Department of Agriculture, Fort Collins, Colorado
- Divakar L, Babel MS, Perret SR, Gupta AD (2011) Optimal allocation of bulk water supplies to competing use sectors based on economic criterion—an application to the chao phraya river basin, thailand. *J Hydrol* 401(1–2):22–35
- GOI (2013a) The National Food Security Act. The Gazette of India, Government of India. September, 2013
- GOI (2013b) Annual report 2013. Center Water Commission, Ministry of Water Resource, Government of India
- GOI (2013c) Ground water year book, 2013. Ministry of Water Resource, Government of India, India
- GOI (2015a) Contingency plan published by Department of Agriculture and Cooperation. Ministry of Agriculture, Govt of India (2014). <http://agricoop.nic.in/agriculture-contingency-plan-listing>. Accessed 24 Apr 2017
- GOI (2015b) Government of India. <http://www.mdws.gov.in/NRDWP>. Accessed 28 May 2015
- GOI (2015c) Government of India. <http://www.censusindia.gov.in>. Accessed 28 May 2015
- Graveline N, Majone B, Van Duinen R, Ansink E (2014) Hydro-economic modeling of water scarcity under global change: an application to the gallego river basin (spain). *Reg Environ Change* 14(1):119–132. doi:10.1007/s10113-013-0472-0
- Griffin RC (2006) Water resource economics: the analysis of scarcity, policies, and projects. MIT Press, Cambridge
- Jain SK, Agarwal PK, Singh VP (2007) Hydrology and water resources of India, water science and technology library, vol 57. Springer, Netherlands
- Juan R, Jose R, Miguel A, Rafael L, Emilio C (2001a) Optimisation model for water allocation in deficit irrigation systems i. Description of the model. *Agric Water Manag* 48:103–116
- Juan R, Jose R, Miguel A, Rafael L, Emilio C (2001b) Optimisation model for water allocation in deficit irrigation systems ii. Application to the bembezar irrigation system. *Agric Water Manag* 48:117–132
- Julien JH, Manuel PV, David ER, Josue MA, Rld Jay, Richard EH (2009) Hydro-economic models: concepts, design, applications, and future prospects. *J Hydrol* 375:627–643

- Kirby M, Mainuddin M, Gao L, Connor J, Ahmad M (2012) Integrated, dynamic economic-hydrology model for the murray-darling basin. In: Fifty-sixth annual conference, Australian Agricultural & Resource Economics Society, Fremantle
- Kragt ME, Newham LTH, Bennett J, Jakeman AJ (2011) An integrated approach to linking economic valuation and catchment modelling. *Environ Model Softw* 26(1):92–102
- Letcher R, Croke B, Merritt W, Jakeman A (2006) An integrated modelling toolbox for water resources assessment and management in highland catchments: sensitivity analysis and testing. *Agric Syst* 89(1):132–164
- McKinney DC, Ximing C, Rosegrant MW, Claudia R, Christopher AS (1999) Modeling water resources management at the basin level: review and future directions. In: International Water Management Institute (IWMI). Colombo, Sri Lanka, p 59
- McKinney DC, Ximing C, Leon SL (1999) Integrated water resources management model for the Syr Darya Basin. Central Asia Mission, US Agency for International Development
- Natasha M (1996) Water and land in South Africa: economy wide impacts of reform a case study for the Olifants river. TMD discussion papers 12, International Food Policy Research Institute (IFPRI)
- Noel JE, Howitt RE (1982) Conjunctive multibasin management: an optimal control approach. *Water Resour Res* 18(4):753–763
- NWP (2012) National water policy. Ministry of Water Resources, Govt of India, New Delhi
- Peter H, Gleick M, IWRA (1996) Basic water requirements for human activities: meeting basic needs. *Water Int* 21:83–92
- Ringler C (2001) Optimal water allocation in the Mekong river basin. ZEF-Discussion Papers on Development Policy No 38, Center for Development Research, University of Bonn, Bonn, Germany, p 50
- Rosegrant MW, Ringler C, Mckinney DC, Cai X, Keller A, Donoso G (2000) Integrated economic hydrologic water modeling at the basin scale: the maipo river basin. *Agriculture* 24:33–46
- The Hindu (2015) A daily newspaper. <http://www.thehindu.com/news/cities/bangalore/private-water-suppliers-hit-pay-dirt-as-water-crisis-worsens/article2984302.ece> Accessed 25 Dec 2014
- Tilmant A, Kelman R (2007) A stochastic approach to analyze trade-offs and risks associated with large-scale water resources systems. *Water Resour Res* 43:W06425. doi:10.1029/2006WR005094
- Tilmant A, Pinte D, Goor Q (2008) Assessing marginal water values in multipurpose multireservoir systems via stochastic programming. *Water Resour Res* 44(12):1–17
- UNICEF (2004). <http://www.unicef.org/sowc04/>. Accessed 25 Dec 2015
- Vedula S, Nagesh Kumar D (1996) An integrated model for optimal reservoir operation for irrigation of multiple crops. *Water Resour Res* 32(4):1101–1108
- Ximing C, Mark WR, Claudia R (2003) Physical and economic efficiency of water use in the river basin: Implications for efficient water management. *Water Resour Res* 39:1013. doi:10.1029/2001WR000748