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DECISION MAKING FOR CONJUNCTIVE WATER USE PLANNING IN INTER-BASIN TRANSFER FRAMEWORK

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ABSTRACT *The Inter-Basin Water Transfer (IBWT) as conceived in inter-linking of rivers is aimed at promoting integration of water resources through a national water grid on the concept of surplus and deficit basins for economic prosperity as well as socio-economic development from the national viewpoint. The present study examines the role of decision making in various issues of IBWT, categorized under conceptual framework, environmental, social and conjunctive water use plans. The study reveals that the main crux of the inter-basin transfer does not lie in identifying the surplus and deficit basins, but in quantifying the amount by which these basins will have surplus or deficit water. The need of conjunctive use of surface water and groundwater in the IBWT is explored and emphasized, and models dealing with and without water quality restrictions/scenarios are presented and discussed. Intervention to the natural hydrologic system with the gigantic order is bound to give sizeable adverse implications, which may be hydrological, environmental, social, economic as well as operational on short-term as well as long-term basis, and thus there is a need to have a holistic approach to visualize the interlinkages of various components of hydrological regimes and their interactions with ecosystems so that potential adverse consequences can be diagnosed and evaluated accurately. Multicriterion approaches to deal with Multiobjective Decision Problems such as adhoc preference function programming, PORTRADE, ε-constraint, weighting and surrogate worth tradeoff methods are also discussed to deal with non-commensurate divergent outcomes resulting from various viewpoints of IBWT to yield meaningful, feasible, viable and implementable solutions that can help greatly in decision making of inter-basin water transfers. It enables in collating and analyzing tangible and intangible outputs obtained from various implications and conjunctive water use studies to address pertinent issues associated with the IBWT, to perform tradeoff analysis and to account for uncertainties associated with hydrological variables and vagueness associated with environmental and social objectives. The approach and models presented can provide an effective Decision Support System in chalking out best policies for the integrated development and management of water resources in the IBWT framework to fulfill the desired economic and social development objectives while ensuring the sustainability of surface water as well as groundwater resources and restricting the damages to ecosystem and hydrosystem below the acceptable threshold limits.*

Key words Decision making; conjunctive water use; optimization model; planning.

INTRODUCTION

The growing concern about availability of freshwater resources is raising many questions pertaining to not only the economic development of the nation, but also about the socio-economic development as well as the sustainability of human lives and biodiversity. A relentless pressure is mounting on water resources due to population growth, rapid urbanization, large-scale industrialization and environmental concerns, which in turn is posing many bottlenecks and herculean tasks for the planners, managers, engineers, scientists and decision makers of water resources almost everywhere, particularly in arid and semi-arid regions and specific areas of acute groundwater quality problems. The increased pressure is spilling over to the groundwater resources as well because of the hydrological uncertainty, growing groundwater contamination problems, excessive and unscientific groundwater mining and shrinking freshwater resources. As a result, availability of per capita freshwater resources is worsening day by day.

Because of uneven distribution of water resources in space (between regions, states, or nations) and time (between years and between seasons within a year), attempts have been made to distribute freshwater resources as evenly as possible in many parts of the world by engineering interventions. The Indian programme for linking of rivers and transferring huge volumes of water from one basin to other basin is also a step in this direction, although order of the magnitude in this case is gigantic. The interlinking project dealing with linking of national rivers is based on the National Perspective Plan for water resources development prepared by the Ministry of Water Resources in 1980. It comprises two main components, namely, the Himalayan rivers development and the Peninsular rivers development (Fig. 1). The Himalayan rivers development is based on multipurpose storages giving benefits of hydropower and flood control besides diverting water to downstream links and to provide necessary discharge for augmentation of flows to enhance inland navigation. It could provide additional irrigation of about 22 million hectare and generation of about 30 million KW of hydropower (MOWR, 2003) besides providing substantial flood control in the Ganga and Brahmaputra basins. The Peninsular rivers development is expected to provide additional irrigation of about 13 million hectare and about 4 million KW of hydropower (MOWR, 2003).

After the order of the Supreme Court in year 2002 to complete this gigantic interlinking project within the next 12 years, the professionals interested in sustainable development of water resources in India woke up to examine the techno-economic feasibility and practical viability of this project, which is perceived as the largest construction project in the world, the order of the cost being almost the same as that of the annual GDP. However, no sound and detailed scientific studies (except Ken-Betwa link study) have been carried out for any of the proposed 30 links (14 Himalayan river links and 16 Peninnsular river links). A number of issues, pros and cons, pertaining to the interlinking of rivers were reported by various researchers and professionals at different platforms (Bandyopadhyay and Shama, 2002; Singh, 2002; Chander, 2003; Keshari, 2004; Subramanian, 2004). The detailed scientific analysis encompasses a wide spectrum of expertise and even if the analysis is conducted, its outcome may be quite divergent with some intangible components. Deriving meaningful convergent conclusions from such analysis for the decision makers, involved in planning, implementing and managing these interlinking projects, may become a very tough challenging task as the outcomes obtained from such exercises may be far from the desirable outcomes with reference to the implementation point of view and in turn may prove futile exercises. The present paper discusses the viewpoint that how such non-commensurate divergent outcomes from various detailed scientific studies could be combined to yield meaningful, feasible, viable and implementable solutions that can help greatly in decision making of Inter-Basin Water Transfer (IBWT). Further, the study reported here emphasizes the need for appropriately accounting groundwater resources in inter-basin water transfer framework, and presents how decision making can play a significant role in drafting conjunctive water use plans for IBWT while maintaining other considerations or restrictions within desirable limits and addressing many hydrological, environmental, social and economic issues appropriately.

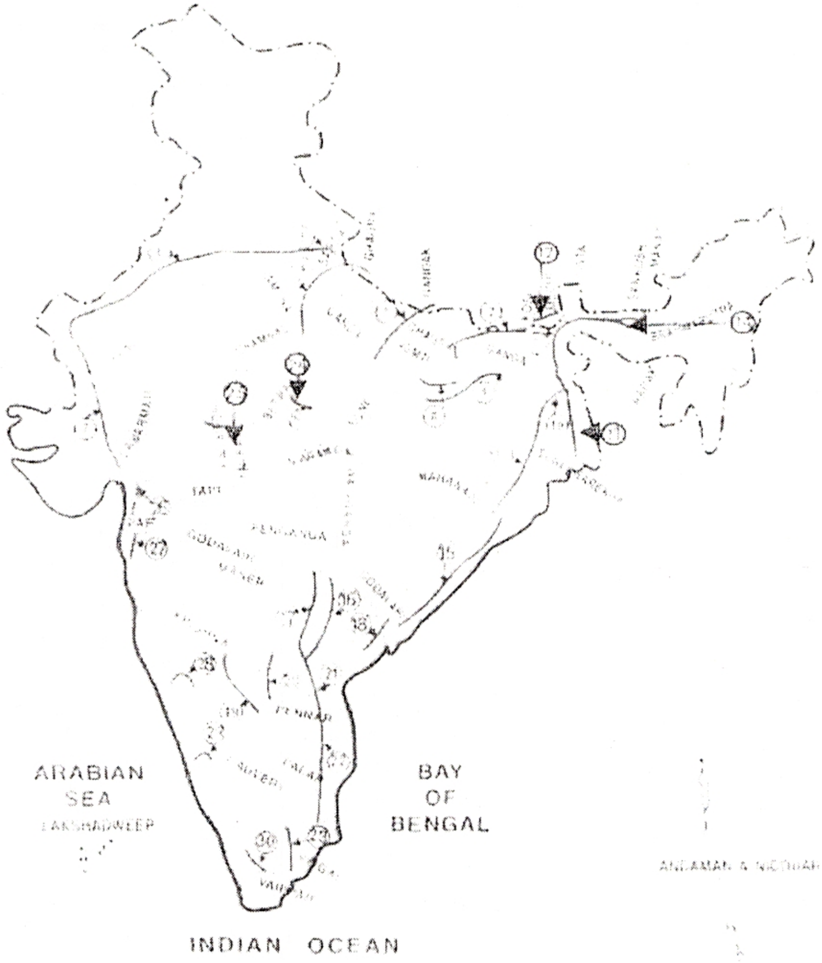

Fig. 1 Proposed interlinking of rivers in India.

DECISION MAKING IN INTER-BASIN WATER TRANSFERS

The announcement of plans by the Indian Government for the Interlinking of Rivers (ILR) has caught the attention of experts from a wide spectrum of fields encompassing engineers, hydrologists, environmentalists, hydrogeologists, ecologists, sociologists, economists, and legal experts. Human societies have always intervened in the natural system in many ways for their economic development.

However, taking cognizance of the size of this engineered intervention allowing diversion of huge amounts of water from one stream or basin to other stream or basin, its potential implications as conceived or perceived by the professionals, activists and society has intensified the debate amongst the scientific, public and decision making communities on the pros and cons of the program. The various dimensions of IBWT which may result into non-commensurate and divergent outcomes for water transfer are described in following sections.

Conceptual Framework

The idea of linking of major rivers of India was mooted long back by K.L. Rao, the legendary irrigation minister of India (Rao, 1975), and later on many such links were conceived, for example, the Ganga-Cauvery Link Canal, the Garland Canals, etc. Rao's ideas were based on the identification of surplus and deficit river basins and solving the water scarcity problem by connecting these through a national water grid. Although, the National Commission for Integrated Water Resource Development Plan (NCIWRDP) examined the then identified proposals but found them not worthy of taking up (NCIWRDP, 1999a, b). The recent revival of the idea of interlinking of surplus basins with deficit basins is the result of work done by the National Water Development Agency (NWDA) on the lines of Rao's proposal (MOWR, 2003). If we analyze the concept behind the ILR from engineering/ technological point of view on a holistic and national basis, it appears to be well proven and scientifically sound. Although the two earlier proposals, Ganga-Cauvery Link Canal and Garland Canals as conceived by Rao and Dastur were not found worthy by the Central Water Commission (CWC) to be followed (MOWR, 2002), but these observations are not strictly true in the present scenario and certainly not for all the links (30 links) as proposed now. The ILR is aimed at promoting integration of water resources for economic prosperity as well as socio-economic development from the national viewpoint. The idea of drawing water from the eastern Indian rivers having larger runoff and potential to cause large flood damages is certainly not a bad idea, and it is equally important to feed the surplus water to the enormously deficient areas such as Rajasthan, Gujarat, Jharkhand and some parts of Penninsular areas where drought and drinking water availability are the real bottlenecks. The whole concept is indeed worth considering.

There have been notable exemplary projects abroad as well as in India for transferring water from one basin to another basin. The developed countries such as USA and Canada are already having inter-basin transfers for more than 30 schemes. Seven such schemes already exist in India. The currently existing IBWT schemes in India includes transfer of water from the west flowing Periyar to Vaigi, the Perabikulam-Aliyar link, the Beas-Sutlej link, the Koyana Stage I transferring water from the easterly flowing Koyana to the westerly flowing Baitarani. The links between five tributaries of Indus have brought agricultural revolution in India as well as Pakistan. Transferring surplus water from Ravi-Beas system to Rajasthan through Indira Gandhi Nahar Pariyojna is another spectacular example of the ILR in recent times, although this has resulted into many undesirable adverse consequences such as water logging and salinity problems.

If the ILR concept in water sector is perceived on the lines of national grid network in energy/power sector, undoubtedly one will appreciate the vast potential benefits of such programs especially looking from the national or regional perspectives of deficit and surplus areas for the concerned sector and their potentiality of hindrance in economic development or damages resulting from hydrological extremes. This concept indeed has emerged as an important strategy in the overall scenario of development of water resources in the country. However, ILR also has the potential to significantly affect the ecosystem and hydrosystem, and may prove fatal for sustaining life if pertinent issues are not addressed appropriately while designing and scaling the ILR for water transfers. More importantly, there is need to identify and examine potential consequences of the ILR on all fronts, hydrological, geohydrological, environmental, social, landscapes, biodiversity, economic and financial, related to such projects and possible tradeoffs with the current practices and methodologies for each of the proposed link utilizing appropriate and advanced technologies in a multidisciplinary framework. Unfortunately only a simple water balance and thumb rule approach has been utilized while conceiving various links of the ILR project and the engineering design is mooted to take off for the implementation.

Defining Surplus and Deficit Basins

It is well known that India is a vast country with its geographical area of 329 million hectare and having large inequities of distribution of water resources in space and time. Some areas receive supplies in excess of the genuine requirement and economic development of the population they support and on the other hand some are facing acute water shortage problem even for drinking purposes of its people. Drought and flood are the two opposite extremes affecting different parts of the country simultaneously. With such inequities in distribution of water resources in space and time, agriculture which is the backbone of the national development is badly affected due to lack of irrigation infrastructure/water availability, and in turn the regional goal of poverty alleviation for the rural population is affected. The annual precipitation including snowfall in India is about 4,000 km^3 and average potential flow in rivers is about 1,869 km^3 while the rest is lost as evaporation, escapes into sea during the floods and partly contributes to groundwater reservoirs following the complex hydrological cycle. To examine the spatial disparity in the distribution of water resources, surface water potentials of some of the important river basins are analyzed and shown in Fig. 2. The per capita annual water availability in these basins based on the 2001 census is shown in Fig. 3. It is evident from these figures that there are large inequities in both average annual surface water potential and per capita annual water availability among various river basins, and there is certainly a need to have some introspection to tackle such disparity in the interest of national development.

The main crux of the interbasin transfer does not lie in identifying the surplus and deficit basins, but in quantifying the amount by which these basins will have surplus or deficit water. This is the point where all bottlenecks are bound to appear whenever any link comes into operation. It will be a herculean task to resolve the differences as is happening currently in most of the projects in delivering the allocated water (Cauvery water dispute – dispute between Karnataka and Tamil Nadu; release of Ganga water at Farakka – dispute between India and Bangladesh; Ganga water release for Delhi – dispute between Delhi and Uttar Pradesh; Yamuna water release – dispute between Delhi and Haryana; dispute between Punjab and Rajasthan on the release of water, etc.), even when such links are located in only one river basin.

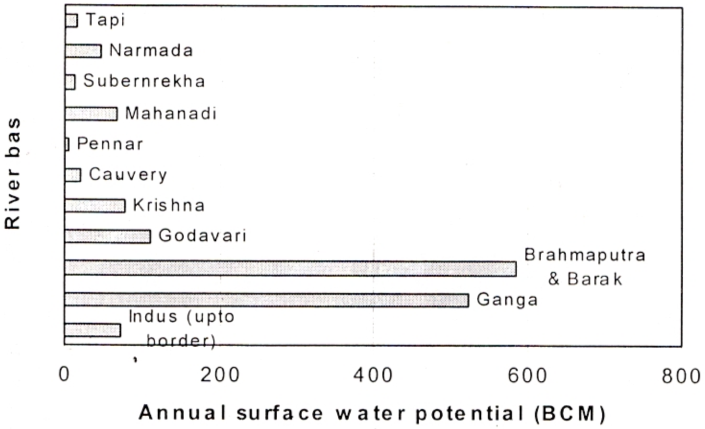

Fig. 2 Annual surface water potential in river basins of India.

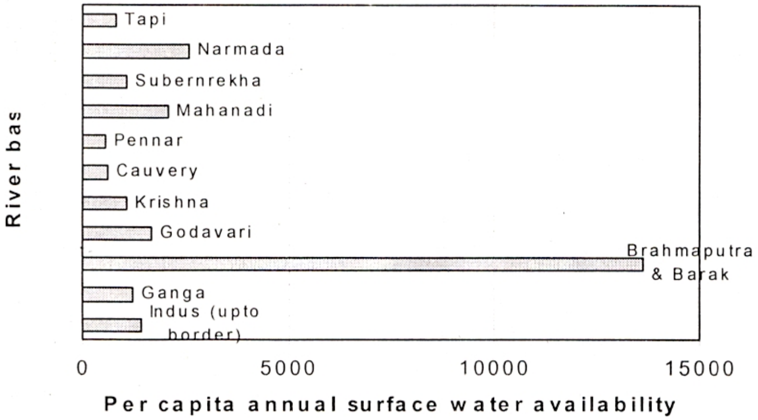

Fig. 3 Annual surface water availability per capita in river basins of India.

It is unfortunate that no sincere thinking has been put into defining and quantifying surplus and deficit waters, and the problem of surplus and deficit, groundwater resources have been totally ignored. Furthermore, surplus and deficit quantity of surface water varies from one basin to another basin, and is managed appropriately by employing river basin planning concept. Taking cognizance of importance of groundwater, as more than 50% of water requirements for irrigation, urban domestic and industrial sectors are met from this resource, conjunctive use of surface water and groundwater is being emphasized by various researchers and professionals. This aspect needs greater attention while quantifying the availability of surplus water in a basin, and its distribution in space and time is more desirable to the scientific and professional community rather than merely the gross annual figures. The methodology utilized to work out the surplus or deficit water is equally important as the planners or professionals may arrive at different figures because of involved uncertainties in various hydrological components and inaccuracies in estimation or modeling various components. This necessitates drafting a standardized procedure with the participation of academicians, researchers, professionals, planners, activists and decision makers as it involves many gray areas where the working procedure may vary depending upon an individual's viewpoint.

The accurate estimation or projection of water demand (requirement) is another dimension which plays a significant role in surplus or deficit estimation. It involves lots of uncertainty, vagueness and political interferences, particularly irrigation requirement which is the biggest consumer of water, amounting to about 85% of current water use. The projected future water demands (MOWR, 2003) for various sectors are shown in Fig. 4. It is evident from this figure that total demand of water for various uses will become, respectively, 813 km^3, 1093 km^3 and 1447 km^3 by 2010, 2025 and 2050. It is to be noted here that the total currently available utilizable water is 1122 km^3, and thus there will be a big gap between the availability and the requirement of water by 2050 unless there is significant climatic and landscape changes increasing the freshwater availability. However, the basin wise rather than national gross mismatch between availability and requirement and its seasonal/temporal breakdown for each of the link will be more useful and can provide more insight into surplus and deficit basins and in turn the justifiability or scale of inter-basin water transfers.

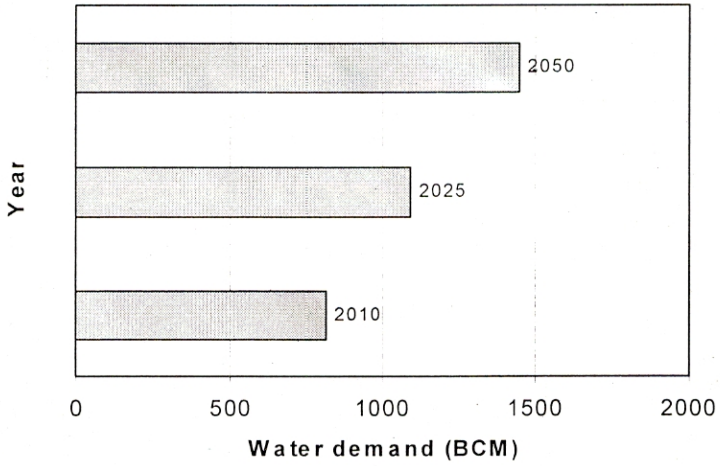

Fig. 4 Total futuristic national water demand in India.

Environmental Impact Assessment

IBWT involves construction of storage reservoirs, large canals and many other civil engineering structures that may result in adverse environmental impacts. A comprehensive environmental impact assessment must ensure sustainability of environmental quality in the donor and the recipient basins as well as the riparian ecosystem. This is desirable to recognize and assess the diverse ecosystem services performed by water in all parts of the river basin, from the moment it precipitates to the time it drains out into the sea. It will be a meaningless and destructive approach (Bandyopadhyay and Shama, 2002; Anwar, 2004; Israili and Saxena, 2004; Rudra, 2004; Sharma, 2004; Thakkar, 2004) to say that civil engineering or water resource engineering sees water purely from the point of storage, transfer and allocation for supplies, and is unable to recognize that every drop performs some ecological service all the time in river basins and from a holistic perspective one does not see any surplus water. More surprisingly, conclusive statements (Israili and Saxena, 2004; Rudra, 2004; Sharma, 2004; Thakkar, 2004) are made without any scientific evidences, just based on philosophical thoughts. In fact, all water resources projects whether small, medium or large, involve comprehensive environmental impacts assessment and water resources engineers take into account these as well as impacts of many others such as social, economic and financial aspects, while carrying out the project feasibility (WAPCOS, 1999; Keshari, 2001a,b,c; Khanna, 2004; Keshari, 2005). It is merely the role of decision makers and implementing agencies how they take these issues over or within the engineering and political framework of the project.

Any intervention in the natural system is bound to give some adverse implications, environmental in particular. It is the question of tradeoff between the possible damages and possible benefits taking cognizance of current and future scenario and how much is acceptable to the society or desirable from the national perspectives in the larger interest. The surprising point is that lots of literature and debate is there on environmental or ecological damages, but these fail to identify explicitly the losses, with and without the project, and the procedure to quantify them. There is nothing in the world which does not damage the environment, and if we go by this rule, we may go to the 'palaeolithic age'. If we take a simple example of Delhi water supply or power, the survival of the people will be questionable if water or power is not released or transmitted from neighbouring states, as there is no surface water of its own available for water supply except groundwater which is already declining and is becoming a major concern, and in the absence of its own source of hydropower, it is needless to say here about the environmental damages from depending mainly on thermal power. Without the quantification, decision becomes more subjective and the role of environmentalists or ecologists become more destructive rather than constructive in the decision making, and many times such deficient information is used in manipulating the tradeoffs to achieve mileage because of invested interests. Thus, there is need to have a holistic approach to visualize the interlinkages of various components of hydrological regimes and their interactions to ecosystems so that potential adverse consequences can be diagnosed and evaluated accurately.

Social Implications

The detailed appraisals of human, social, equity, gender and socio-economic aspects also need to be addressed scientifically while IBWT projects are conceptualized and designed, as these aspects involve many intangible values and are significantly influenced by the decision making policies. Many projects are already witnessing many rehabilitation and compensation problems (Patekar, 2004; Thakkar, 2004) which are becoming hurdles not only in the success of the project, but also the livelihood of the affected society. The spatial and temporal variations in the precipitation over India often lead to human sufferings through scarcity of drinking water, inundation of agricultural lands and human habitats, failure of crops and economic development. There is no doubt that satisfying the domestic water needs should be seen as a basic human right and should receive the highest priority in our water policy. Further, protection of rain fed farm lands from variations in the climate, long spells of droughts in particular, should be equally important and deserve to get high priority in India's water policy. The IBWT may play crucial role in solving human sufferings from floods, droughts, and water scarcity. Also food security and socio-economic assessment may indicate conclusively that both the basins may be ready to bear the disruptions, discomfort and losses that may accrue in order to achieve the larger benefits and goals in the long term and broader national perspectives.

CONJUNCTIVE WATER USE PLANNING

In view of the large investment required for IBWT and its various pros and cons as discussed above, it is imperative that groundwater must be accounted for while quantifying the water availability in the basin and conjunctive water use practices must be sincerely considered while arriving at the surplus and deficit quantities of water for the donor and the recipient basins in order to reduce the load on supply and thereby reducing the scale of IBWT, which in turn will cause less damages to eco- and hydro-systems and social problems. While planning for the conjunctive use of surface and ground water, optimal water allocation, optimal blending of canal and groundwater in case of utilization of poor quality groundwater under water deficit scenario, efficient distribution and application, evolution of proper cropping patterns for different agroclimatic regions ensuring environmental sustainability, economic viability and social acceptability are the key issues to be addressed within the decision framework of IBWT. Reuse and recycling, rain water harvesting and artificial groundwater recharge are other important measures to be considered within conjunctive water use plans.

Some of the conjunctive water use models and studies are presented in following subsections under two different cases: (i) when there are no groundwater quality constraints, and (ii) when there is scarcity of canal water so that utilization of poor quality groundwater is necessary. Use of multiobjective optimization techniques in conflicting scenario of conjunctive water use of surface water and groundwater is presented in the next section under multicriterion approach.

Without Groundwater Quality Constraints

The management models dealing with the conjunctive use of groundwater and surface water can be conceptualized as resource allocation models of the water resources system. These types of models optimally distribute the water resources of a river basin to competing water demands or water uses over a planning or design horizon. By controlling the total water resources of a region, conjunctive water use planning can increase the efficiency, reliability and cost-effectiveness of water use, particularly in river basins with spatial or temporal imbalances in water demands and natural supplies. It is often observed that regions of high rainfall and runoff rarely coincide with those of extensive water development and water demand, while periods of lowest stream flow and recharge usually coincide with the largest demand, or vice versa. Conjunctive water management can reduce these deficiencies by using groundwater to supplement scarce surface water supplies during the water deficit seasons. During periods of medium or high runoff, surface water can then be used to satisfy the water demands and to recharge the groundwater systems in spreading basins, abandoned stream channels and wells. In hydraulically coupled stream-aquifer systems, which generally occur in alluvial formations, conjunctive water use can also affect the magnitude and timing of irrigation return flows and capture intended for downstream water use.

The conjunctive use planning or operational problem can be formulated as an optimization model of the water resources system. The decision or control variables of the model are the groundwater and surface water allocations in each planning period. The optimal decisions maximize the objectives of the water resource system while satisfying the hydraulic response equations of the surface and groundwater systems, and any constraints limiting the head variations and the surface water availability. Conceptualization of such conjunctive water use optimization model is shown in Fig. 5, in which it is assumed that the water resources system consists of m groundwater sources ($i = 1, \ldots m$), n surface water supplies ($j = 1, \ldots n$), and l water demands ($k = 1, \ldots l$).

The objective function of the planning model can be formulated assuming that the water demands in a basin are known or can be inferred from market information. The appropriate economic benefit resulting from the allocation of groundwater and surface water is the sum of the consumer surplus and the revenue generated through the sale of the water. Equivalently, the benefit function is the willingness to pay for the resource or the area beneath the demand functions for each water user. Defining GW^t_{jk} as the groundwater allocated from groundwater basin j to demand k, SW^t_{ik} as the surface water from source i used to satisfy demand k in period t, $p_k(Q^t_k)$ is the demand function for each water use, the economic benefit function for any time period can be expressed as (Willis and Yeh, 1987):

$$\sum_k \int_0^{Q^t_k} p_k(Q^t_k)\, dQ \qquad (1)$$

where Q^t_k is total water allocation for demand k in period t, and can be expressed as:

$$Q^t_k = \sum_j GW^t_{jk} + \sum_i SW^t_{ik} \tag{2}$$

The capital, operation and maintenance costs for any time period of demand are functions of the groundwater and surface water allocations, and can be expressed as:

$$\sum_k \sum_j f^t_{jk}(GW^t_{jk}) + \sum_k \sum_i f^t_{ik}(SW^t_{ik}) + \sum_i \sum_j f^t_{ji}(SWR^t_{ji}) \tag{3}$$

where f_{jk}^t , f_{ik}^t and f_{ji}^t are the costs associated with allocating groundwater from basin i to demand k, surface water from source j to demand k, surface water for the artificial recharge of basin i and SWR^t_{ji} is the volume of water for artificial recharge in basin i from source j in period t.

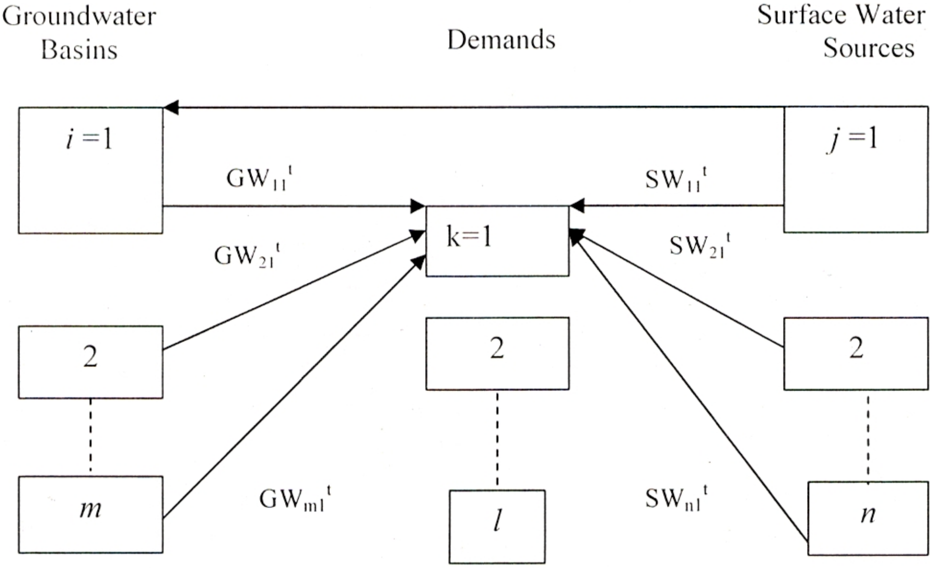

Fig. 5 Conjunctive water use model.

The groundwater and surface water allocations are constrained within any planning period by the hydraulic response equations, balance equations for pumping and recharge, and possible limitations on surface water availability and head variations in each groundwater system. The groundwater recharge constraints prescribe that the recharge target for each groundwater system is satisfied for any planning period. The institutional restrictions for river management and administration also should be given due consideration in conjunctive water use planning (Fredericks *et al.*, 1998) as water exchanges or transfer may be intervened by water rights regulations, especially when stream-aquifer is hydraulically connected.

The conjunctive water use model as discussed above can be appropriately utilized in accurately quantifying the surplus or deficit water in a basin, which can play a significant role in appropriately sizing the inter-basin water transfer. The surface water alone should not be seen as the basis for the IBWT. Groundwater potentials of basins also need to be considered, and even Inter-Basin Groundwater Transfer (IBGT) which naturally occurs beneath watershed topographic divides has a significant influence on surface water quantity and quality, although such studies, for example, studies in the lowland rainforest watersheds at La Selva Biological Station in Costa Rica, are currently rare. The availability of groundwater resources in some of the important Indian basins are shown in Fig. 6. To illustrate the role of conjunctive water use models in estimating surplus or deficit, availability of surface water and groundwater in the Saurashtra region by the year 2010 is shown in Fig. 7. The paradigm of shift of groundwater contribution to irrigation as compared to surface water irrigation is shown in Fig. 8 (IWMI, 2003). Nearly 85% of the currently exploited groundwater is being used for irrigation.

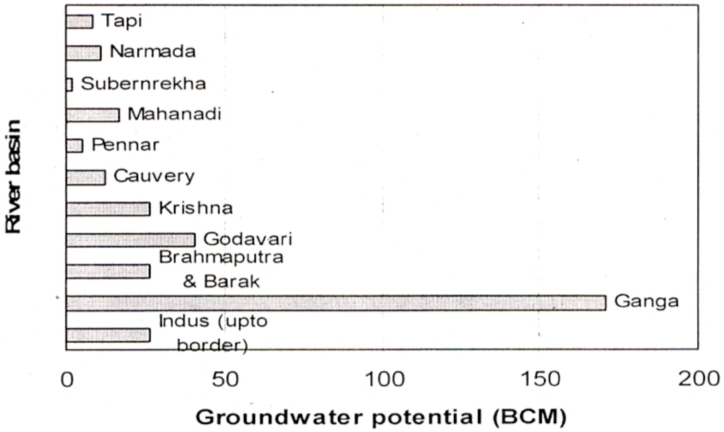

Fig. 6 Groundwater potential in rivers basins of India.

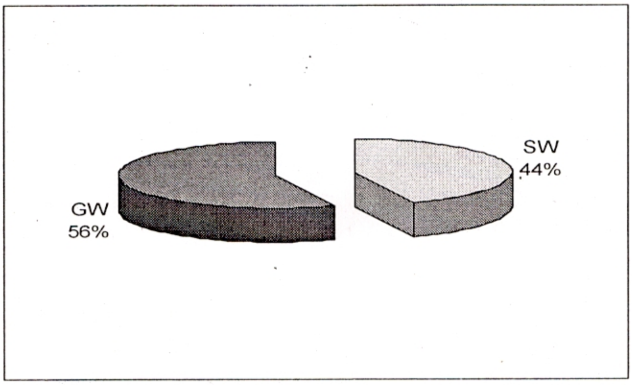

Fig. 7 Surface water (SW) and groundwater (GW) availability in Saurashtra region by year 2010.

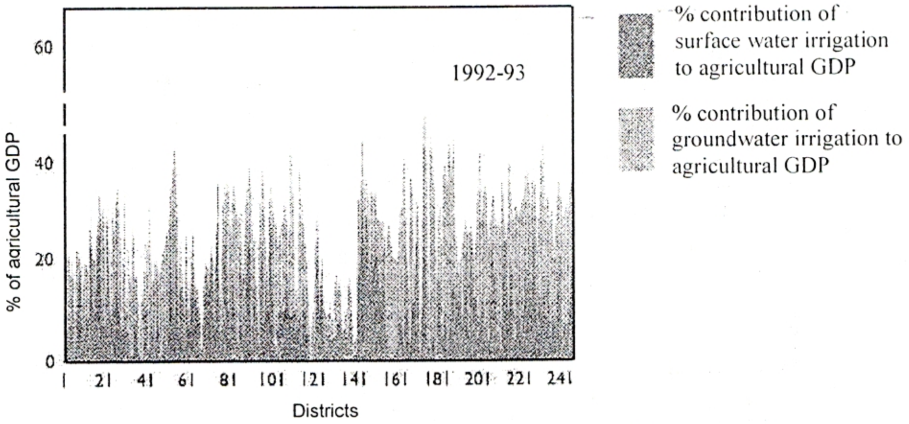

Fig. 8 Comparison of surface water and groundwater irrigation in India.

With Groundwater Quality Constraints

Groundwater quality surveys have indicated that in arid and semi-arid regions of India, use of poor quality waters is in range of 32-84% of the total irrigation by groundwater (Kaledhonkar and Keshari, 2005a). In such brackish water areas, an average extent of saline, sodic and saline-sodic waters are approximately 20, 37 and 43%, respectively (Yadav and Kumar, 1995). The study conducted by Kaledhonkar and Keshari (2005a,b) for regional scale distributed modeling to understand irrigation induced salinisation processes in the command of Kheri distributory of Bhakra system brought out the guidelines and changes required in the current policies for the sustainability of the prevailing conjunctive water use policy of utilizing poor quality groundwater along with canal water. Irrigation water salinity may affect the wheat cultivation in the Kheri command, and growing of cotton crop in the command can be more economical than the wheat crop as cotton is not affected by irrigation water quality.

The effect of conjunctive water use on the root zone salinity was investigated and is shown in Fig. 9 for the two cases where canal water and poor quality groundwater is used as an alternate or mixed in 1:1 ratio, for irrigating the crop. It is evident from this figure that wheat crop in Sirhan, Kirhan, Khabra Kalan areas may preferably be grown with canal water or mixed water to keep the salinity below 4.0 dS/m, as root zone salinity for wheat and cotton harvest should not exceed threshold salinity values of 4.0 and 7.7 dS/m, respectively. The conjunctive use planning can be more successful under multi-cropping pattern as compared to mono cropping in the irrigation command.

MULTICRITERION APPROACH

A number of issues as discussed earlier emerge from various viewpoints, namely, hydrological, environmental, social, economic as well as operational on short-term as well as long-term basis for the IBWT. Such water transfers are bound

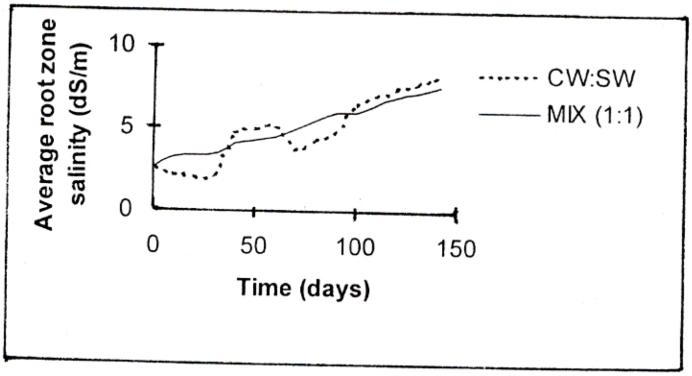

Fig. 9 Effect of conjunctive water use on root zone salinity.

to give significant intangible losses too, and thus it may not be proper to make the decisions on the basis of quantified benefits in terms of irrigation, hydropower, water supply and navigation alone. Defining surplus water, water transfer allocation, pollution spreading, implications on groundwater resources, stream-aquifer exchanges in terms of both quantity and quality, hydrological imbalances in a watershed, sediment transfer, morphological changes, channel processes dynamics, impact on floras and fauna, submergence, water riparian rights, socio-economic consequences such as rehabilitation, economic redistribution and inter-state disputes are going to be major issues that need to be addressed appropriately in a scientific manner to come out with actual figures that can be taken up during the decision making.

The donor basins may apprehend that large scale diversions may cause significant reduction in their non-monsoon flows and their demands may not be met at critical times. Considering the spatial and temporal variability of hydrological components, it is imperative to examine whether the donor basin experiences high flows when the recipient basin experiences drought; the future development of the donor basin is significantly constrained by the inter-basin water transfer; the recipient basin faces a substantial deficit in meeting present and projected future demand; the magnitude of surplus (in donor basin) and deficit (in recipient basin); and scale of inter-basin water transfer ensuring acceptability of environmental and socio-economic adverse consequences in both the donor and the recipient basins. Some IBWT schemes may have international dimension, and thus water sharing conflicts will spill not only over the states but also over the nations.

Many objectives/outputs of various analyses may be conflicting and non-commensurate, and thus combining outcomes of these analyses necessitate a multicriterion approach. It helps in collating and analyzing tangible and intangible outputs obtained from various implications and scenarios associated with the IBWT. It also enables to perform tradeoff analysis and to account uncertainties associated with hydrological variables and vagueness associated with environmental and social objectives while obtaining the best compromise optimal solution. Such analysis can help in assessing the long-term consequences and can provide an effective Decision

Support System (DSS) in chalking out best policies for the integrated development and management of water resources in donor and recipient basins to fulfill the desired objectives while restricting the damages to ecosystem and hydrosystem below the acceptable threshold limits and ensuring the sustainability of water resources.

There are many methods that can be utilized to deal with Multicriterion or Multiobjective Decision Problems (MDP) to combine different commensurate and non-commensurate outcomes. Some notable approaches are adhoc preference function programming, PORTRADE, ε-constraint, weighting and surrogate worth tradeoff methods (Chankong and Haimes, 1983; Keshari and Datta, 1996; Keshari, 2000). An adhoc preference function programming method is based on the global preference and combines adhoc direct assessment of value of utility functions with appropriate search procedures. One assesses the value function $v(f_1,\ldots,f_n)$ by questioning the decision maker and subsequently translating the MDP into a surrogate MDP as described below for deterministic (Eqs. (4)-(5)) and stochastic or uncertain (Eqs. (6)-(7)) cases:

$$\text{Max. } v(f_1(x),\ldots,f_n(x)) \tag{4}$$

$$\text{subject to } x \in X \tag{5}$$

$$\text{Max. } E[u(\mathrm{f}_1(x),\ldots,f_n(x))] \tag{6}$$

$$\text{subject to } x \in X \tag{7}$$

Application of this method requires a decision maker with responsibility for maximizing a value function or expected utility. Otherwise a different decision rule should be employed in the formulation of multiobjective problem. After transforming the multiobjective decision problem into a surrogate MDP, the task of finding the best compromise solution involves applying suitable scalar optimization techniques depending on whether the problem is deterministic or probabilistic.

If the value function or utility function does represent the true preference structure of the decision maker, then the best compromise solution, according to the value function or expected utility maximizing rule, need not be noninferior. This situation arises when $v(.)$ or $u(.)$ is not monotonic. For example, when $v(.)$ is unimodal on the set of alternative X, we may have two feasible alternatives x^1 and x^2 such that $f(x^1) \geq f(x^2)$ and $v(f(x^1)) > v(f(x^2))$. Hence, x^2 dominates x^1 (in minimization problems) and yet x^1 is preferred to x^2 since the value function x^1 is greater then that at x^2. This is explained clearly in Fig. 10 for the two-dimensional case. If the value function is monotonic (increasing or decreasing), in the feasible region X, noninferiority can and should be a necessary property of the best compromise solution.

The PORTRADE method uses complete knowledge of the preference structure under uncertainty in the form of the assessed utility function. It also uses information concerning tradeoffs between the levels of attainment of objectives and the probabilities of attaining those levels. Here, tradeoffs between risk levels and goal attainment levels are used rather than among objective function. The ε-constraint method where tradeoffs among objectives are used is employed by

Keshari and Datta (1996) for determining optimal well locations and pumping rates in the conjunctive water use allocation and Keshari (2000) to determine the level of aquifer restoration for the utilization of poor quality water in conjunctive water use plan for irrigation. The level of aquifer restoration for conjunctive water use in case of salinity problem as obtained from bicriterion optimization model utilizing the ε-constraint along with the surrogate worth tradeoff method is shown in Fig. 11.

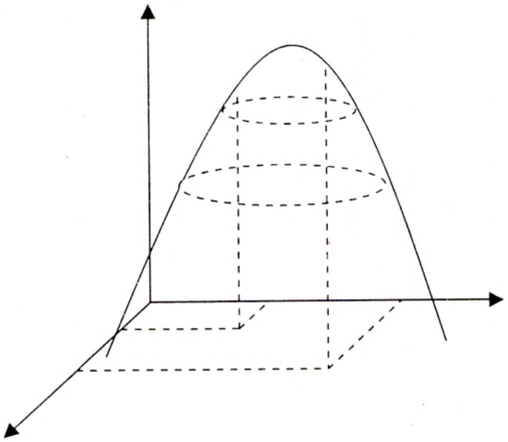

Fig. 10 Example showing in which non-inferiority may not be necessary.

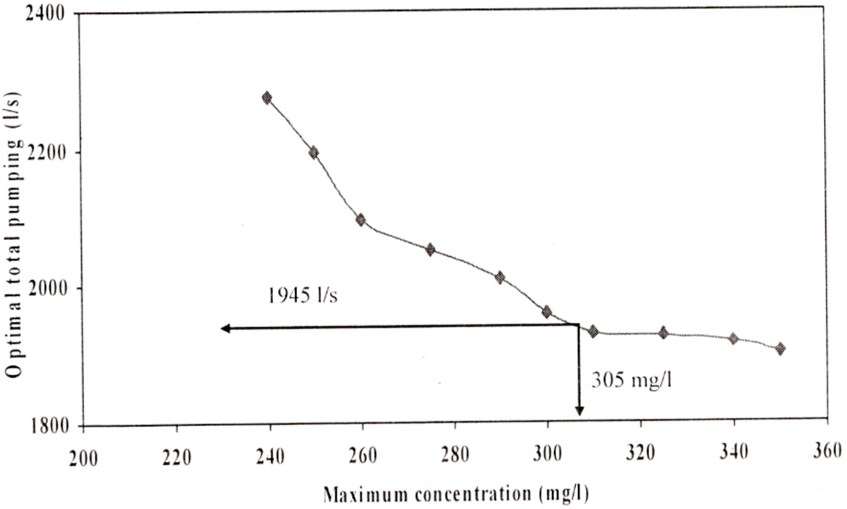

Fig. 11 Determining level of aquifer restoration for conjunctive water use of surface water and saline groundwater for irrigation.

CONCLUSIONS

The role of decision making in IBWT has been examined under conceptual framework, environmental, social and conjunctive water use plans. The study reveals that the main crux of the inter-basin transfer lies in quantifying the amount by which the basins will have surplus or deficit of water. The need of conjunctive use of surface water and groundwater in IBWT has been explored. Models dealing with and without water quality restrictions/scenarios are presented and discussed. It is observed that alternate use of canal and poor quality groundwater for irrigation can be appropriate conjunctive water use plan in arid and semi-arid areas where water scarcity and the root zone salinity are major concerns. The conjunctive water use planning can be more successful under multi-cropping pattern as compared to mono cropping in the irrigation command. Intervention on a gigantic order to the natural hydrologic system is bound to give sizeable adverse implications, which may be hydrological, environmental, social, economic as well as operational on short-term as well as long-term basis, necessitating a holistic approach to visualize the interlinkages of various components of hydrological regimes and their interactions to ecosystems. Multicriterion approaches, adhoc preference function programming, PORTRADE, ε-constraint, weighting and surrogate worth tradeoff methods have been discussed to deal with Multiobjective Decision Problems of IBWT which may have non-commensurate divergent outcomes to yield meaningful, feasible, viable and implementable solutions. Solution of bicriterion optimization model utilizing the ε-constraint along with the surrogate worth tradeoff method has been discussed in determining the level of aquifer restoration for conjunctive water use in case of salinity problem. The approach and models presented can provide an effective Decision Support System in chalking out the best acceptable policies for the integrated development and management of water resources in the IBWT framework.

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