SYSTEMS TECHNIQUES FOR PLANNING INTER-BASIN WATER TRANSFERS

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ABSTRACT *This paper presents a broad overview of systems techniques that may be used in the study of inter-basin water transfer. A simulation-optimization model, a dynamic programming model and a reservoir analysis model used for decision making in inter-basin water transfer are discussed in brief. Recent developments in the fuzzy systems theory that may be used in conflict resolution in large scale water transfer are discussed. Limitations of the techniques in addressing uncertainties and complex interactions among the components are discussed and directions for future work are identified.*

Key words Systems techniques; optimization models; conflict resolution; fuzzy systems theory.

INTRODUCTION

The term 'water transfer' refers to transport of water through engineering structures, usually across river basins for some beneficial purposes. Inter-basin water transfer (IBWT) is one of the possible solutions of water deficiency and is somewhat similar to other alternatives, such as dams, desalination, groundwater extraction etc. (Jain and Singh, 2003a). It involves transportation of surplus water from a basin to another basin which is deficient in water. The impact of inter-basin water transfer is multidisciplinary and controversial, considering social, ecological, hydrological, political and economical issues. Controversies in transfer result from losses and damages in the basin of origin. It may be safely claimed that no other water resources subject has created greater problems or more difficult controversies in water resources planning in modern times than the transfer of water from one river basin to another (Yevjevich, 2001). Planning for IBWT should include the benefits and losses of donor and recipient basins, hydrological aspects, environmental and ecological risks, economical, political, and social issues, which necessitate the use of systems techniques for decision analysis.

In this paper, a broad overview of the systems techniques is provided, with a more detailed discussion on some models that have been developed specifically for proposed interlinking of rivers in India. Potential use of the recent techniques of fuzzy logic and fuzzy optimization for conflict resolution in an interbasin transfer system is discussed next. Discussion on future research directions is provided.

OVERVIEW OF SYSTEMS TECHNIQUES

Planning for large scale IBWT requires a broad knowledge of systems techniques that may be used for multireservoir planning and operation. This section presents an overview of the optimization models used in multireservoir operation. A detailed survey of system techniques may be found in Mujumdar and Narulkar (1993). Models used for this purpose are Dynamic Programming (DP) model, Optimal Control Model (OCM), Linear Programming (LP) Model, Network Flow Algorithm (NFA) and Nonlinear Programming Models.

Among all the techniques, DP is particularly favoured by water resources systems engineers because of the ease with which multistage problems are handled by the DP algorithm. A key feature of the algorithm resulting in its successful application to problems in various fields in general and water resources in particular is that a complex multistage problem is decomposed into a series of simple sub problems that are solved recursively one at a time. In addition, non linear problems and problems involving stochastic variable may be readily accommodated in the general framework of dynamic programming, making it an extremely flexible optimization technique. Detailed discussion of application of dynamic programming to water resources problems may be seen in Yakowitz (1982) and to reservoir operation problems in particular may be seen in Yeh (1982). DP in its various forms is extensively applied to multi reservoir planning, mainly because of the multistage and nonlinear nature of such problems. There are various kinds of DP algorithms like Incremental Dynamic Programming with Successive Approximation (IDPSA) (Giles and Wunderlich, 1981), State Incremental Dynamic Programming (SIDP) (Fults *et al.*, 1976; Yeh, 1982), Multilevel Incremental Dynamic Programming (MIDP) (Nopmongcol and Askew 1976), Binary state Dynamic Programming (BSDP) (Ozden, 1984), Differential Dynamic Programming (DDP) (Yakowitz and Rutherford, 1984), Constrained Differential Dynamic Programming (CDDP) (Chow *et al.*, 1975) and Progressive Optimality Algorithm (POA) (Marino and Loaiciga, 1983).

The Optimal Control Algorithm for discrete time steps consists of determining an admissible control sequence that minimizes a cost function over a finite time horizon for which a system is operated. The optimal control theory and its extension to determine constrained control in the form of two point boundary value problem (in which the initial and final states are assumed to be fixed) has been extensively applied to multireservoir problems. Hanscom *et al.* (1980), used maximum principle in solving a problem through the optimal control methodology. Stochastic OCM was successfully used by Mizyed *et al.* (1992), and Georgakakos (1989).

Although most reservoir problems are non-linear and approximations are necessary to formulate them as Linear Programming (LP) problems, LP is still the most widely used technique. This is especially true for multireservoir problems because of the computational difficulties associated with the use of other optimization techniques for solving such problems. Another advantage of LP is that, if the solution is feasible, LP algorithm always converges to global optimum. The nonlinearity in reservoir problems (e.g., nonlinear benefit or loss functions and nonlinear relationships with physical and/or hydrologic variables) is often accounted for by piecewise linearization or successive application of LP. For multireservoir operation, sometimes LP models are developed with Integer Programming (IP) or Mixed Integer Programming (MIP) (Trezos, 1991). To handle multiobjective models, Goal Programming (GP) can be modeled to incorporate multiple goals (Shane and Gilbert, 1982). Explicit stochastic applications through LP are achieved by Stochastic LP (SLP) and Chance Constrained LP (CCLP). The SLP solves for the optimal steady state probabilities for the releases and storages assuming the inflows to follow a single step Markov chain. Loucks *et al.* (1981) have presented an extensive discussion on this topic. CCLP formulation permits the use of reliability in the constraints. Use of CCLP in multireservoir problems was initiated by Nayak and Arora (1971). Some other LP applications to multireservoir problems may be found in Vedula and Rogers (1981), Stedinger *et al.* (1983) and Mohan and Raipure (1992).

The Network Flow Algorithm (NFA) introduced by Ford and Fullkerson (1962) can be considered as a simple transformation of LP problems which can be represented as a network. It permits a faster solution of a problem as compared to the LP algorithm. The general configuration of multireservoir system makes it possible to represent them in the form of capaciated network. Reservoir releases, storages, losses and other parameters are represented as arcs originating or destined to nodes representing a reservoir, a control point or a demand point. Each arc has a value associated with it representing, generally, the cost of flow per unit volume and also an upper and a lower limit on the flow. The optimization problem is to maximize the flow within the network or minimize the cost of flow in the network. The coefficient matrix in the constraint comprises of node-arc incidence constants with a value 1 assigned to an arc leading away from the node, -1 to an arc approaching the node and 0 if the nodes are not linked with each other. For the solution of a Network Flow Problem (NFP) the Out-of-Kilter algorithm (OKA) and the primal algorithm are used. Application of OKA and primal algorithm may be found in Orlob (1979) and Ikura and Gross (1984), respectively.

Nonlinear programming (NLP) models are used in multireservoir planning, where the objective functions or the constraints in the optimization model are non-linear. Normally power generation problems are nonlinear and pose a great difficulty for their solutions. An important application of NLP to NW Pacific Hydrosystem was presented by Hicks *et al.* (1974). Use of successive QP to solve a nonlinear problem was demonstrated by Diaz and Fontance (1989).

Recent developments in soft-computing techniques (e.g. Artificial Neural Network, Genetic Algorithms and Fuzzy Logic) have proved useful for deriving policies for complex water resources systems. Theory of fuzzy decision making has been used by Jairaj and Vedula (1997, 2003) for multireservoir operation to address uncertainty due to imprecision. Genetic Algorithm (GA) has been used for multipurpose operation (Wardlaw and Sharif, 1999; Sharif and Wardlaw, 2000). Artificial Neural Network is a black box model used for nonlinear regression, where the relationship between input and output is not known. ANN may be suitably adopted for complex water resources systems decision making problems. (e.g., Jain and Srivastava, 1999; Solomatine and Avila Torres, 1996). Recently, some new methods like Ant Colony Optimization, Particle Swarm Technique (Jangareddy and Nagesh Kumar, 2005a,b) are also used in multi-reservoir systems operation for nonlinear programming.

SYSTEMS ANALYSIS OF INTER-BASIN WATER TRANSFERS

As per the practice being followed in India, if the water available in a basin at a specified dependability is more than the demands that are likely to arise in the foreseeable future (time-span of 50 years or so), then this basin is considered as water surplus basin. The volume of water over and above the projected demands is labeled as surplus for the basin and this can be made available for transfer to other deficient basins. The storage reservoirs form the basic units in an inter-basin water transfer, and may be denoted as nodes in the system. Water may be transferred from one node to another. The water stored in a reservoir of a particular river basin can be utilized for three broad purposes (Vijay Kumar *et al.* 1996). In order of priority they are (a) to meet the demands from the command area of the reservoir itself, (b) to meet completely or partially the demands of the intermediate downstream reservoir in the same river basin, and (c) to meet completely or partially the demands at a reservoir in another basin through transfer link. A 'diversion' from a reservoir is defined as the water supplied to meet its own demand, a 'release' as the water supplied to meet the deficits at the downstream reservoirs of the same basin, and a 'transfer' as the water supplied to meet the deficits at the reservoirs of other basins (Vijay Kumar *et al.*, 1996).

A number of inter-related issues need to be addressed in systems models dealing with large-scale transfer of water from one region to another. The magnitude of the problems will differ from one project to another, but some of the major variables that should be considered are the following (http://www.unu.edu/unupress/unupbooks/80157e/80157E02.htm):

I - Physical System

(a) Water Quantity: level; discharge; release from reservoir; velocity; groundwater; losses.
(b) Water Quality: sediments; nutrients; turbidity; salinity and alkalinity; temperature effects; toxic chemicals.
(c) Land Implications: erosion; sedimentation; salinity; alkalinity; waterlogging; changes in land use patterns; changes in mineral and nutrient contents of soil; earthquake inducement; other hydrogeological factors.
(d) Atmosphere: temperature; evapotranspiration; changes in microclimate; changes in macroclimate.

II - Biological System

(a) Aquatic: zooplankton; phytoplankton; fish and aquatic vertebrates; plants; disease vectors.
(b) Land-based: animals; vegetation; loss of habitat; enhancement of habitat.

III - Human System

(a) Production: agriculture; aquaculture; hydropower; transportation (navigation); manufacturing; recreation; mining.
(b) Socio-cultural: social costs, including resettlement of people; infrastructural developments; anthropological effects; political implications.

The environmental, ecological, economical, and geological risks should be properly quantified and taken into account for minimizing them in the objective functions of a systems model. Only a very few studies, however, are available in literature that directly deal with use of system techniques on IBWT. Lund (1993) has shown how economic impacts such as transaction cost of water transfer can be used in decision making for IBWT.

A Simulation-Optimization Model

Vijay Kumar *et al.* (1996) used a simulation-optimization procedure for evaluating the extent of inter-basin transfer of water in the Peninsular Indian river system of 15 reservoirs on 4 river basins of Godavari, Krishna, Pennar and Cauvery (Fig. 1). This study is carried out in two steps.

In the first step, a detailed simulation model is developed and a large number of solutions are generated. The sensitivity of the system performance to changes in priorities, storage zone levels, demands and operational strategies is examined in this step and ranges of different parameters for which the system performance is sensitive are identified. This step generates a huge database to supply some of the inputs required for the second step.

In the second step, a nonlinear optimization problem is solved to identify the best solution within the range identified in the first step for each parameter. The solution of the optimization model specifies the zone levels at each reservoir, the extent to which the water availability can be raised at a reservoir and the extent of possible inter-basin transfer.

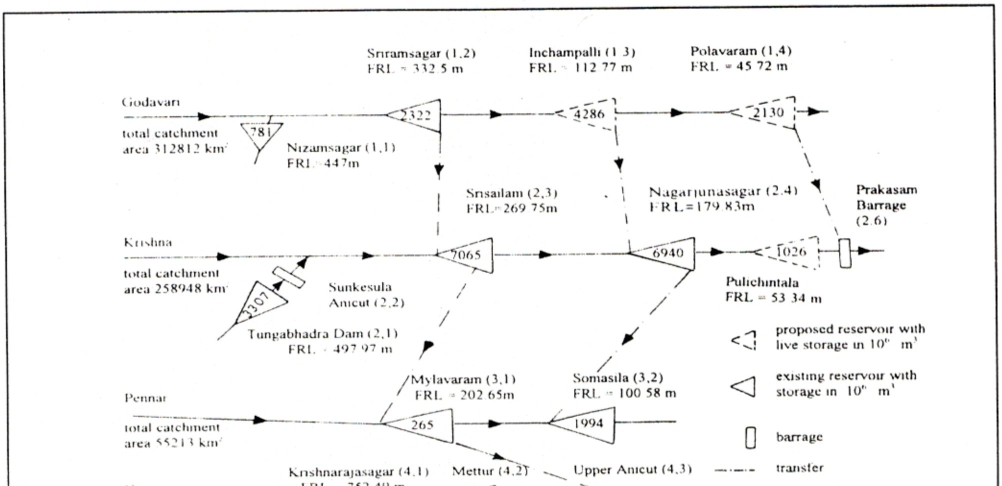

Fig. 1 Peninsular system of inter-basin transfer considered by Vijay Kumar *et al.* (1996).

The simulation model generates a large number of solutions corresponding to various levels of the four storage zones. The significance of these zones for the operation of the reservoir is as follows. The minimum storage (S_{MIN}) is the dead storage capacity and the maximum storage (S_{MAX}) is the live storage capacity of a reservoir. Both these zones (S_{MIN} and S_{MAX}) are known constants for every reservoir. The other two storage zones, the releasable storage (S_{REL}) and the transferable storage (S_{TRA}) facilitate release to downstream reservoirs and transfers to reservoirs of other basins, respectively. By definition, if the storage at a reservoir, after satisfying its own demand in a period, is more than S_{REL}, then the excess water over S_{REL} can be released to meet the deficits of the downstream reservoir of the same basin. Similarly, after meeting the basin requirements in a period, if the storage is more than S_{TRA}, then the excess water over S_{TRA} can be transferred, if a link exists, to meet the deficits of reservoirs of the other basins.

The aim of the simulation model is to examine the performance of the system for several alternatives of storage zones and to identify an initial value and a range for each parameter for use in the optimization model subsequently. The flow chart of the model is given in Fig. 2.

The release policy of a reservoir aims at the minimization of the spills out of the system. The downstream reservoirs are depleted first before withdrawing water from upstream reservoirs. The release policy is invoked at a reservoir M, when the available storage, after accounting for diversion to meet the demands at the reservoir itself, is more than S_{REL}. Release $R_t^{M,L}$ from the reservoir M to a downstream reservoir L, if exists, is given by

$$R_t^{M,L} = MIN \begin{cases} S_{1t}^{M} - S_{REL,j}^{M}, \text{ if } S_1^M > S_{REL,j}^{M}, \text{ and} \\ DEF_t^L - S_t^L, \text{ if } S_t^L < DEF_t^L, \end{cases} \tag{1}$$

$$= 0 \quad \text{otherwise}$$

where $S_{1,t}^{M}$ is the storage at reservoir M during period t after accounting for its own demand d_t^M, releases and transfers committed to the reservoir M from other reservoirs and release commitments made from the reservoir M to other reservoirs downstream of M; S_t^L is the storage at the reservoir L after accounting for all transfers and releases from other reservoirs downstream of M, committed to it during the period; and $S_{REL,j}^{M}$ is the releasable storage for the reservoir M in season j to which the period t belongs. Here, seasons are denoted by j.

The transfer policy is similar to the release policy. The deficit at a reservoir, after accounting for diversion from the particular reservoir itself and releases from reservoirs in its own basin, is met either partially or fully by transfer from reservoirs of other basins if a transfer link exists. The amount of water transferred, $T_t^{M,P}$, from reservoir M of a basin to reservoir P of another basin in period t, when a transfer link exists is given by:

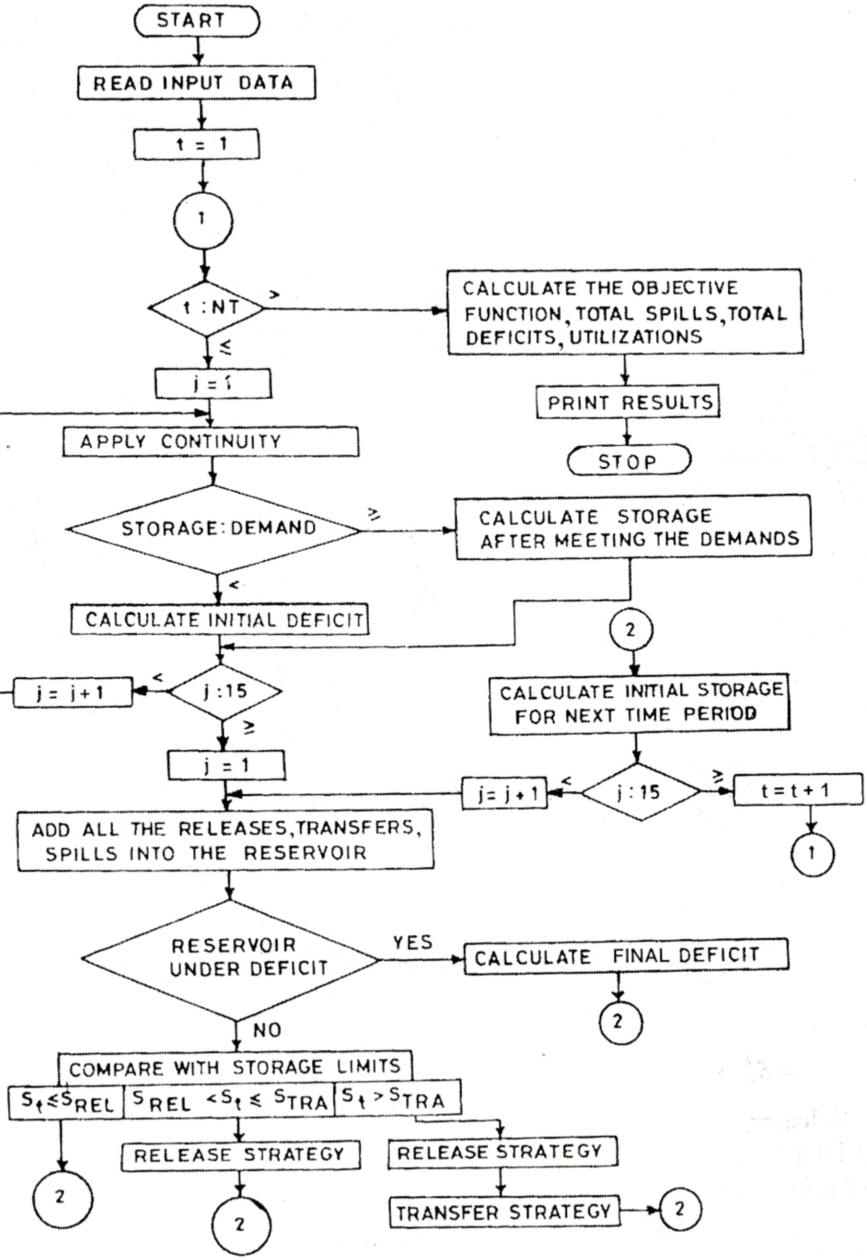

Fig. 2 Flow chart for the simulation model (Vijay Kumar *et al.* 1996).

$$T_t^{M,L} = MIN \begin{cases} S_{2t}^{M} - S_{TRA,j}^{M}, \ if\ S_{2j}^{M} > S_{TRA,t}^{M}, & \text{and} \\ DEF_t^{P} - S_t^{P}, \ if\ S_t^{P} < DEF_t^{P} \end{cases} \qquad (2)$$

$$= 0 \quad otherwise$$

where S_{2t}^{M} is the storage available at reservoir M after accounting for the diversion and release; $S_{TRA,j}^{M}$ is the transferable storage in reservoir M for the season j to which the period t belongs; S_t^P is the storage at the reservoir P after accounting for diversion, release and transfers committed to it for the period (by other reservoirs during the computations prior to those of reservoir M); and DEF_t^P is the deficit at reservoir P in period t corresponding to the storage S_t^P. Two parameters, *INCR1* for the monsoon season and *INCR2* for the non-monsoon, are introduced as multiplying factors to the irrigation demands in the corresponding periods.

A sensitivity analysis with all the parameters (*INCR1*, *INCR2*, $S_{REL,1}$, $S_{REL,2}$, $S_{TRA,1}$ and $S_{TRA,2}$) is carried out to identify the most productive range for each parameter and to evaluate the performance of the system under various alternatives. The parameters to which the system performance is sensitive, their possible ranges and the associated increments by which the parameters should be varied in the optimization are all identified by the simulation analysis. Sensitivity analysis, thus, prepares the ground for more accurate and more systematic optimization.

Within the range identified for a particular parameter, an optimal value of parameter is determined by solving an optimization model. The optimization model formulated by Vijay Kumar *et al.* (1996) is as follows:

$$MAX \quad \sum_k \sum_t \alpha U_t^k - \beta D_t^k \tag{3}$$

subject to:

(i) Diversion policy,

$$\begin{aligned} DIV_t^k &= d_t^k \quad if \;\; S_{it}^k + I_t^k > d_t^k \\ &= S_{it}^k + I_t^k \quad otherwise \end{aligned} \tag{4}$$

(ii) Release policy, Eq. (1)
(iii) Transfer policy, Eq. (2)
(iv) Definition constraints:

(a) $$\begin{aligned} D_t^k &= d_t^k - U_t^k, \quad if \; d_t^k - U_t^k \; is \; positive \\ &= 0 \qquad\qquad otherwise \end{aligned} \tag{5}$$

(b) $$U_t^k = DIV_t^k + R_t^k + T_t^k \tag{6}$$

(c) $$\begin{aligned} d_t^k &= INCR1^k (DEM_t^k), \quad \forall t \in monsoon \;\; season \\ &= INCR2^k (DEM_t^k), \quad \forall t \in nonmonsoon \;\; season \end{aligned} \tag{7}$$

(v) Storage continuity, physical constraints and non-negativity of variables.
(vi) Constraints due to priorities of different demands.

In this model, α represents the economic value of the water actually utilized;

and β represents the penalty (i.e., loss) associated with not meeting the demands. Both α and β are complex functions of operation priorities, the purpose for which the water is used, market conditions and even the societal preferences. The system performance has been evaluated with the performance criteria of reliability, resiliency, vulnerability and deficit ratio.

A Dynamic Programming Approach

Sarma and Srivastava (2003) used dynamic programming approach for IBWT. A Procurement Problem Model (PPM) and a Controlled Input Model (CIM) are formulated to solve the problems of interlinking with dynamic programming approach in their analysis. For both PPM and CIM using dynamic programming, the time period is considered as a stage variable, while reservoir storage is considered as a state variable in the models. The backward process of dynamic programming is used. Consider N to be the total number of stages to go; and r be the number of stages to go, such that r = 1, 2, ..., N. Let S_r be the reservoir storage at the beginning of r stages to go; S_{r-1} be the reservoir storage at the end of r stages to go; I_r be the total inflow to reservoir at r stages to go; P_r be the precipitation directly upon reservoir in r stages to go; $\bar{I}_r$ be the local inflow to reservoir from surrounding area in r stages to go; El_r be the reservoir evaporation losses with r stages to go; Y_a be the live capacity of reservoir; Y_{max_r} be the storage capacity up to full reservoir level in r stages to go; and Y_{min_r} be the storage capacity up to Minimum Draw Down Level (MDDL) of reservoir with r stages to go.

Procurement Problem Model (PPM)

For a reservoir, when demands are known and during water deficit periods option is open for water import from some other sources or reservoirs, it is important to know how much import of water is required to meet the demands fully. In PPM, the decision variable is import of water required to meet the demands completely. Figure 3 explains the basic parameters of the model.

Let O_r be the import of water required (a decision variable) to reservoir to meet demands without failure at r stages to go; $D_{r,p}$ be the target water demand for purpose p to be met from reservoir at r stages to go; and $g_r(S_r, O_r)$ be the return function for r stages to go. The overall objective function is:

$$MIN \sum_r g_r(S_r, O_r) \tag{8}$$

Here, $$g_r(S_r, O_r) = CTR_r \times O_r + CSR_r \times S_{r-1} + CSP_r \times TSP_r \qquad \forall r \tag{9}$$

where CTR_r is cost of import or water transfer at r stages to go; CSR_r is cost of reservoir storage at r stages to go; CSP_r is cost of reservoir spill at r stages to go; and TSP_r is spill from the reservoir at r stages to go.

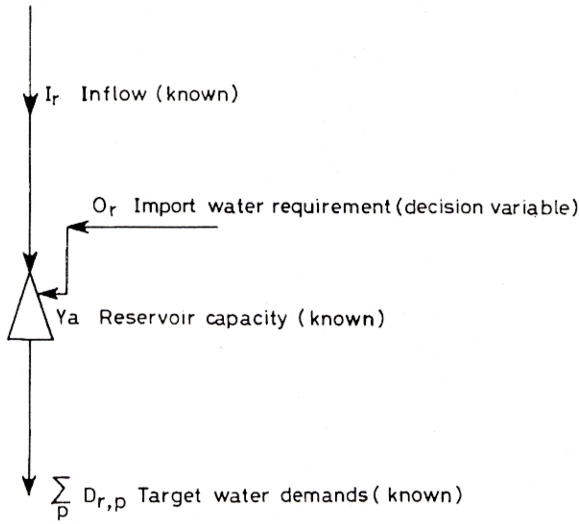

Fig. 3 Procurement problem model (Sarma and Srivastava, 2003).

The objective function (Eq. (8)) is subjected to the following constraints:

(a) $O_r \geq O \qquad \forall r$ (10)

(b) The continuity equation for the reservoir is

$$S_{r-1} = S_r + I_r + O_r + P_r + \bar{I}_r - El_r - \sum_r D_{r,p} \qquad \forall r \tag{11}$$

Putting $X_r = P_r + \bar{I}_r - El_r$,

$$S_{r-1} = S_r + I_r + O_r + X_r - \sum_r D_{r,p} \qquad \forall r \tag{12}$$

(c) The equation for bound in storage is

$$0 \leq Y_{\min_r} \leq S_{r-1} \leq Y_{\max_r} \leq Y_a \qquad \forall r \tag{13}$$

A negative value of O_r indicates that reservoir will spill, i.e.,

$$TSP_r = -O_r \quad and \quad O_r = 0 \qquad \forall r \tag{14}$$

The general recursive equation using dynamic programming for PPM for all r stages to go can be written as:

$$f_r(S_r) = MIN\left[g_r(S_r, O_r) + f_{r-1}(S_{r-1})\right] \tag{15}$$

subject to constraints (3) to (7) where $f_r(S_r)$ represents the cumulative minimum value of the return functions up to r stages to go with a water storage level S_r during r stages to go.

Controlled Input Model (CIM)

After calculation of target water demands for various water use purposes, it is necessary to know if these demands can be satisfied by the reservoir releases. The decision variable is the amount of water to be used from reservoir inflow, other than from reservoir storage to meet these demands. If the target demands cannot be met fully, they are to be revised (design demands). The upper value of decision variable is limited to the inflow in that period. Basic parameters of the model are given in Fig. 4.

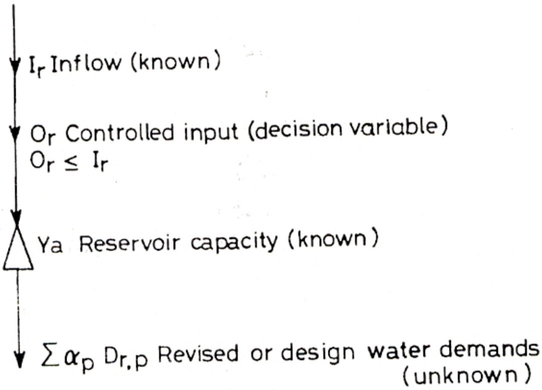

Fig. 4 Controlled input model (Sarma and Srivastava, 2003).

Let O_r be the amount of water to be used from reservoir inflow (a decision variable) to meet the demands at r stages to go; $D_{r,p}$ be the target water demand for purpose p to be met from reservoir at r stages to go; and $g_r(S_r, O_r)$ be the return function for r stages to go. The overall objective function is:

$$MIN \quad \sum_r g_r(S_r, O_r) \tag{16}$$

Here,

$$g_r(S_r, O_r) = CSR_r \times S_{r-1} + CSP_r \times TSP_r + \sum_p \{CDD_{r,p}(D_{r,p} - \alpha_p D_{r,p})\} \quad \forall r \tag{17}$$

where CSR_r is the cost of storage at r stages to go; CSP_r is the cost of spill (i.e., unused water) at r stages to go; $CDD_{r,p}$ is the cost of not being able to meet the demand for purpose p at r stages to go; TSP_r is the total unused water, i.e., includes $(I_r - O_r)$ and spill from storage at r stages to go; $\alpha_p D_{r,p}$ is the design water demand (i.e., revised water target) for purpose p, or the actual water release from reservoir excluding reservoir spill for purpose p at r stages to go; and α_p is the coefficient for demand revision for purpose p, lying between 0 and 1.

The objective function (Eq. (16)) is subjected to the following constraints:

(a) $O_r \geq O \quad \forall r$ (18)

(b) $O_r \leq I_r \quad \forall r$ (19)

(c) The continuity equation for reservoir is

$$S_{r-1} = S_r + O_r + P_r + \bar{I}_r - El_r - \sum_p \alpha_p D_{r,p} \quad \forall r \tag{20}$$

Putting $X_r = P_r + \bar{I}_r - El_r$,

$$S_{r-1} = S_r + O_r + X_r - \sum_p \alpha_p D_{r,p} \qquad \forall r \tag{21}$$

(d) The equation for bounds on storage is

$$0 \le Y_{\min_r} \le S_{r-1} \le Y_{\max_r} \le Y_a \qquad \forall r \tag{22}$$

The general recursive equation using dynamic programming for CIM for all r stages to go can be written as:

$$f_r(S_r) = MIN\left[g_r(S_r, O_r) + f_{r-1}(S_{r-1})\right] \tag{23}$$

subject to constraints (18) to (22). Here, $f_r(S_r)$ represents the cumulative minimum value of the return functions up to r stages to go with a water storage level S_r during r stages to go.

The combined application of PPM and CIM can be very useful to both reservoir planning and operation for IBWT. PPM can be applied for reservoir planning only, whereas CIM is useful to both reservoir planning and operation.

Operating Policy for Inter-basin Water Transfer

A generalized computer package, known as Software for Reservoir Analysis (SRA), developed by Jain and Goel (1996), was used by Jain *et al.* (2005), to derive the operating policy for IBWT. This study on use of systems techniques for interlinking comprises the following features: carrying out long-term simulation for integrated operation of the reservoirs in each basin pertaining to the link system and to find out the operational reliabilities; optimizing the performance of each reservoir through simulation and to quantify surface water surplus or deficit in each basin; considering groundwater in the planning and to work out net water deficits; and determining the amount of diversion and transfer to meet the deficits and study the effect of diversion and transfer on the performance of the reservoirs. The model incorporates water transfer from one node to another through a link. In the SRA model, water available at a node for allocation is computed as:

$$A_v = S_{int} + I_L + r_{ds} + r_f \times r_{iu} + s_u \tag{24}$$

where S_{int} is the initial reservoir storage; I_L is the local inflow; r_{ds} is the release from the upstream node(s) to the current node; r_f is the irrigation return flow factor; r_{iu} is the irrigation release from the upstream structure; and s_u is the spill from the upstream node.

The final storage in the reservoir at the end of a period is:

$$S_f = A_v - e_l - T_r - L_d - S_p \tag{25}$$

where T_r is the total release, L_d is the link diversion and S_p is the spill from the node.

The complete analysis was done by Jain *et al.* (2005) in three stages:

Stage I The performance of each sub-system was studied in the ultimate water development scenario (considering only surface water), roughly corresponding to year 2050 AD, by carrying out multi-reservoir simulation. The rule curves for the various reservoirs were derived by repeated simulation runs considering different priorities of water allocation.

Stage II The water b[illegible] position obtained in Stage I, was refined in Stage II by planning conjunctive use o[illegible] and the net deficit in each basin was assessed. This deficit will require supplementation through IBWT. The necessity of this stage arose because some states of India currently do not consider in-basin groundwater resources (although it is prudent to do so) prior to assessing requirement of IBWT.

Stage III The link diversions, as required, were planned and the effect of these water transfers on the performances (reliability) of the reservoirs in each basin was studied.

This analysis results in policies that ensure releases to meet the project demands at a desirable reliability. The analysis clearly shows the complexity in planning a large IBWT scheme and the efficacy of system techniques in finding acceptable and efficient solutions.

CONFLICT RESOLUTION USING THE FUZZY SYSTEMS THEORY

Interlinking of rivers is an extremely complex problem involving a large number of conflicting goals and interests. A number of uncertainties exist in such a complex system, and therefore the classical, deterministic approaches will not provide useful tools for arriving at good decisions. Uncertainties due to randomness of hydrologic and physical variables such as the rainfall, streamflow, temperature, crop consumptive use, flood discharge etc. are traditionally addressed by the theory of probability. Stochastic optimization and simulation methods may be used to address such uncertainties, although the large size of the interlinking system may limit their applications. Another type of uncertainty that is prevalent in any water transfer system is that due to a large number of stakeholders with conflicting goals and interests. This type of uncertainty is ideally addressed through the fuzzy decision theory.

Fuzzy Decision Theory

Bellman and Zadeh (1970) considered the following approach for decision making when there are *fuzzy goals* and *fuzzy constraints* for the set of alternatives (the decision vector) $\boldsymbol{X}$, as decision making in a fuzzy environment. A fuzzy goal G and a fuzzy constraint C are fuzzy sets on the set of alternatives $\boldsymbol{X}$ which are characterised by the following membership functions:

$$\mu_G : X \rightarrow [0,1] \quad (26)$$

$$\mu_C : X \rightarrow [0,1] \quad (27)$$

Fuzzy decision Z is defined as the intersection of a fuzzy goal G and a fuzzy constraint C. In other words, the fuzzy decision is defined by

$$Z = G \cap C \quad (28)$$

and its membership function is characterized by

$$\mu_Z(x) = \min\left(\mu_G(x), \mu_C(x)\right) \quad (29)$$

Furthermore, in the general case in which k number of fuzzy goals $G_1, G_2, ..G_k$, and m number of fuzzy constraints $C_1, C_2, ..C_m$ exist, fuzzy decision Z is defined as the intersection of these:

$$Z = G_1 \cap G_2 \cap \ldots \cap G_k \cap C_1 \cap C_2 \cap \ldots . C_m \qquad (30)$$

and is characterised by the membership function

$$\mu_Z(x) = \min\,(\mu_{G1}(x), \mu_{G2}(x), \ldots .\mu_{Gk}(x), \mu_{C1}(x), \ldots \mu_{Cm}(x)) \qquad (31)$$

The optimal fuzzy decision corresponds to the x with the maximum degree of membership in Z. That is, to find x^*, such that

$$\mu_Z(x^*) = \max\, \mu_Z(x) = \max\{\min(\mu_{G1}(x), \mu_{G2}(x), \ldots \mu_{Gk}(x), \mu_{C1}(x), \mu_{C2}(x), \ldots \mu_{Cm}(x))\} \qquad (32)$$

For example, considering the set of alternatives $X = [0, \infty]$, let the membership functions for a fuzzy goal 'make x sufficiently larger than 10', and a fuzzy constraint 'x must be a lot smaller than 30', be given subjectively as follows:

$$\mu_G(x) = \begin{cases} 0 & \text{if } x \le 10 \\ 1-(1+(0.1(x-10))^2)^{-1} & \text{if } x > 10 \end{cases} \qquad (33)$$

$$\mu_C(x) = \begin{cases} 0 & \text{if } x \ge 30 \\ 1-(1+(x(x-30))^2)^{-1} & \text{if } x < 30 \end{cases} \qquad (34)$$

The fuzzy decision and maximizing decision in this instance turn out as shown in Fig. 5.

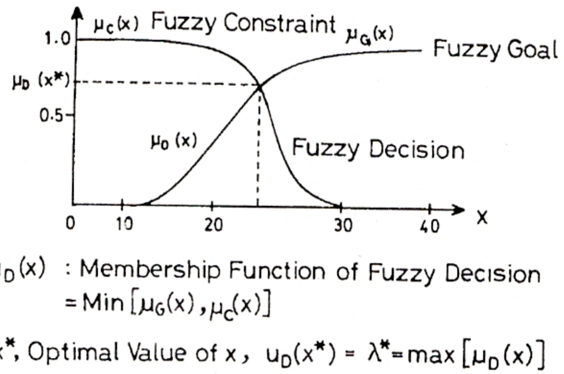

Fig. 5 Fuzzy decision and maximizing decision.

It may be noted that the fuzzy membership functions may indicate the response of stakeholders to a given decision. For example, in the case of a interbasin transfer of water, the recipient state may respond with, 'the higher the water transfer from the donor basin the better', which may be modeled with a non-decreasing membership function, similar to the membership function, $\mu_G(x)$, shown in Fig. 5 above, whereas the donor basin may respond with 'the smaller the water transfer (beyond a prescribed minimum) the better' which may be represented by a nonincreasing membership function, similar to $\mu_C(x)$ shown in Fig. 5. In practical situations, there will be a large number of users each with a number of responses to various decisions. Fuzzy optimization considers such responses to provide the best compromise solutions. Example applications of the fuzzy optimization to resolve conflicts in a water quality management problem may be found in Mujumdar and Sasikumar (2002), Mujumdar and Subba Rao (2004) and Subba Rao *et al.* (2004).

In situations where the membership functions may be approximated with linear functions, we may use the fuzzy linear programming for conflict resolution. A simple development of a general fuzzy linear programming problem is described here for completeness. More rigorous treatment may be found in Ross (1997) and Asai (1995).

A general form of linear programming may be expressed as

$$Min.\ Z = \mathbf{CX}$$
$$\text{subject to } \mathbf{AX} \le \mathbf{B} \qquad (35)$$
$$\mathbf{X} \ge 0$$

where $\mathbf{C}$ is a n-dimensional row vector, $\mathbf{C} = (c_1,c_2,..c_n)$; $\mathbf{A}$ is a $m \times n$ matrix, $\mathbf{A} = [a_{ij}]$; $\mathbf{X}$ is a n-dimensional column vector, $\mathbf{X} = (x_1,x_2,\dots x_n)^T$; and, $\mathbf{B}$ is a m-dimensional column vector, $\mathbf{B} = (b_1,b_2,\dots b_m)^T$.

The linear programming problem with fuzzy goals and fuzzy constraints, called the *fuzzy linear programming*, may be written as

$$\mathbf{CX} \sim< Z_0$$
$$\mathbf{AX} \sim< \boldsymbol{b}$$
$$\mathbf{X} \ge 0 \qquad (36)$$

The symbol '$\sim<$' represents a fuzzy inequality, for example, '$x \sim< a$' means 'x is about a or less'. In the above problem, the fuzzy goal, 'the objective function must be about Z_0 or less', and the fuzzy constraint '$\mathbf{AX}$ should be about $\boldsymbol{b}$ or less' are given.

The fuzzy optimization procedure yields the 'best compromise solutions', in the presence of conflict of interests. In an IBWT problem, the stakeholders and purposes conflicting with each other include upstream and downstream water users, ecology and environment, hydropower, municipal and irrigation demands, water quality, salinity intrusions, and resettlement and rehabilitation. The fuzzy systems concepts provide a means to include conflicting and often non-quantifiable goals and objectives of such stakeholders. The concept of 'equity' of water allocations in inter-basin transfer of water may also be addressed effectively with the fuzzy systems tools.

RECENT DEVELOPMENTS AND FUTURE RESEARCH DIRECTIONS

Traditional approaches to addressing uncertainty in models are unsuitable for systems with complex interactions among several critical segments, such as the inter-basin transfer system. Characterization of joint probability distributions of uncertain inputs in the models is impossible because the information is limited, is imprecise and the driving mechanisms are generally difficult to model. In all water resource management models, setting up of goals, limits on constraints, standards for non-violation and even objective functions introduce uncertainty due to subjectivity and imprecision. Uncertainty in water management systems additionally arise from a number of factors such as parameter and scenario uncertainties, stochastic input variations and a broad range of possible alternate formulations, which include differing perceptions on risks. Recent interests in addressing uncertainty due not only to randomness but also to imprecision, subjectivity and human judgment has lead to use of fuzzy systems theory through which failure events can be defined in a more flexible form than the usual crisp form. The concept of fuzzy probability aids in deriving a new risk analysis methodology which includes subjective definition and assessment of failures. The implication of probability, as symbolized by the concept of randomness, is based on the chance that exists in a real world event. Fuzziness, however, takes in another aspect of uncertainty – which represents ambiguity that can be found in all management systems. Development of the fuzzy systems theory has opened up the question of precision, or indeed, the lack of it, in our ability to assign probabilities to critical events.

Large scale water management systems – such as those in the inter-basin water transfers – are neither entirely *black* (systems with completely unknown information) nor entirely *white* (systems with completely known information and mapping). There is a need to address all water management systems as *grey* systems – with partially known and quantifiable information, and partially unknown or imprecise, unquantifiable information. Complex interactions arising out of integration of the climate-hydrologic-economic-environmental-societal-human systems introduce uncertainties due to randomness, fuzziness, lack of information and even lack of understanding. With more and more segments introduced in the water management system, it becomes imperative that newer dimensions of uncertainties are addressed in the modeling framework. The *grey systems* theory (e.g., Deng, 1982; Liu and Lin, 1998; Huang *et al.*, 1995), provides a useful tool to develop models addressing such uncertainties. Because of the extremely complex interactions involved in large scale interbasin transfers, the system dynamic approaches (e.g., Simonovic, 2002; Ahmed and Simonovic, 2004) appropriately addressing all major forms of uncertainty may prove to be useful.

Analysis of measured hydrometeorological data suggests that the climate of earth may be undergoing important long-term changes. For a water planner, this change may manifest in altered spatial and temporal patterns of precipitation, evapotranspiration, and streamflows. Such changes, if at all they take place, might adversely influence the reliability of the river interlinking projects. Some of the components may fail to perform up to the mark and others may become redundant. Therefore, climate change impact on hydrology should be incorporated in developing optimization models for planning and management of IBWT (Jain and Singh, 2003b).

CONCLUSIONS

Developing models for decision making in IBWT is a challenging task as it is one of the most complex interdisciplinary water resources problems, with interactions among hydrologic, physical, sociological and legal components. Planning of IBWT with systems techniques incorporating hydrological, physical, sociological and legal aspects may lead to useful solutions for a critical problem of water deficit and hydrologic extremes in the country. Very few studies are at present available on this topic and most of them address mainly the hydrologic aspects of water demand, water excess and water deficit. Inclusion of other components and risks associated with river interlinking in systems models will increase their utility. Recent developments in the fuzzy systems theory and artificial intelligence may need to be exploited for conflict resolution and to provide best-compromise decisions.

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