Integrated River Basin Developments: Water Availability, Utilizations, Transfers and Conflicts - Solutions in Space and Time

D. K. Srivastava
Emeritus Fellow, Dep't of Hydrology, Indian Institute of Technology, Roorkee, India
dksfhy@rediffmail.com

KEYWORDS
Optimization, multi-reservoirs, water-disputes, water-transfers, solutions

ABSTRACT

In planning a river basin water resources development, determination of water availability and its utilization in space and time is most important. In assessing the water availability more realistically, the regulation effect of storages of the existing, ongoing and contemplated reservoir projects is very significant and useful. Therefore, resource planning in case of water should be carried out for a hydrological unit, such as firstly at each reservoir level, secondly at each sub-basin level and then lastly at the basin as a whole. The integrated system modeling is often a quite complex problem because it depends on spatial and temporal distribution of various parameters, such as, physical configuration of the system; site specific characteristics of reservoirs; active reservoir storage capacities; distribution of natural stream flows entering into the reservoirs; and multi-reservoir operating policy, large scale water transfers, and interstate trans-boundary water disputes (conflicts), etc. At a water export point in river a certain amount of pre quantified amount of water is being diverted for use at its downstream. Usually these exports are governed by several interstate trans-boundary water disputes tribunal awards regarding the share of water amongst the concerned riparian co-basin states involved. These shares (exports) are to be made available at a given water export point (generally at a specified reservoir through releases) as an import of water to a downstream state, which is (the shares) to be released as a water export from a set of specified contributing reservoirs located in an upstream state. Practically in real time operations, quantifying and managing contributions made from multi-reservoir releases for diversion at the water export point during the within-year time periods in space and time is a cumbersome task. The solution to all such problems lies in carrying out detailed and comprehensive analysis of the integrated multi-reservoir system involved. For evaluation of efficient water utilizations in space and time, application of systems analysis modeling approach can provide answers to these intricate issues. A direct application of trial and error search, based on simulation model as an initial screening tool is bound to be unsuccessful, though it being very realistic in model presentation. Whereas, the LP based comprehensive reservoir yield models as optimization models serve the purpose of preliminary screening and thereby achieve near to the expected optimal developmental solutions which would produce a reliable and sustainable water resources system and may be preferred at the first instance. These models analyze optimal integrated large scale trans-boundary river basin water resources developments. In the Indian context, several studies have been carried out for river basins under the domain of tribunal awards and inter-state agreements among riparian co-basin states for sharing river waters. These provide answers to many intricate inaccessible untold solutions in respect of water in space and time in a river basin during a normal water-year, i.e., expected water availability, utilizations, crop planning, food security, shares, exports and detailed multi-reservoir operation policies during the within-year time periods. This of course is a herculean and tedious task requiring a lot of effort.

1.0 INTRODUCTION

Water is very scarce resource and without any doubt is the most precious natural resource available for the survival of the mankind after the air, but a very little value is assigned to it by its user. We receive water for our use and sustenance from Natural Rivers which are the lifeline of the mankind. Comprehensive integrated water resource planning and analysis of a river basin is then required for efficient water use in an optimal manner. There is a strong belief that the next World War is bound be on the Water. Knowing this, one should be prepared to fight against it.

Linear Programming (LP) based optimization model, i.e., reservoir yield models are used for the purpose of preliminary screening to directly screen out a large number of non-optimal developmental alternative solution strategies and thereby retaining other better prospective alternatives near to the expected optimal developmental solution which would produce a reliable and sustainable water resources system. On the other hand the well-known simulation technique, though being very realistic in model presentation in comparison to any optimization model, would not be directly capable to serve the required purpose of screening up to the same extent as that provided directly by the optimization. This had earlier given rise to the importance of using the well-known screening-simulation modeling technique (Loucks et al., 1981; Chaturvedi and Srivastava, 1981; and Srivastava, 1976). Where an optimization model first serves the purpose of the preliminary screening then followed by the simulation for further screening for refinement and producing efficient and reliable developmental outcomes from the system which could be implemented later. This essentially resulted in emphasizing the extent and need of using a simulation model for analyzing large river basin system water availability and utilization; of course this should always follow up to a large extent the preliminary screening. The importance of simulation is described in a study by Wurbs (2005), through Texas water modeling system, where availability and reliability of water were assessed from 3,365 reservoirs based on simulating river/reservoir system management and water allocation practices. The water use was within the mandate of water management legislation enacted by Texas legislation in 1977, which was based on water rights and regulations prevalent/proposed in respect of the Texas river system. In the detailed evaluation of basin wise impacts of water management decisions, the prior appropriation water rights and other institutional mechanisms for allocating streamflow and reservoir storage resources among numerous water users were considered.

In this paper basically emphases given on the use of LP based screening models for analyzing large size river basin systems in an integrated manner in space and time and provide answers for the solutions of many intricate problems.

1.1 The Water Availability and River Basin Water Balance

The water balance of a river basin should ideally take into consideration the regulation effect of storages of the existing, ongoing and contemplated reservoir projects in the basin. In assessing the water availability more realistically of the river basin, the importance of spatial and temporal distribution in parameters is very significant and useful. Studies on such water balance so far have usually lacked consideration of aerial distributions in water availability and demand (utilization). These considerations could enable different reservoir projects situated in the concerned basins/sub-basins to be evaluated in an integrated manner. Furthermore, in order to ascertain the excess/shortage in water availability in the basin for a possible export/import, there is a need for determining optimal integrated multi-reservoir yields from the system.

1.2 The Trans-Boundary Interstate Water Disputes and Tribunal Awards

There are several Tribunal awards towards resolving trans-boundary interstate water disputes (conflicts) regarding the share of water amongst the concerned riparian co-basin states involved. These awards in general usually provide the annual quantum of the total part of the share of trans-boundary river waters as transfers (imports) from a co-basin state to other concerned co-basin state or states. At times these shares are to be made available at a given point (generally at a specified reservoir through releases) as an import of water to a downstream state, which is (the shares) to be released as a water export from a set of specified reservoirs located in an upstream state. On the other hand up to a large extent, these awards do not always provide some guidelines regarding the important aspect of the quantum of releases along with their within-year time distributions to be made from each of these individual specified reservoirs. This is because, for these awards the availability of water is usually derived only based on a specified water-year. For this purpose conventional method of water balance of rivers at a specified point is carried out and which is generally based on the 75% water-year dependability criteria. Due consideration to the various awards of the Tribunal therefore should be given in various studies involved on basin water availability and its utilization in space and time in an optimal and integrated manner.

1.3 The Water Exports and Managing Real Time Operations of Multi-Reservoirs

At a water export point in river a certain amount of pre quantified total annual amount of water is to be diverted for use at it's downstream. This total annual quantum of water at the water export point might be shared by annual contributions from releases made by a large number of pre specified reservoir projects lying in its upstream catchment/river reaches. This pre decided total annual quantum of water being diverted is usually time dependent during a year/water-year and is governed by its within-year quantum distributions from each upstream contributing reservoir. It is not directly possible to quantify or specify its distribution or share for water diversions among the upstream contributing reservoirs. As said earlier or in other words their space and within-year time wise distributions are not available or are not being estimated during planning stages. Under such conditions practically in real time operations, quantifying and managing contributions made from multi-reservoir releases for diversion at the water export point during the within-year time periods in space and time is a huge and cumbersome task. This again needs optimal integrated approach towards trans-boundary river basin planning.

1.4 The Systems Approach and Importance of Its Application to Real Life Problems

The National Water Policy of Ministry of Water Resources, Government of India emphasizes to utilize the basin's available water resources to maximum possible extent. The resource planning in the case of water should be carried out for a hydrological unit, such as at each sub-basin level and then at the basin as a whole. To achieve this, all the major individual developmental reservoir projects formulated by the states and considered within the frame work of such an overall plan for a basin or sub-basin should be analyzed, so that the best possible combination of options of water use was made available. The matter of application of systems approach on the issues involving water utilizations and transfer of waters had been recommended by the working group on inter-linking of rivers.

1.4.1 Need of a scientific assessment

The purpose of appraising water resources system of a river basin is to determine the source, extent and dependability of supply and the character of water on which an evaluation of their control and utilization is to be made. Quantity, quality and reliability are the important considerations. Reservoirs in a river system should be able to provide reliable supplies during the period of water distress. Therefore, through scientific assessment in spatial and temporal variations of water availability and demand (utilization) would bridge the gap and differences existing in the perception and evaluation of the extent of system's behavior. This essentially needs systematic optimal integrated river basin planning.

The integrated system modeling is often a quite complex problem because it depends on various factors, such as, physical configuration of the system; site specific characteristics of the reservoir projects; active reservoir storage capacities; distribution of natural stream flows entering into the reservoirs; and multi-reservoir operating policy, etc.

No systems studies so far were earlier attempted or are found in literature for the optimal evaluation of water utilizations and water export potentials of various interstate trans-boundary rivers in space and time under the constraints put by rivers' water disputes tribunal awards on such a large scale. This of course is a herculean and tedious task requiring a lot of expertise in the field of systems analysis.

Advantages of linear programming (LP) based preliminary screening optimization models for planning and management of large complex water resources systems is already well established and acknowledged (Loucks et al., 1981; Chaturvedi and Srivastava, 1981; and Srivastava 1976). When a large number of single-purpose and multi-purpose reservoirs are present in the system the number of system constraints and variables become very high. Then one faces a very difficult task of modeling and solving the large integrated system for its solution. This cause basically restricts many in attempting such problems. Of course simulation should always follow the preliminary screening optimization models for further refinement. This, while after the optimization model has already pre-screened and eliminated non-optimal solution options of developments, and produced a solid initial base for the simulation process to begin its trial and error search for an early solution near to optimal (Wurbs 2005).

2.0 THE WATER AVAILABILITY IN SPACE AND TIME

Stream flow data are generally not available at many project sites. Various approaches existing along with one proposed have been used to estimate long-term monthly inflow data series at each and every reservoir site in a multi-reservoir system.

2.1 Estimation of Stream Flows at various Sites in the System

The following approaches have been adopted to estimate the stream flows at individual sites in different situations (Sethi, 2009):

(i) Projects where some flow data are missing/not available,
(ii) Reservoir on tributaries with no upstream regulation, with upstream/downstream gauged data available,
(iii) No gauging site in the stream across which the projects are situated/ proposed, but gauged data available at nearby site, and
(iv) Downstream gauged site in series receiving regulated contributions from just upstream reservoirs, with long term water utilization data available/not available.

3.0 THE EFFICIENT WATER UTILIZATIONS IN SPACE AND TIME

Linear programming (LP) based approximate reservoir yield models in the present form, used as optimization models for preliminary screening purposes and described later in the Para 6.0, were continuously developed and improved with time with varying water use purposes and objectives (Loucks, 1981; Dahe, 2001; Panigrahi, 2006; Sarma, 2006; Thube, 2007; Sethi, 2007; Jhajharia, 2012; Padhi, 2012; and Choudhary, 2012). The models are multi-yield, multi-reservoir, and which may also consider conjunctive water utilization and incorporates multi-objectives.

These comprehensive models, for planning integrated multi-purpose multi-reservoir system have various provisions, which during a normal water-year are capable of providing in space and time for each reservoir the following:
(i) Annual multi-yields, i.e., firm and secondary (with within-year distributions) from reservoir,
(ii) Over year carry over storage capacity in reservoir,
(iii) Within year variations in storages in reservoir,
(iv) Gives due consideration for crop planning which
(a) Takes care of the food habits of the population in the region,
(b) Takes care of the minimum food requirements of the farmers in the region on age group basis for their survival during recurring droughts, and
(c) Takes care and improves health (i.e., food nutritional values) of the people in the region.
(v) Mitigates the deteriorating environmental conditions in the river,
(vi) Incorporates system constraints pertaining to river water disputes, constrained by Tribunal Awards,
(vii) Allows for inter-basin water transfers (with within-year contributions) at export points,
(viii) Incorporates system constraints pertaining to conjunctive water use planning, and
(ix) Allows for multi-objective planning.

4.0 THE WATER DISPUTES AND SHARES

In India, the right of states in an inter-state river is determined by applying the rule of equitable apportionment, each unit getting a fair share of the water of the common river. The riparian rights usually govern the rights of private parties. But it does not help in settling inter-state water disputes satisfactorily. While allocating the waters to each riparian co-basin states in certain proportions, the present committed water utilizations in a water-year for the projects at down below by the other states is protected. The water resources development in the basin takes place in different phases. Therefore, the unused waters, if any, as of on a given date would come up for use in future, which the co-basin states are entitled to use in every water-year is also protected along with any surplus waters and which may be allocated in certain different proportions.

4.1 The Krishna Trans-Boundary River Water Dispute in Brief

The special features (Thube, 2007) of the Krishna Water Disputes Tribunal (KWDT) award are briefly described here. The KWDT in 1973, in its Final Order (FO) allocated the 75 percent water-year dependable flow of Krishna River among its riparian co-basin states (KWDT, 1973; and Bhongle, 2004). In addition to the above quantities, the KWDT also allocated them the estimated regenerated flows in the Krishna basin. Under the Scheme-A, the waters to each riparian co-basin states in a water-year were allocated in certain proportions. Further, in order to protect the committed utilizations in a water-year for the projects at down below by the other states, the KWDT placed additional restrictions in certain sub-basins, i.e., on the use of some specified waters on the states of Maharashtra, Andhra Pradesh and Karnataka. The Tribunal also stated that use of underground water by any state shall not be reckoned as use of the water of the river Krishna. Under the Scheme-B, the Tribunal also ruled that unused waters as of May 2000 would come up for reallocation along with any surplus waters in certain different proportions in every water- year. In effect, unlike Scheme A, which was binding on the three states, Scheme-B is dependent on the consent among the states.

4.2 The Cauvery Trans-boundary River Water Dispute in Brief

The special features (Sethi, 2009) of the Cauvery Water Disputes Tribunal (CWDT) award are briefly described here (CWDT, 2007). In 2007 in its Final Order (FO), the CWDT has directed the state of Karnataka to ensure a certain amount of ordered annual water release (with specified quantities of the within-year time/monthly/weekly distributions of release schedules), which is based on 50% water year dependable flow in normal years. The monthly release schedule is to be measured at the inter-State border point (Billigundlu G&D site). These ordered releases are meant for the state of Tamil Nadu and out of which a given quantity of water is to be used for environmental protection. There are no ayacut limitations on Karnataka. Ground water has been kept out of purview.

4.3 The Godavari Trans-boundary River Water Dispute in Brief

The Godavari Water Disputes Tribunal (GWDT) award given in 1980 and its Final Order (FO) have the following special features (GWDT, 1980; and Jhajharia, 2012):

(i) The award is very comprehensive, descriptive and elaborate in nature in comparison to the awards of the other river water disputes in India. Therefore, it may be a very difficult task to easily interpret and understand it.
(ii) The award does not specify the quantities in terms of the actual volume of the water to be shared by each of its co-basin states. Instead, most of the shares are defined in terms of the fractions or in percentages of the water-year river flows that would be available or expected during a normal water-year (the 75% dependable water-year) at some specified points in the various sub-basins. These shares were usually based on the various agreements earlier reached among these concerned riparian co-basin states. The agreements in effect imply a series of inter-state compacts in the sense that the specified co-basin states are free to utilize flow of river Godavari or its tributaries up to certain specified one or more reservoir sites.

4.4 Generalized System Constraints Derived Based On Various Tribunal Awards

A few modeling studies (Thube, 2007; Sethi, 2009; Padhi, 2012; and Jhajharia, 2012) were carried out earlier on trans-boundary interstate river basins regarding their respective optimal integrated water resources developments. The approximate reservoir yield models based on LP optimization technique were employed, as explained later. Apart from system's basic model constraints, a number of additional system constraints were incorporated in these models based on the tribunal awards and specified water exports. After going through them, these constraints may be otherwise classified in some general form for modeling purposes. These may be termed as the mandatory, recommendatory, contractual, and public demand constraints, etc as follows.

4.4.1 Constraints for water share allocations among riparian co-basin states during a water-year

4.4.1.1 Mandatory constraints
(i) Site specific (up to and/or below a reservoir or a given location in the river) water shares of river flows
(a) Restricted water use shares
(b) Free use of water shares
(ii) Specified reservoir and/or multi-reservoirs wise water shares
(iii) Sub-basin wise water shares
(iv) Water share between two or more states
(v) Total water shares among each individual state

4.4.2 Water release/storage (water-year and/or within-year) allocation constraints

4.4.2.1 Mandatory constraints:
(i) Reservoir wise scheduled releases including exports

(a) From a specified reservoir
(b) From specified multi-reservoirs
(ii) Scheduled sub-basin releases
(iii) Ensure downstream environmental releases including environmental exports

4.4.2.2 Recommendatory constraints:
(i) Provision of storage reservation in specified multi-reservoirs and/or a reservoir
(ii) Increase reservoir yields by
(a) Provision of over-year storage capacity in reservoirs to improve water availability
(b) Maintaining monsoon end storage in reservoirs to guarantee ordered releases during the following non-monsoon season/or otherwise

4.4.2.3 Public demand constraints:
(i) Public demand that stipulates annual quantum of water to be ensured by specified state/states for safety of the crops in a given region

4.4.3 Crop constraints

4.4.3.1 Contractual constraints:
(i) Limitations on cropping areas of crop /multi-crops
(a) Site specific (up to and/or below a reservoir or a given location)
(b) Reservoir wise
(c) State wise

4.4.4 Other constraints
(i) Proportioning of firm and secondary reservoir yields including exports
(ii) Meeting reservoir wise annual target demands
(iii) Site specific crop areas (up to and/or below a reservoir or a given location)

5.0 THE WATER TRANSFERS IN SPACE AND TIME

The task of quantifying and managing expected contributions made from multi-reservoir releases for diversion at the water export point during the within-year time periods in space and time have now become mandatory. This is due to the fact that the Tribunal Awards of various interstate river water disputes direct the exporting states concerned to release and divert some pre quantified total annual amount of water at the water export points. The within-year time period distributions for these expected total quanta of water diversions at the water export point are sometimes specified. But these distributions for the within-year time periods in space and time remain undefined. Therefore, the concerned exporting states responsible for water diversions may face lot of hardships in deciding these expected diversion quanta during within-year time periods in real time operations. Ultimately, these diversions are required to be shared among the multi-reservoirs involved.

Further, multi-reservoir operation policy of the system shall only determine and could specify these expected diversion quanta shares in space and time among the multi-reservoir system. The solution to all such problems lies in carrying out detailed and comprehensive analysis of the integrated multi-reservoir system involved in water diversions in an optimal manner.

6.0 ANSWERS TO INTRICATE INACCESSIBLE UNTOLD SOLUTIONS IN SPACE AND TIME

Several model applications using various systems analysis techniques along with other analysis tools were made especially on Indian rivers to evaluate and analyze their system behavior in an optimal manner. These include applications on single reservoirs and integrated multi-reservoir systems.

6.1 Single Reservoir Applications: Use of Various Modeling Techniques

In the single reservoir applications, the modeling approach varied using a single modeling approach to use of several lumped models at tandem. These studies basically carried out optimal storage-yield evaluations and/or derived reservoir operation policies, planning for canal scheduling, optimal planning and sequencing of hydro plants in irrigation canal, etc. For Mula reservoir Srivastava and Awchi (2009) carried out storage-yield evaluation and operation using lumped models and applied techniques of LP, DP, Simulation, ANN, hedging rules (also refer Awchi, 2004). Jain et al. (1999) earlier used ANN for reservoir inflow prediction and operation. Jena (2004) analyzed Harbhangi irrigation reservoir (i) for reservoir yield using LP based approximate reservoir yield model, and (ii) derived optimal irrigation canal water distribution schedules using DP models. This reservoir has a cascade of small hydropower plants also on the main irrigation canal and for this; the cascade system was optimally sized using DP, an optimal capacity expansion and sequencing schedule was obtained, and an optimal unit commitment policy was suggested for an efficient operation. Kohistani (1995) in his work showed the LP modeling approach for analyzing for planning and operation of single purpose irrigation and hydropower reservoirs, and a multipurpose reservoir. In the reservoir operation the monsoon's total inflows and its end storage were the parameters considered. Srivastava and Patel (1992) showed the use of screening-simulation models for planning Karjan irrigation reservoir. The LP based complete reservoir yield model was used for the purpose of initial screening. Talukdar (1999) applied stochastic dynamic programming for developing optimal multi-objective operation policies for each month for SSP reservoir. Mishra (1998) derived operation policy of a Ramganga reservoir. For the long term daily flow simulation a SCS-CN based model was employed. For Harabhangi (Sanimer 2008) reservoir a study on optimal water utilization and management of irrigation system (considering irrigation and non-irrigation days) is presented. For daily inflow generation hydrological simulation model based on modified SCS-CN method is used. LP based approximate reservoir yield model for optimal reservoir releases and crop plans is used. An improved planning model for canal scheduling of rotational irrigation is developed and a canal operational schedule is proposed a tabular form. Software is developed for this in a spreadsheet environment by developing macros in MS Excel's internal language: Visual Basic for Applications (VBA), (also refer Sanimer et al., 2013).

6.2 Multi-Reservoir Applications: Use of Various Modeling Techniques

In the multi-reservoir applications different modeling approaches using systems analysis techniques were employed. These studies basically carried out planning and development of multi-reservoir systems. Waikar (1998) analyzed future water resources development in Narmada river basin. As the river system is partially developed and 30 major and medium reservoirs would finally be built, therefore he considered the problem of optimal expansion and sequencing of multi-reservoir system using DP technique. The planning was carried out for two phases of water resources development in the river basin as per its Master Plan. The objective was meeting of the envisaged proposed system's future plan irrigation targets. Penalties in not meeting the proposed targets were also imposed. Deepti Rani (2004) used a set of linked optimization models at tandem to evaluate planning and operation of a proposed Pamba-Achankovil-Vaippar (PAV) water transfer link consisting of a system of three reservoirs. The shortage of irrigation water in the Vaippar basin led to the need of import of water from the Pamba and Achankovil basins. The LP, DP and simulation techniques were used for the linked models. The models were applied at three levels. The first two were at the field and at the project levels for the planning, i.e., level-1 (i.e., LP for optimal crop planning for estimating irrigation demand and level-2 (i.e., DP for optimal water transfer, and multi-reservoir sizing), respectively. The last was at the project level for the operation of the system, i.e., level-3 (i.e., DP for optimal multi-reservoir operation, and canal water distribution). Srivastava (1987) described the importance of preliminary screening simulation models in water resources project evaluation.

6.3 Multi-Reservoir Applications: Use of LP Based Complete Reservoir Yield Models

In the beginning initially contributions were made to analyze a few trans-boundary multi-reservoir river systems for the basins' optimal integrated water resources developments. Systems analysis techniques, i.e., the LP based complete reservoir yield models were used. One of the earliest widely used optimization model in the field of water resources for planning and operation of reservoir system is called the complete reservoir yield model. The complete reservoir yield model had many drawbacks.

Chaturvedi and Srivastava (1981) made an attempt to study the problem of disputed height of the SSP reservoir in Narmada river basin with the help of screening-simulation modeling approach. The LP based complete reservoir yield model was used for the preliminary screening purposes to eliminate non optimal developmental strategies, and then followed by simulation model for further finer screening purposes. They concluded that the results of the preliminary screening model provide an initial starting base (the first question to be answered before one starts a simulation process) for simulation to follow next (also refer Srivastava, 1976). Sunita Devi, et al. (2005) applied the LP based complete reservoir yield model with modification for optimal water utilization and crop plans for multi-reservoirs in Subernarekha river system. The study was carried out to analyze the system under the constraints of the bounds put on the water utilizations for each riparian co-basin states of Bihar, Orissa and West Bengal, based on the tripartite agreements arrived by them (also refer Sunita Devi 1997). For Cauvery river basin development Patil (2004) applied the LP based complete reservoir yield model with suitable changes for optimal conjunctive water utilizations including intra-basin water transfers. Srivastava (1991) described that various software available for solving LP based optimization models require input data matrix in some standard specified formats. He showed the need and importance of generation of such input data matrix especially for multi-reservoir water resources systems, and for explanation provided a sample computer code for an algorithm in FORTRAN language for the purpose.

6.4 Multi-Reservoir Applications: Use of LP Based Approximate Reservoir Yield Models

In another set of major developments in the modeling approach later, contributions from applications on several trans-boundary multi-reservoir river systems were made for the basins' integrated water resources developments in an optimal manner. Systems analysis techniques, i.e., the LP based approximate reservoir yield models were employed. The approximate reservoir yield optimization model is an LP-based implicitly stochastic screening model, which was an improvement over the earlier used complete reservoir yield model (Loucks et al., 1981). He concluded that the model produced reasonable reservoir designs with the release reliabilities near targets. Stedinger et al. (1983) reviewed and compared deterministic, implicitly stochastic, and explicitly stochastic reservoir screening models. The models were applied to a hypothetical three-reservoir water supply problem, and the results were compared with simulation. From the results, he further confirmed the above findings of Loucks et al. (1981). During a period of about last 10 years, several major improvements were made towards the development of the reservoir yield model available in the present form.

The reservoir yield model of Loucks et al. (1981) existed about three decades ago before its extended version developed by Dahe and Srivastava (2002) and Dahe (2001) were applied to river Narmada a large river basin. Further improvements in the yield model were later made by Panigrahi and Srivastava (2005) and Panigrahi (2006), Sarma (2006), Thube (2007), Sethi (2007), Jhajharia (2012), Padhi (2012) and Choudhary (2012). These studies were applied to many interstate trans-boundary rivers in India for their respective water resources developments in an integrated and optimal manner. Due consideration and importance was given to the modeling of various constraints related to the provisions made in respect of these rivers' water disputes tribunal awards. The major issue for each river basin was of sharing of river's waters among its respective co-basin states. The sole aim of these studies was to determine and analyze that how far within the bounds of the rivers' tribunal awards; the waters of these rivers' can be optimally utilized for development.

These models have the ability to deal with all the water resources planning options as described in the Para 3.0 earlier. For the sake of mathematical modeling and its application to various river basin systems, the interpretations of various tribunal awards were made for the purpose of the academic study only. Based on these interpretations, additional constraints as described in the Para 4.0 earlier were introduced in the models, as per the problem requirement. The outcomes derived from these studies are many fold and important, which provide answers to some intricate problems in respect of systems' expected behavioral aspects in space and time, as explained in the Para 7.0 later.

These comprehensive developments in the reservoir yield models were incorporated at different times in the form as described below:
(i) Dahe and Srivastava (2002) introduced the concept of a failure fraction to allow for a pre-specified deficit criteria in annual yield targets, meant for the farmers' survival during expected drought periods in order to avoid complete failures under critical conditions. The modeling approach was demonstrated for 8 multipurpose reservoirs in river Narmada. Further, the integrated planning study of 30 multi-purpose (irrigation and hydropower) reservoirs in river Narmada is available in Dahe (2001). The study also incorporated some aspects of the river's tribunal award,
(ii) The yield model was further improved with the additions of crop plans and provision of downstream mandatory water requirement by Panigrahi and Srivastava (2005). Panigrahi (2006)

showed the integrated modeling approach by applying the model to about 50 multipurpose reservoirs in the Mahanadi river basin lying in Orissa,
(iii) Sarma (2006) applied the yield model with improvements to study Kalisindh-Chambal inter-basin water transfer links, which envisages different proposals of water transfers.
(iv) Later inclusion of multi-objective analysis was incorporated in the yield model by Thube (2007). In this study the model was applied to about 130 multipurpose reservoirs in Krishna river basin under the limitations of the river's tribunal awards. The constraints of the Schemes A and B of the award were incorporated in the model. The objective was to minimize the deviations in not meeting the water shares as per the river's tribunal award as one of the multi-objectives,
(v) Conjunctive water use modeling and incorporation of import and export of water was made in the yield model by Sethi (2009). The integrated modeling approach was applied in a very comprehensive manner to Cauvery river basin under the domains of the river's tribunal award to about 52 multipurpose reservoirs,
(vi) Jhajharia (2012) applied the yield model with some improvements to Godavari river basin under the domains of the river's tribunal award and carried out integrated analysis of about 400 major and medium reservoirs. As per the award about 38 water shares at different sites (reservoirs)/locations in the sub-basins were interpreted and defined and their provisions were studied. The study provides detailed comprehensive analysis of the optimal water utilizations for the river basin system in space and time,
(vii) Padhi (2012) has studied the proposed peninsular inter-basin water transfer links with the help of generalized yield model. The study included about 200 major reservoirs and provides expected water transfers with their within-year distributions at various exporting points in space and time.
viii) A study (Choudhary 2012) on optimal integrated planning and operation of Ken-Betwa water transfer link project is presented. The LP based improved approximate reservoir yield model was employed as an optimization model for planning. The fuzzy approach along with the above model (MOFLP) was employed for operation of the system to obtain the solution of the problem to obtain some compromise solution in the purview of prevailing conflicting water issues, which exist everywhere these days. The two fuzzy objectives were the firm vs. secondary within year reservoir yields available from the multi-reservoirs to meet various existing and future mandatory and irrigation water needs in the system.

6.5 The Solution Methodology

Though, standard software for the linear programming problem (LP) solution, e.g., LINDO, LINGO etc. is also available to solve very large size problems and is widely used in all kinds of disciplines (LINDO, 2002). But, while using this software, its input data requirement preparation for the problem matrix which is constructed for the model's constraints and variables is only in the form of text. The formulation and preparation of such input data matrix in any required form is many times very difficult and complicated, but is mandatory prior to software's application. Therefore in case of very large systems its use becomes prohibitory.

In the field of water resources in case of a river basin, for this reason, handling a very large size integrated trans-boundary water resources development problems became difficult. This is because of the complexity arising in the river system due to its physical configuration and special nature of any water resources system (where in every river system its reservoirs are at tandem and every reservoir differs in its system behavior) and a large number of system constraints present in the LP model describing the river system's behavior.

Algorithm developed over the years and used to generate the required input data matrix is essentially oriented towards and molded for attempting and handling any large size integrated trans-boundary water resources developmental problem of a river basin. Further its application is easy and requires only the basic (i) water planning related data of the river system and (ii) information about the physical configuration of the various reservoirs located at tandem in the river system, etc. At the same time most important is that it should be fool proof.

6.6 Information retrieval from LINDO outputs and analysis of results

One Algorithm developed was used in some cases later for the retrieval of different required sets of variables from the results obtained through the LINDO outputs consisting of several thousands of system variables, certainly without which the task of analysis would have been very difficult one. From the retrieved information, this also carries out detailed behavioral analysis of the various reservoirs in the river system.

6.7 The Outcomes from Studies

These studies have provided answers for many intricate inaccessible untold solutions to problems related to the water resources development in these basins, and which previously were remained out of reach or were left unanswered. During a normal water year these were basically the values of:

(a) (i) The expected optimal quantum of the annual reservoir releases or yields and their within-year distributions to be made or available from each and every reservoir in the system and (ii) The expected optimal quantum of the annual shares and their within-year distributions of the river waters by its co-basin states required from the individual reservoirs concerned under the bounds of the tribunal awards,
(b) The expected physical behavior of each and every reservoir in the river system and their respective behavioral statistical properties, and
(c) The expected optimal crop plans at each reservoir.

Providing these answers was very much essential and which could not be directly derived otherwise by any other approach or means. The methodology and the approach used in these studies should be essentially applied to many other such river systems, which is mandatory for the water resources to develop in future. This is because such required information could only be achieved through a detailed integrated analysis of a river system through modeling by means of optimization. Keeping this in mind, such studies require tremendous efforts, are manifold in size and out of expectations.

7.0 SUMMARY

Answers for many intricate solutions to various well known problems related to the behavior of integrated multi-reservoir system in a river basin have been derived from the detailed information derived from various systems analysis studies carried out earlier for different trans-boundary river basins with the help of approximate reservoir yield models.

7.1 The Important Answers Derived in Respect of Systems' Expected Behavioral Aspects

Various integrated systems studies mentioned earlier could achieve optimally the following:

(i) Detailed analysis of the expected multi-yields [firm and secondary] with their within-year distributions from each reservoir;
(ii) Detailed analysis of the expected cropping statistics [i.e., at each reservoir level, sub-basin/sub-basin levels and spatially, about (a) various cropping intensities and (b) various food produce, etc.] within the river system;
(iii) Detailed expected multi-reservoir operation policies [i.e., for each reservoir during the within-year time periods by (a) the initial rule curve for reservoir operation and (b) the continuous hedging rules for reservoir operation];
(iv) The expected statistics of the reservoir performance in terms of each reservoir's (a) either full condition [i.e., the month during the monsoon, if it spills or fills] or partial full condition [i.e., at the end of the monsoon, if it doesn't spill] and (b) empty condition during the non-monsoon, if any; and
(v) The expected quanta of the within-year time distributions of the water shares from each reservoir amongst the concerned specified multi-reservoirs involved in various disputed trans-boundary inter-basin river waters for allocating and diverting/exporting them among their respective riparian co-basin states.

These estimates are preliminary in nature and are only expected values in future which may be attained or achieved if all the projects are implemented and full development takes place in the system. These are just or tentative values obtained from a linear optimization model which needs refinements through the use of simulation modeling approach for accounting non-linearity in the system. Again these values are liable to change, due to the obvious reasons mainly that as and when good and reliable estimates of the available flows at each project sites could be quantified in future then there is a possibility that outcomes could be further modified. On the other hand these flows in the current study were estimated and their derivation was subjected to assumptions and which may not free from errors. The authenticity and correctness of the huge multi-disciplinary nature of the data needed for such a large system and used in the current study is not otherwise guaranteed. The above said estimates are broad guidelines and provide a platform to a planning manager for a better understanding of the systems' behavior which would lead to a sustainable planning and development of the river's water resources. Detailed analysis of the rivers' various water planning related aspects lay ahead which are mandatory and should be compulsorily done. However, the findings of this study achieved through the systems modeling approach would certainly serve useful purpose towards the rivers' water utilization up to a great extent irrespective of their method of derivation and accuracy. These studies have also built trained manpower up to some extent in this field as well.

The restructuring of water resources sector of many major rivers are already being taken or are being proposed by the various concerned states. At the same time need of carrying out integrated system modeling of rivers for their optimal water resources utilizations is being emphasized over and again from time to time. The task is difficult and requires trained manpower.

8.0 CONCLUSION

The basic objective of water use modeling is to plan/review of the schedule of release of water from reservoirs, crop diversification, and to make available dependable water release to maintain environmental flow in rivers. The purpose of preparing basin plan is (i) to prepare a long term perspective plan for the development of the basin water resources, (ii) to develop an integrated approach to the development of water and other natural resources with due regard to constraints imposed by water availability, and (iii) to identify and set priorities for promoting water resource development projects.

The various studies described above could arrive at answers to many problems related to the water resources development in various river basins, and which were previously at times remained out of reach or were left unanswered. Knowing these answers was very essential and which could not be directly derived or obtained otherwise by any other approach or means. With the consideration of the National Water Policy and application of the various reservoir yield models, comprehensive water resource planning and analysis were carried out for various river basins within the frame work of an overall plan for the basin/sub-basin within the provisions of tribunal award, water transfers, and all the water needs for the environmental purposes, M&I water supply, irrigation and in some cases hydropower etc. Further, the above applications have resulted in creating the required manpower for carrying out similar studies in future.

Thus there is a great possibility to enhance the knowledge about the properties of the system's behavior in terms of the expected extents of the water availability and its utilization with respect to space and time in more detail. That would then open more desirable alternative planning options and encourage and assist in the comprehensive planning for increased utilization of the water resources potential in the region. The entire process in turn is certainly going to boost and raise better developmental prospects in the river basin leading towards water resources sustainability in the future. The difficulties arising in the water sector should be considered as opportunities and only by act on our ideas would our waters be sustained for the mankind.

REFERENCES

Awchi, T. A. (2004): Optimal Planning and Operation of a Reservoir, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Bhongle, S. (2004): Krishna Water Dispute a Comprehensive Review, Rajhans, Prakashan, Pune, India.

Cauvery Water Disputes Tribunal (2007): The Report of the Cauvery Water Disputes Tribunal with the Decision, Government of India, New Delhi.

Chaturvedi, M. C. and Srivastava, D. K. (1981): Study of a complex water resources system with screening and simulation models, Journal of Water Resour. Res., 17(4), 783-794.

Choudhary. M. K. (2012): Optimal Planning and Operation of a Water Transfer Link, PhD Thesis submitted, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Dahe, P. D. (2001): Planning For Optimal Development of a River Basin, PhD Thesis, Dep't of Hydrology, Univ. of Roorkee, Roorkee, India.

Dahe, P. D., and Srivastava, D. K. (2002): Multi reservoir, multi yield model with allowable deficit in annual yield, Journal of Water Resour. Plann. Manage., 128(6), 406-414.

Deepti Rani (2004): Multilevel Optimization of a Water Resources System, PhD Thesis, Dep't of Mathematics, I I T Roorkee, Roorkee, India.

Godavari Water Disputes Tribunal (GWDT) Award (1980): The Final Report, Government of India, New Delhi.

Jain, S.K., Das, A., and Srivastava, D.K. (1999): Application of ANN for reservoir inflow prediction and operation, Journal of Water Resour. Plann. Manage., 125(5), 263-271.

Jena, J. (2004): Systems Analysis of an Irrigation and Cascade Hydropower Scheme, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Jhajharia, D., (2012): Planning for Optimal Water Resources Development of Trans-boundary Godavari Basin, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Krishna Water Disputes Tribunal (KWDT) Award (1973): The Final Report, Government of India, New Delhi.

Kohistani, A., (1995): Integrated Planning and Operation of a Reservoir, PhD Thesis, Dep't of Hydrology, Univ. of Roorkee, Roorkee, India.

LINDO (2002): Release 6.1 (15 Jan. 02) Copyright © 2002 by LINDO Systems, Inc., Chicago, USA.

Loucks, D.P., Stedinger, J.R., Haith, D.A. (1981): Water Resource Systems Planning and Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Maharashtra Water and Irrigation Commission (1999): Sub-basin wise planning and management, MWIC Report, Vol. II, Govt. of Maharashtra, pp. 534.

Mishra, S. K. (1998): Operation of a Multipurpose Reservoir, PhD Thesis Dep't of Hydrology, Univ. of Roorkee, Roorkee, India.

Padhi. C. S. (2012): Optimal Large Scale Water Transfers in Space and Time, PhD Thesis submitted, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Panigrahi, R. K. (2006): Optimal Utilization of Water Resources of Mahanadi River Basin in Orissa, India, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Panigrahi, R. K. and Srivastava, D. K. (2005): Assessment of Optimal Yield in a System of Reservoir, Hydrological Perspectives for Sustainable Development Vol. II, International Conference HYPESD-2005, Dep't of Hydrology, I I T Roorkee, Allied Pubs. Ltd., New Delhi.

Patil, M.D. (2004): Optimal Water Utilization and Intra-Basin Water Transfers in Cauvery Basin, India, PhD Thesis, WRDTC, I I T Roorkee, Roorkee, India.

Sanimer Kaur (2008): Optimal Water Utilization and Management of an Irrigation System, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Sanimer et al. (2013): Improved planning model for canal scheduling of rotational irrigation, Posted Ahead of Print on Jan. 5, 2013, Journal of Irrig. Drain. Eng.

Sarma, B. (2006): Planning For Optimal Inter Basin Water Transfer, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Sethi, B.K. (2009): Optimal Development of Water Resources of Cauvery Basin, PhD Thesis, Dep't of Hydrology, I I T Roorkee, Roorkee, India.

Srivastava, D. K. (1976): Optimization of Complex Water Resources System by Screening-Simulation Model, PhD thesis, Dep't of Civil Engg., I I T Delhi, New Delhi, India.

Srivastava, D.K. (1987): Preliminary Screening Simulation Model in Water Resources Project Evaluation, Proceedings First National Water Convention, Central Board of Irrigation and Power, Malcha Marg, Chanakyapuri, New Delhi, Vol. IV.

Srivastava, D.K. (1991): Generation of Input Data Matrix for Linear Programming Model in Water Resources Systems, Seminar Proc., National Seminar on Use of Computers in Hydrology and Water Resources, I I T Delhi, New Delhi, India.

Srivastava, D. K. and Patel, I. A. (1992): Optimization-simulation models for the design of an irrigation project, Journal of Water Resources Management, Kluwer Academic Publishers, the Netherlands, 6 (4), 315-338.

Srivastava, D.K., Awchi, T.A. (2009): Storage-yield evaluation and operation of Mula reservoir, India, Journal of Water Resour. Plann. Manage., 135 (6), 414-425.

Stedinger, J. R., Sule, B. F., and Pei, D. (1983): Multiple reservoir system screening models. Water Resour. Res., 19(6), 1383-1393.

Sunita Devi, Srivastava, D. K., and Mohan C. (2005): Optimal allocation for the transboundary Subernarekha River, India, Journal of Water Resour. Plann. Manage., 131(4), 253-269.

Sunita, Devi (1997): Optimization of a Large Size Water Resources System. PhD Thesis, Dep't of Mathematics, Univ. of Roorkee, Roorkee, India.

Talukdar, B. (1999): Operation of a Multipurpose Reservoir Using Stochastic Dynamic Programming, PhD Thesis, Dep't of Hydrology, Univ. of Roorkee, Roorkee, India.

Thube, A.D. (2007): Optimal Utilization of Water Resources of in Trans-boundary Krishna River Basin, PhD Thesis, Dep't of Hydrology, I I T, Roorkee, India.

Waikar, M. L. (1998): Capacity Expansion of Water Resources System, PhD Thesis, Department of Hydrology, Univ. of Roorkee, Roorkee, India.

Wurbs, R.A. (2005): Texas water availability modeling system. J. Journal of Water Resour. Plann. Manage., ASCE, 131(4), 270-279.