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Research Paper

INTEGRATED CONJUNCTIVE USE MODEL

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Increasing shortages of water supplies coupled with deteriorating quality of the sources has made the earlier paradigms of water resources planning irrelevant. Today's planner needs to adopt a holistic systems approach which considers surface water and ground water as complementary resources paving the way for implementation of conjunctive use concept. In the present study, the conjunctive use model is constructed as an allocation model of surface water and ground water which is constrained by system dynamics comprising of recharge-discharge boundaries of ground water aquifers and inflow-outflow of surface water bodies. The resulting non-linear programming model is solved by employing Sequential Unconstrained Minimization Technique. Finite element method is employed for solving the governing groundwater flow equation and the resulting hydraulics are incorporated in the optimization model by adopting unit response matrix technique. The validity of the developed integrated model is demonstrated by applying it to a field problem. The results indicate that the developed mathematical model is robust and capable of simulating the system hydraulics satisfactorily and is responding to the demand variations, cost variations, surface water mass balance and ground water draw down constraints reliably.

Keywords: Conjunctive Use, Constrained Non-linear Optimization, Mathematical Modelling, Unit Response Matrix, Application to real field problem

INTRODUCTION

Countries which depend on monsoon related rainfall have to deal with the problem of rationalizing the spatial and temporal variations in the rainfall receipts, as a substantial part of the total annual precipitation happens to occur during a short period of three to four months in a year. The problem is further compounded as periods of monsoon usually coincide with periods of low water demand.

India is one such country which depends on monsoon for meeting its water requirements. The traditional method of impounding surface water during periods of excess rainfall by implementing

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river-valley projects has been in use in the country since several decades. These projects require a good network of canal system to distribute the impounded water spatially and temporally. Water resources planners have mostly exploited the surface water bodies with little attention being paid to the ground water resources. Surface reservoirs have many disadvantages; evaporation, sedimentation, water logging and spread of diseases like malaria, to name a few.

The increasing cost of river valley projects and the associated problem led the planners to start looking at ground water as an alternate source of water supply. This realization, coupled with rapid urbanization has lead to a situation where several communities have begun to depend on ground water supplies to meet their water demands. Deficient rainfall leading to insufficient surface water supplies compels the people to overexploit the groundwater thereby paving the way for manifestation of problems like ground water mining, land subsidence and sea water intrusion in coastal belts.

Thus, water, which in reality was an abundant renewable resource, has today become the bone of contention between various states and countries thereby compelling decision makers to look at various alternate options to resolve the problem.

SUSTAINABLE WATER RESOURCES DEVELOPMENT

The term ‘Sustainable Development’ has been used by various professionals to convey a similar concept but with subtle differences. Perhaps the best and most profound definition of sustainable development is contained in the Bruntland Report (World Commission on Environment and Development, 1987) which defined it as ‘Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.’

With reference to water resources, sustainability is viewed as holistic systems concept applied for the design and operation of water resources systems with the objective of meeting the communities’ water needs while maintaining the environmental and hydrological balance of the system.

Even though the concept dates back to several decades, practical implementation based on mathematical simulation has not been observed until recently. Of late, improved computational capabilities have made it possible to implement sustainable development policies in a realistic manner.

CONJUNCTIVE USE AS A TOOL FOR SUSTAINABLE DEVELOPMENT OF WATER RESOURCES

Dependence on either surface water or ground water alone not only leads to scarcity of the resource but it also causes deterioration in the quality of the water supplies. Conjunctive use visualizes a deliberate combined use of the surface and ground water resources to meet the varying demands in different time periods. Conjunctive use concept views the ground water as subsurface storage which can be recharged during periods of excess availability and pumped at different spatial and temporal locations depending upon the demand.

The history of conjunctive use is not as clear as one would wish it to be. Jamieson *et al.* (1996)

report that the concept of integrated hydrosystems management has been recognized by practitioners since the early 1970s. This perception was endorsed by the United Nations in the Dublin Statement in 1992.

Conjunctive use management applied to field problems has been found to be employing different solution techniques. The chief techniques among them are:

Conceptual Application of Conjunctive Use: The non-mathematical conjunctive use method merely recognizes that the entire water demand in a river basin has to be met totally from the surface water reservoirs during the periods of abundant precipitation and through either a combination of surface water and ground water or purely ground water sources during the dry periods. Jenkins (1992), Babu Rao *et al.* (1997), Dwarakanath *et al.* (1997), Rao (2000) and Nageswara Rao (2004) have documented some of the non-mathematical applications of conjunctive use. Bannerman (1997) has documented the failure of conjunctive use principles in Ghana due to inadequate attention paid by the engineers to the management and protection of the ground water resources. Daniel P Loucks (2000) has stressed the importance of demand management in conjunction with resource management for successful implementation of integrated management of water resources.

Non-Integrated Conjunctive Use Applications: In this method, appropriate optimization techniques are employed to solve the conjunctive use problem in a scientific and technically sound manner. The surface water and ground water equations are solved numerically and the solution is passed on to the optimization model which yields the optimal solution for the decision variables consisting of ground water and surface water allocations. Buras and Hall (1961), Johnston *et al.* (1973), Jagmohan Das (1978), Osman Coskunoglu and Shetty (1981), Nishikawa (1998), Pamela G Emch and William W-G Yeh (1998), Laxmi Narayan Sethi *et al.* (2002), Paul M Barlow *et al.* (2003), Manuel A Pulido-Velazquez (2003), Paul W McKee *et al.* (2004), James McPhee and William Yeh (2004) have documented some of the non-integrated applications of conjunctive use.

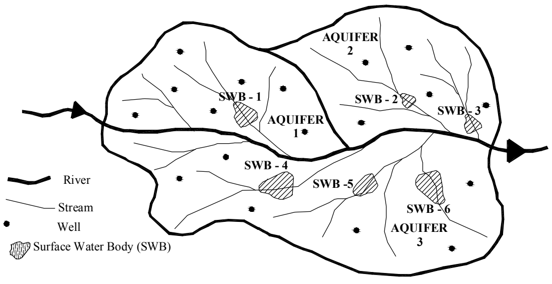
Integrated Conjunctive Use Application: In the integrated conjunctive use method, the numerical model for the solution of surface water and ground water equations is integrated with the optimization model leading to a single mathematical model. Maddock (1972), Gorelick (1983) and (1984), Yeou-Koung Tung (1986), Gordu *et al.* (2001) and Theodossiou (2004) have presented some of the integrated conjunctive use applications. The present work draws its inspiration from the presentation of Robert Willis and William W-G Yeh (1987). The conjunctive use model is formulated as a non-linear programming problem with ground water and surface water allocations from one or several sources as decision variables with the objection function comprising of the cost of allocation which is minimized.

CONCEPTUALIZATION OF THE INTEGRATED CONJUNCTIVE USE MODEL

The mathematical conjunctive use model is formulated as a resource allocation model of the water resources system. The goal of the model is to optimally allocate the surface water and groundwater of a river basin, over a chosen planning horizon, to competing water demands.

The conceptual formulation of the model is explained with reference to Figure 1. The river basin is deemed to have 'M' aquifers (i = 1, 2, 3, …, M) and 'N' surface water bodies (j = 1, 2, 3, …, N). The 'L' water demands are represented by k = 1, 2, 3, …, L.

Figure 1: Conceptual Representation of The Conjunctive Use Problem



The model aims at optimal allocation of surface water and groundwater from the 'M' aquifers and 'N' surface water bodies to the 'L' demands in each of the planning periods. The total planning periods may be considered as 'P' with t = 1, 2, 3, …, P.

The decision variables of the problem are the individual allocations from each of the surface water and groundwater sources to each of the demands. The variables are represented as GW_{ik}^t (groundwater allocation from aquifer 'i' to demand 'k' in planning period 't') and SW_{jk}^t (surface water allocation from surface water body 'j' to demand 'k' in planning period 't'). The groundwater allocation from aquifer 'i' to demand 'k' in planning period 't' is the sum of the allocations from all the wells within the aquifer 'i' during the planning period 't'.

The objective function of the conjunctive use model is formulated to minimize the total cost of allocation of groundwater from 'M' aquifers and surface water from 'N' water bodies over 'P' planning periods subject to the groundwater and surface water system constraints, demand constraint, capacity constraints and head constraints. The conceptual representation of the problem is presented in Figure 1.

Mathematical Formulation of the Integrated Conjunctive Use Model

The objective function of conjunctive use model is formulated as:

$$Min\,Z=\sum_{k}\left[\sum_{i}f_{ik}^{t}\left(GW_{ik}^{t}\right)+\sum_{j}f_{jk}^{t}\left(SW_{jk}^{t}\right)\right] \quad ...(1)$$

where f_{ik}^t and f_{jk}^t are the costs of unit water allocation from the i^th^ aquifer and j^th^ surface water body respectively to the k^th^ demand in time period 't'.

The objective function is constrained by the following equations:

Surface water system equation

$$\overline{SW}_{j}^{t}=\overline{SW}_{j}^{t-1}+R_{j}^{t}-\sum_{k}\left(SW_{jk}^{t}\right) \quad ...(2)$$

where

$\overline{SW}_j^t$ = Volume of water in storage in water body 'j' at the end of time 't'

$\overline{SW}_j^{t-1}$ = Volume of water in storage in water body 'j' at the end of time 't–1'

R_j^t = Volume of inflows during the period 't'

SW_{jk}^t = Volume of water allocated from water body 'j' to demand 'k' in time period 't'

Ground Water System Equation

$$\left([B]+\frac{1}{\Delta t}[C]\right)[h]_{t+\Delta t}-\frac{1}{\Delta t}[C]\{h_t\}=[F]_{t+\Delta t} \quad ...(3)$$

where

$h\}$ = Matrix of hydraulic head in the aquifer.

Δt = Time increment in the Finite Difference Solution of time derivative.

$[B]$ = Permeability matrix in Finite Element Method.

$[C]$ = Storativity matrix in Finite Element Method.

$[F]$ = Flux matrix (Right hand side vector) in Finite Element Method.

Ground Water Balance Constraint

The $\sum_i GW_{ik}^t$ term in Equation (1) is replaced with the sum of discharges from each of the active well sites in 'M' aquifers. In many practical applications only one ground water aquifer may be encountered in the implementation of the conjunctive use model. In such a scenario, the $\sum_i GW_{ik}^t$ term can be replaced with the sum of discharges from all the active wells in the aquifer.

$$\sum_i GW_{ik}^t=\sum q_a^t \text{ where } a\in\Delta_i \quad ...(3a)$$

where 'q' is the discharge and represents the set of control nodes in aquifer 'i'

Surface Water Quantity Constraint

$$\bar{S}\bar{W}_j^t\le SW_j^* \quad ...(4)$$

where SW_j^* **=** Maximum capacity of the surface water body 'j'.

Head Constraint

$$h_{i,a}^t\le h_{i,a}^* \quad a\in\Delta_i \quad ...(5)$$

Non-negativity Constraint

$$GW_{ik},SW_{jk}\ge 0.0 \quad ...(6)$$

The optimization model whose objective function is given by Equation (1) is a non-linear programming model which is subjected to constraints represented by Equations (2) to (6). Sequential Unconstrained Minimization Technique is used to obtain the optimal solution for this non-linear optimization problem of conjunctive use.

SOLUTION OF THE OPTIMIZATION PROBLEM

Sequential Unconstrained Minimization Technique (SUMT) has been adopted in the present study for solving the constrained non-linear programming problem of conjunctive use. The algorithm presented by Bazaara (1979) has been coded in FORTRAN programming language and the same has been validated with reference to the standard problems present in the same textbook.

Penalty functions have been employed for converting the constrained problem into an equivalent unconstrained problem which has then been solved by the non-gradient based Hooke and Jeeve's method. Bisecting search algorithm has been adopted for one dimensional minimization.

IMPLEMENTATION OF THE CONSTRAINTS

Among the various constraints the ground water system constraint and surface water system constraint require special consideration as they are governed by respective system equations. In the present study the groundwater system equation is solved by employing finite element algorithm and the surface water system constraint is incorporated by means of simple mass balance technique.

Finite Element Model for Ground Water Flow Equation

Incorporation of the ground water system constraint represented by Equation (3) into the optimization model requires numerical solution of the ground water flow equation whose general form is given by:

$$\frac{\partial}{\partial x}\left[T_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[T_{yy}\frac{\partial h}{\partial y}\right]=S\frac{\partial h}{\partial t} \qquad ...(7)$$

In the present study finite element solution is obtained by employing Galerkin formulation (Sreenivasulu, 1982). Time integration is performed by using Implicit Finite Difference method which is unconditionally stable. The resulting system of linear simultaneous equations (Equation 3) is solved by using banded Gaussian Elimination. The algorithm has been coded in FORTRAN Programming language and validated with reference to the known case study of Ghazipur aquifer of Uttar Pradesh (Kumar, 1987). The model has been found to be simulating the aquifer satisfactorily.

Surface Water System Constraint

This constraint is implemented by employing simple mass balance technique. The available quantity of surface water is computed at the end of each planning period by making a balance between the storage, inflows and allocations. The mass balance is represented by Equation (2).

COUPLING OF THE FINITE ELEMENT MODEL WITH THE OPTIMIZATION PROGRAM

The solution obtained by the finite element model needs to be incorporated as the constraint of the optimization model. This is accomplished by one of the following ways (Pulido, 2003):

Embedding Approach: In this method, the finite element equations are directly incorporated in the constraint set.

Simulation Optimization Approach: In this method, repeated calls are made to the finite element model in order to obtain the values of the state variables and gradients.

Unit Response Matrix Approach: This method is based on the principle of linear superposition and is applicable in linear or slightly non-linear systems. Here, the finite element model is solved as many times as the number of pumping wells with a unit stress applied only during the first period of pumping and to only one of the wells at a time. The response matrix coefficients are constructed based on the head matrix obtained during the simulation run. The drawdown at different time levels due to pumping at a combination of wells is obtained by applying the principles of linear superposition.

The response matrix for transient ground water flow is constructed by applying a unit rate of pumping in stress period 1 only (Maddock, 1972) and computing the drawdown responses to this stress in all time periods. This necessitates that all the stress periods are of equal duration. The drawdown in each period is not only induced by pumping in that period, but also by pumping in previous periods. Since stress periods are of equal length, drawdown in period 3 due to a stress in period 2 is the same as drawdown in period 2 due to the same stress in period 1. This feature allows the entire response matrix for transient systems to be constructed by staggering the responses appropriately in the time frame.

The format of response matrix adopted in the present work is shown in Equation (8). Ten time periods of equation duration are considered with pumping wells located at nodes 7, 13 and 17. The response of the aquifer to pumping is computed at the control nodes 3, 9, 12 and 19.

In Equation (8), $S_{i,k}$ represents the response at control node i due to pumping in time period k, $R_{i,j,k}$ represents the drawdown obtained at the end of time period 'k' at node 'i' due to unit pumping at well j during the first time period and $Q_{j,k}$ represents the actual pumping rate at node j during time period k.

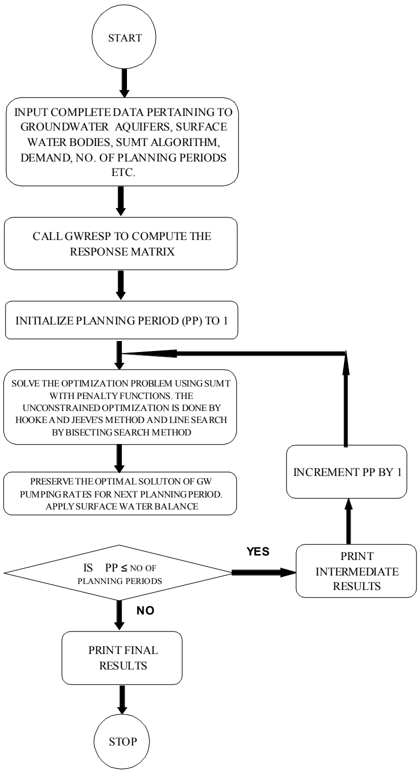
Hence by using the response matrix the need to solve the finite element model repeatedly during the optimization process is avoided and this leads to a faster solution to the problem.

$$\begin{bmatrix} S_{3,1} \\ S_{9,1} \\ S_{12,1} \\ S_{19,1} \\ S_{3,2} \\ S_{9,2} \\ S_{12,2} \\ S_{19,2} \\ \vdots \\ S_{3,10} \\ S_{9,10} \\ S_{12,10} \\ S19,\ 10 \end{bmatrix} = \begin{bmatrix} R_{3,7,1} & R_{3,13,1} & R_{3,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{9,7,1} & R_{9,13,1} & R_{9,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{12,7,1} & R_{12,13,1} & R_{12,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{19,7,1} & R_{19,13,1} & R_{19,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{3,7,2} & R_{3,1,3,2} & R_{3,17,2} & R_{3,7,1} & R_{3,13,1} & R_{3,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{9,7,2} & R_{9,13,2} & R_{9,17,2} & R_{9,7,1} & R_{9,13,1} & R_{9,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{12,7,2} & R_{12,13,2} & R_{12,17,2} & R_{12,7,1} & R_{12,13,1} & R_{12,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{19,7,2} & R_{19,13,2} & R_{19,17,2} & R_{19,7,1} & R_{19,13,1} & R_{19,17,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{19,7,10} & R_{19,13,10} & R_{19,17,10} & R_{19,7,9} & R_{19,13,9} & R_{19,17,9} & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & R_{19,17,1} \end{bmatrix} \begin{bmatrix} Q_{7,1} \\ Q_{13,1} \\ Q_{17,1} \\ Q_{7,2} \\ Q_{13,2} \\ Q_{17,2} \\ \vdots \\ Q_{7,10} \\ Q_{13,10} \\ Q_{17,10} \end{bmatrix} \quad \ldots (8)$$

INTEGRATED CONJUNCTIVE USE MODEL

The flow chart of the integrated conjunctive use model is shown in Figure 2. The FORTRAN code for the flow chart has been validated with

Figure 2: Flowchart of the Integrated Conjunctive Use Model

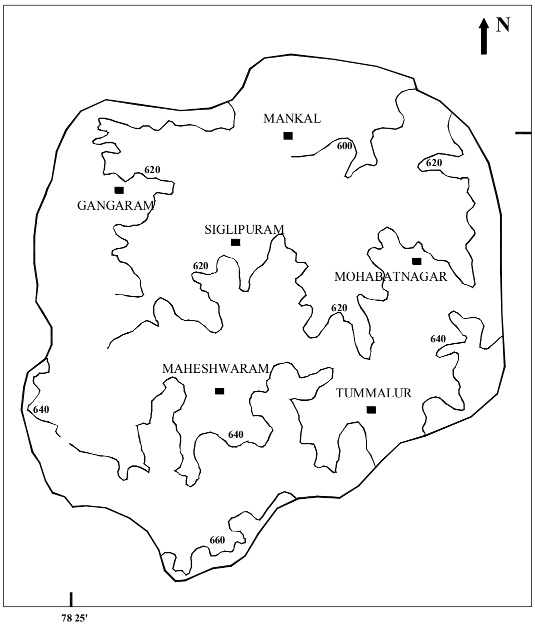


reference to a known solution of a hypothetical rectangular aquifer (Jafari, 2006). The applicability of the model to real field problems is demonstrated in the present study with reference to Maheshwaram Watershed in Andhra Pradesh State of India.

MAHESHWARAM WATERSHED

The Maheshwaram Watershed is located in Maheshwaram Mandal of Ranga Reddy District, Andhra Pradesh State, India and is spread over an area of about 60 sq. km. The watershed is located between geographical coordinates of Latitude 17^0 06' 20" to 17^0 11' 00" N and Longitude 78^0 24' 30" to 78^0 29' 00" E. The region is represented in the Survey of India Toposheet No. 56K/8. Figure 3 shows the topographic map of the Maheshwaram Watershed with superimposed contours. The area is situated at an elevation ranging between 600 and 670 m above Mean Sea Level and exhibits an undulating topography with about 2% slope. The climate of the area is semi-arid and it receives an average of 812 mm of rainfall, over 80% of which is from the SW Monsoon (WENEXA, 2003)

Figure 3: Contour Map of Maheshwaram Watershed

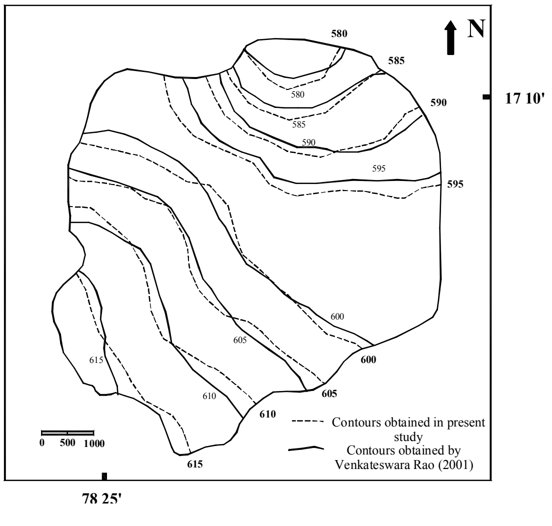


The Maheshwaram Mandal covers six villages, viz., Maheshwaram, Siglipuram, Gangaram, Tummalur, Mohabatnagar and Mankal with a population of 18,454 as per 2001 Census.

Simulation of the Aquifer

The hydro-geologic data pertaining to Maheshwaram watershed as presented by Rao (2001) is used for calibration of the finite element simulation model. The existing water table elevations of November 1987 are taken as steady state solution and transient calibration of the model is demonstrated by comparing the predicted levels of June 1992 with the observed levels. Figure 4 shows that the model has been calibrated satisfactorily. The calibrated model is then used for generating the response matrix required for integrated conjunctive use model solution.

Figure 4: Transient State Calibration of the Groundwater Flow Model



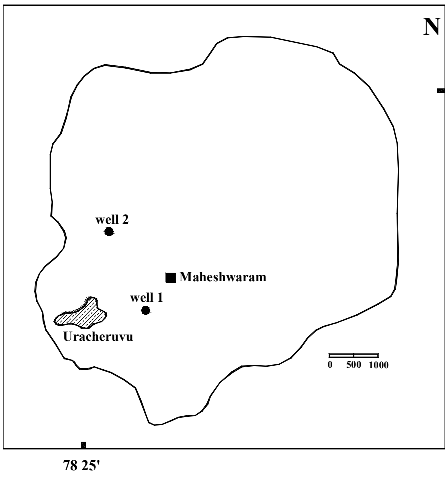
FORMULATION OF THE CONJUNCTIVE USE PROBLEM

In order to demonstrate the satisfactory working of the developed integrated model, it is applied to the Maheshwaram Watershed by considering a single demand to be met by allocations from two wells and one surface water body. Figure 5 shows the location of the demand (Maheshwaram Village) along with the location of wells (Wells 1 and 2) and surface water body (Uracheruvu).

Planning Horizons

The model is run for a total planning period of 3 years with a time increment of 6 months.

Figure 5: Location of Wells and Surface Water Source in the Watershed



Water Demand

The demand of water at Maheshwaram Village is taken as 3, 2, 2.5, 1, 3.5 and 2.5 million cu m during the 6 planning periods.

Cost Coefficients

The cost coefficients have been computed by considering the capital and operation and maintenance costs. Prevailing local rates have been taken for computation of costs. In order to convert discrete cost coefficient data into a continuous function, equations have been fitted to the data and the same have been included in the integrated model.

Equations are obtained for surface water and ground water supply with gravity and pumped mains separately. The equations are shown in Table 1 as functions of x, where x is the supply in million cu. m per half year period.

Appropriate expressions for cost coefficients are constructed in terms of functions f_1 to f_5 and included in the objective function. The contour map given in Figure 3 is used to estimate the elevation difference and Figure 5 is used to obtain distances between the sources and destination.

Table 1: Cost Coefficient Equations for Surface Water and Groundwater Supply Through Gravity and Pumped Mains

Particulars of Cost	Gravity Main	Pumped Main (per m head)
Capital Cost of Conveyance / half year / Km length (Rs. in Lakhs)	$f_1(x) = 7.04481 + 23.70929\ x - 3.0289\ x^2$	$f_2(x) = 9.12359 + 27.56677\ x - 3.70425\ x^2$
O & M Cost of Conveyance / half year / Km length (Rs. in Lakhs)	$f_3(x) = 0.25627 + 0.0281x + 0.000449\ x^2$	$f_4(x) = 0.44673 + 0.08099\ x + 0.00756\ x^2$
O & M Cost of lifting GW to the Surface/MCM/ half year (Rs. in Lakhs)	$f_5(x) = 0.00666 + 0.3848\ x$	

Note: gravity and pumped mains.

For example, the cost of supplying ground water through pumped main can be expressed in lakhs of rupees as:

$$f_5(LH)*X + f_2(X)*L + f_4(X)*L*H \qquad ...(9)$$

where (LH) is the lifting head, X is the supply discharge, L is the distance between the well and the demand location and H is the elevation difference between them.

Maximum Capacity of the Surface Water Body

The maximum capacity of Uracheruvu (surface water body) is taken as 2.56 million cu m and the volume at storage at the beginning of the planning period is 0.25 million cu.m.

Inflows in to the Surface Water Body

The inflows during the 6 planning periods into Uracheruvu are taken as 1.298, 0.623, 2.118, 0.328, 2.768 and 0.24 MCM.

Head Constraint

Maximum drawdown constraint is applied only at the two pumping wells. A liberal value of 13 m is specified in order to permit unrestricted pumping.

MODEL OUTPUT

The satisfactory working of the model is demonstrated by considering its response to the following parameters:

- Demand satisfaction.
- Surface water mass balance verification.
- Effect of variation of cost coefficients.
- Response to changes in head constraint.

Demand Satisfaction

Table 2 presents extracts from the output of the model which shows that the sum of surface water and ground water allocations equals the demand in each of the planning periods. The results are depicted graphically in Figure 6.

Table 2: Abstracts from the Output for Demand Satisfaction

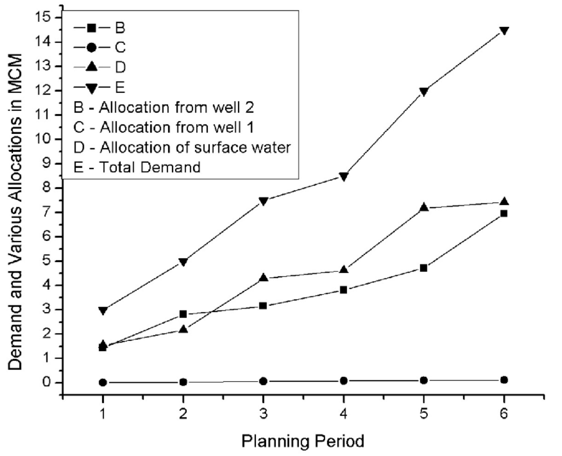
Planning Period (1)	Number of iterations in SUMT (2)	Values of the three decision variables in MCM (3)	Sum of the Allocations made in MCM (4)	Demand to be met as per given input in MCM (5)
1	10	0.14443026E+01 0.71513710E-02 0.15482824E+01	2.999736371	3
2	10	0.13575166E+01 0.19159168E-01 0.62297618E+00	1.999651948	2
3	9	0.35277307E+00 0.28692970E-01 0.21181509E+01	2.49961694	2.5
4	11	0.65091574E+00 0.21137823E-01 0.32776569E+00	0.999819253	1
5	9	0.91722677E+00 0.21980286E-01 0.25603239E+01	3.499530446	3.5
6	10	0.22348882E+01 0.22997230E-01 0.24186082E+00	2.49974625	2.5

Well 1 is located closer to the source but it employs a pumping main as it is at a lower elevation than Maheshwaram Village. Supply from well 2 is by gravity main. It may be noted that in all the planning periods, despite its proximity to the demand site, allocations made from well 1 are negligibly small compared to the allocations from well 2. This is attributed to the fact that well at node 1 employs pumping main and hence the associated O and M costs are higher.

Surface Water Mass Balance Verification

In Table 3, values marked with asterisk constitute input. The surface water allocations in column (4) are taken from the output presented in Table 2. The computation of storage volume at the end of a planning period is shown in column (5). It is observed that the entire inflow is allocated during all the planning periods. In period 5, the inflow exceeds the maximum reservoir capacity and hence, the storage is restricted to the specified maximum capacity of 2.56 MCM.

Figure 6: Verification of demand satisfaction



Effect of Variation of Cost Coefficients

In order to study the response of the model to variation in cost coefficient the lifting head at well (2) is increased to 70 m from 31 m. The resulting output is shown graphically in Figure 7.

In the present run it is observed that the production well 1 has become active. In fact the total allocation from well 2 is now almost zero during planning periods 1 to 4 and it is meager during planning periods 5 and 6. This is explained in terms of the increased lifting head at well 2 which has made supply from well 1 more economical.

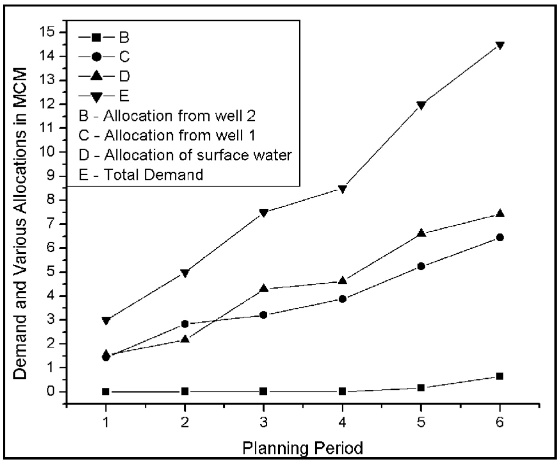
Response to Changes in Head Constraint

In all the solutions discussed so far the head

Table 3 : Surface Water Mass Balance Verification

Planning period (1)	Storage volume at the beginning of the planning period in MCM (2)	Inflow during the planning period in MCM (3)	Allocation during the planning period in MCM (4)	Water balance is computed as the sum of storage volume at the end of planning period 't-1'and the inflow during the planning period less the allocation made during the planning period (5)
1	0.25*	1.298*	1.548	0.25 + 1.298 - 1.548 = 0.0
2	0.0	0.623*	0.623	0.0 + 0.623 – 0.623 = 0.0
3	0.0	2.118*	2.118	0.0 + 2.118 – 2.118 = 0.0
4	0.0	0.328*	0.328	0.0 + 0.328 – 0.328 = 0.0
5	0.0	2.768*	2.56	(Since the maximum capacity of reservoir is 2.56 MCM the allocation is restricted to it even though the inflow is 2.768 MCM)0.0 + 2.56 - 2.56 = 0.0
6	0.0	0.24*	0.24	

Figure 7: Verification of Effect Of Change in Cost Coefficient



constraint was made deliberately inactive by specifying a liberal value of 13 m for permissible drawdown. In the present run of the model, the drawdown is restricted to 5 m in order to study the response of the model to head constraint. Abstracts from the output are presented in Table 4 and the graphical representation is shown in Figure 8.

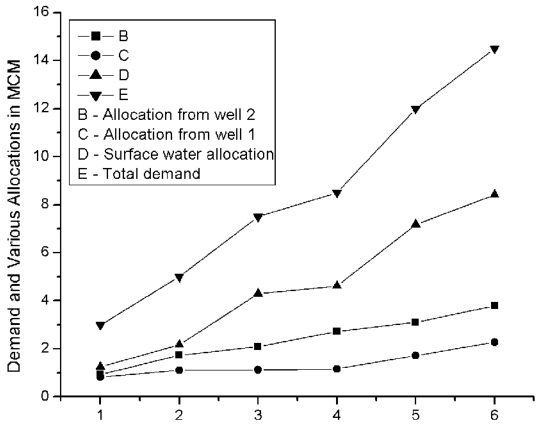
Referring to Table 4 it is observed that the ground water allocation during the first planning period, from well 1 was 1.444 MCM when the drawdown constraint was 13.0 m. This has now reduced to 0.928 MCM due to imposition of the 5.0 m drawdown limit. Obviously, the pumping from the other well at node 19 has been stepped up to meet this deficit as surface water is not adequate to meet the entire demand of the planning period.

Figure 7 shows that the ground water allocations have rationalized and both the wells are now pumping comparable discharges. This rationalization of pumping is attributed to the implementation of drawdown constraint in the current run of the model.

Table 4: Response to changes in head constraint

Planning Period	Number of iterations in SUMT	Values of the three decision variables in MCM	Sum of the Allocations made in MCM	Demand to be met as per given input in MCM
1	6	0.92815745E+00 0.82459637E+00 0.12460598E+01	2.99881362	3.0
2	11	0.79989140E+00 0.27478370E+00 0.92506660E+00	1.9997417	2.0
3	11	0.35850535E+00 0.23320773E-01 0.21179960E+01	2.499822123	2.5
4	9	0.63314260E+00 0.38257983E-01 0.32814075E+00	0.999541333	1.0
5	9	0.37791740E+00 0.56136425E+00 0.25602601E+01	3.49954175	3.5
6	10	0.70395216E+00 0.55388879E+00 0.12419429E+01	2.49978385	2.5

Figure 8: Implementation of Head Constraint



Hence it is concluded that the model is responding suitably to the imposed head or drawdown constraints.

CONCLUSION

Recent trends in water resources planning indicate increasing concerns about sustainability of the supplies. A holistic systems concept is therefore needed in order to ensure that the management decisions lead to sustainable development of the resource. Conjunctive use is one such concept which can be implemented to obtain sustainable development of water resources of a river basin. In the present study, the integrated conjunctive use model has been formulated as an allocation model which is a constrained non-linear programming problem which has been solved by employing Sequential Unconstrained Minimization Technique. Ground water and surface water dynamics constitute two important constraints of the model. The governing equation of ground water flow is a partial differential equation and its solution has been obtained by employing finite element method. The resulting solution has been incorporated in the optimization model by using unit response matrix technique. The surface water constraint has been implemented by employing mass balance technique. The final integrated model has been validated and its applicability to field problems demonstrated by formulating a simple allocation problem for the Maheshwaram Watershed in Andhra Pradesh, India. The results indicate that the developed model is very general in nature and can be applied to any real field problem.

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