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Modelling Techniques for Conjunctive Water Management: A Review

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ABSTRACT

Optimal allocation of surface water and groundwater is the key factor for conjunctive water management. Proper planning is necessary for optimal allocation of water for maximizing crop yield benefits and/or minimizing water quality problems. With the advent of computers, by the late 1960s, computer-aided mathematical models came into use to help decision-makers in planning conjunctive water management. Optimization models were popular in the early decades. Then researchers came to know the advantage of mimicking the situations and analyzing them before arriving at optimal solutions. Thus, simulation models and integrated simulation-optimization models came into existence. Multi-objective models were developed to solve more complicated physical situations. The computational burden of running thousands or lakhs of simulations before getting an optimum solution, generated evolution algorithms like ANN and GA to reduce the running time of models and obtain a more accurate solution. Even now we can't say the modelling approach is perfect to solve the real-world water-related issues that involve complicated physical phenomenon. A model which is more accurate, simpler and very near to real situations, may be developed in near future.

Key words: Conjunctive use, Irrigation, Optimization, Simulation, Water quality.

India is a water-stressed country with a per capita water availability of 1544 m^3 (Dhawan, 2017). As in other developing countries in India also almost 85% of water is used in the field of agriculture, mainly for irrigation (Reddy and Nayak, 2018). Irrigated agriculture is necessary to produce enough food for the growing population. In India, 56% of food grain production is achieved by irrigated agriculture (Raul and Panda, 2013; Khare *et al*., 2006). Water-stressed status of the country may adversely affect the irrigation sector (Saxena *et al*., 2015) and thereby the food security of the nation. Integrated use of available water resources is a possible solution to face the situation. Water stored in above-ground storage structures like dams and below-ground aquifers is the two major resources of water available for irrigation (Bejranonda *et al*., 2011; Singh, 2014; Foster *et al.,* 2010). Better integration of these major water resources through conjunctive use may give water to meet growing irrigation demands.

Combined use of surface water and groundwater is required to fulfill the irrigation requirement in tropical, semi-arid and arid regions (Foster *et al.* 2010; Karamouz *et al.,* 2004; Singh, 2014). The risk due to the stochastic nature of surface water supply is not there in conjunctive water use (Montazar *et al*., 2010). An increase in agricultural productivity, improved use of water sources with reduced degradation, adaptation to climate variation, reduced fluctuation of groundwater level and reduced environmental impact are the major advantages of conjunctive use of water (Bejranonda *et al*., 2011; Singh, 2014; Rezaei *et al*., 2016; Reddy and Nayak, 2018; Soares *et al*., 2019)

Farmers usually combine the surface water and groundwater use in an unscientific manner. Sustainability and optimal use of water resources may not be considered.

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Conflicts between stakeholders' interests may occur (Lari *et al*., 2009; Ejaz and Peralta, 1995). A systematic approach to the integrated use of surface and groundwater that requires coordinating mechanisms grounded on hydraulic and hydrological knowledge which is necessary to decide the quantity of groundwater abstraction is called conjunctive water management (Bejranonda *et al*., 2011; Foster and Steenbergen, 2011; Wrachien and Fasso, 2007). Water management through conjunctive use is thus a good tool to optimize productivity, equity in water distribution and sustainability of the environment through the coordinated management of surface and subsurface water resources. Groundwater withdrawal reduces waterlogging problems, soil salinity and thereby leaching requirement in a conjunctive water management system (Bejranonda *et al*., 2011). Water quality and groundwater sustainability issues are generally coined to conjunctive water use. Here comes the importance of proper planning when water is used conjunctively.

Burt, the first researcher who introduced the idea of conjunctive use of water in 1964, considered surface water and groundwater as two independent components of a combined water system (Burt, 1964 in Rezaei *et al*., 2016). Later it is realised that the use of one resource has an impact on the other (Ross, 2018) since they are hydrologically connected. Conjunctive water use utilizes this hydrological connection (Dudley and Fulton, 2005). The storage capacity of aquifers could be exploited in planned conjunctive water use. This reduces the construction cost of huge dams and reservoirs (Wrachien and Fasso, 2007; Montazar *et al*., 2010). Pumping from aquifer storage compensates for surface water scarcity, at the same time avoids waterlogging in the succeeding monsoon season, which creates a cycle of storage and discharges with dynamic equilibrium (Khan *et al*., 2014).

Mathematical modelling techniques are being used to aid the planning of conjunctive water management. Optimization models, simulation models and simulation-optimization models are there to solve water management issues. Some researchers arrived at an optimum cropping pattern for an area, to maximize the benefits by utilizing surface and groundwater conjunctively, using the modelling approach. Several researchers developed economic optimization models and some others developed multi-objective models. Evolutionary optimization techniques like Genetic Algorithm, Artificial Neural Network, *etc*. are used nowadays to reduce the computational burden involved in the simulation-optimization methods.

Optimization models

An optimal solution/strategy is mathematically the best that can be developed from the formulated mathematical problem of the system/situation. In a conjunctive management system, a groundwater pumping strategy that is optimal for one situation is often sub-optimal for a different situation. Various optimization techniques like linear programming, non-linear programming, dynamic programming, *etc*. are used to find out optimal solutions corresponding to each situation (Noel *et al*. 1980; Safavi *et al*., 2010; Peralta and Shulstad, 2004).

Linear programming

Linear programming is the simple and popular optimization technique used in conjunctive water management. It depicts complex relationships between decision variables into linear functions (Vedula and Mujumdar, 2005). Several numbers of software *viz* LINGO, LINDO, Solver, *etc*. are available for doing optimization with linear programming. More than a few studies have been reported on modelling conjunctive water management with optimization techniques using linear programming.

Linear programming can be used to work out the optimum cropping pattern suited for a region to maximise the returns through the conjunctive management of available water resources. Kumar and Pathak developed a model for the area between the Yamuna River and the Eastern Yamuna Canal. The developed model determines the optimum share of the canal and groundwater supply on a monthly basis. Vedula *et al*. (2005) developed a mathematical model using linear programming to arrive at an optimum policy for the allocation of canal water and groundwater to maximise the sum of relative yields of multiple crops in the command area of a reservoir-canal-aquifer system. The crop water allocations were attained by satisfying the three major constraints, *viz*., the mass balance of water at the reservoir, soil moisture balance for individual crops and limits of groundwater level fluctuation. The authors validated the applicability of the model by carrying out a case study in the command area of a reservoir in Chitradurga district, Karnataka State.

Linear programming was used to develop an optimization model and an irrigation scheduling model to plan conjunctive water use for the irrigation command area of the Hirakud multipurpose project (Raul *et al*., 2012). The predicted crop yield under full and deficit irrigation policies from the irrigation scheduling model was fed to the optimization model to optimise the allotted crop area and surface water based on net irrigation requirement. The results showed that the net annual return is highest with a full irrigation strategy and decreases as water scarcity increases.

Linear programming is useful in solving multi-objective optimization problems as well. Nikam and Regulwar (2015) developed an optimization model with linear programming for the conjunctive water use in the command area of a multipurpose reservoir. The developed model was suitable to find out the best operative strategy for a reservoir and the model was tested in a case study at Jayakwadi reservoir, Maharashtra. Optimum discharges for power generation and irrigation were obtained from the model after giving the first water supply priority for drinking and industrial use.

Non-linear programming

Even though linear programming is easy to formulate and apply it is unable to solve problems related to non-linear situations (Singh, 2014). Most of the conjunctive water management situations are non-linear in nature. So, non-linear programming is used for optimization, in such a situation where it is difficult to express the objective function and constraints as linear functions (Vedula and Mujumdar, 2005).

The best example of optimization using non-linear programming is the model developed by Montazar *et al*. (2010) for deriving an optimum cropping pattern for conjunctive use of surface and groundwater in a semi-arid region of Iran. Several conjunctive use scenarios, including deficit irrigation practices, were tested, along with several cropping patterns. Results showed that the conjunctive use scenario of 78% surface water and 22% groundwater allocation and the proposed cropping pattern would save a significant quantity of water. The study also showed that 20% deficit irrigation is ideal for maximising the overall benefits if it is possible to compensate for the groundwater draft through annual recharge.

Dynamic programming

Non-linear programming is also insufficient to solve sequential decision problems in conjunctive management of water resources. Hence, dynamic programming (DP) is used in such situations. An example of the sequential decision problem is the release of canal water. It depends on reservoir storage and this, in turn, varies temporally. So, the decisions need to be taken at different time periods according to the storage. Unlike linear programming, problems cannot be formulated by single standard algebraic functions. Specific features of the problems need to be considered while formulating dynamic programming problems. DP problems may be single-stage problems or multi-stage problems (Vedula and Mujumdar, 2005).

A multi-objective dynamic optimization model was developed by Karamouz *et al*. (2004) for planning the conjunctive use of surface water and groundwater in complex water use and recharge system in Tehran. The supply of water to meet agricultural demands, the reduction in pumping costs, the reduction of groundwater levels, *etc*., was the major objectives. A number of scenarios were tested to determine the long-term impact of conjunctive use planning and it was found that the developed model was effective for planning conjunctive water use.

Safavi *et al.* (2011) developed a conjunctive water use model using fuzzy dynamic programming to plan an optimum crop pattern to overcome uncertainties due to climate change for the Najafabad Plain in Iran. Interactions between surface water and groundwater were accounted for in the simulation model and an optimum crop plan and conjunctive allocation of surface water and groundwater were decided by the optimization model. The results obtained from the optimization model were used to run a simulation model. Results of the study indicated that the model is successful in optimum crop planning based on predicted climatic conditions with the conjunctive use of surface water and groundwater in arid and semiarid regions.

The Zayandehrood river basin in Iran is an area where the available surface water is insufficient to meet water demands like domestic, industrial, agricultural and environmental demands, which puts high pressure on groundwater resources. Safavi *et al*. (2013) developed an optimal model using dynamic programming for the operation of a reservoir in the area with the conjunctive use of surface water and groundwater resources. The authors developed fuzzy models as a simulator to reduce the computational burden of the DP model and to form operating rules for the reservoir.

Simulation models

Simulation is a modelling technique that is used to imitate the performance of complex water resource systems. It is particularly useful where optimization techniques cannot be used because of their limitations. Simulation, alone, is not an optimization technique but can be used to get near-optimal results, which are as useful as the optimum solutions in water resources modeling. With the help of computer programmes written for a specific problem, the simulation could predict the system's performance. Under various operating policies or decisions, the researcher can analyse the performance or output of the system by running simulation models. Characteristics of the system like rainfall and other hydrologic parameters should be given as input variables (Paling, 1984; Mohan and Jyothiprakash, 2003).

Inputs, outputs, physical relationships between variables and constraints and operating rules are the components of a simulation model. The model transforms inputs into outputs according to physical relationships, constraints and operating rules. First, a complex system must be divided into sub-systems and proper linkages must be established between them. Computer programmes are formulated for each sub-system to convey information from one sub-system to another. Verification of the model is necessary with known inputs and outputs. After verification, the model is ready to run with alternate sets of inputs to get corresponding outputs. Simulation runs give a set of outputs for each set of inputs (Vedula and Mujumdar, 2005).

Bejranonda *et al*. (2011) conducted a simulation study to address the problem of increased water requirements for farming in Thailand, where rice is a major crop. The surface water-groundwater interaction was investigated and mimicked using a mathematical model. The groundwater potential of the area was estimated by running simulations with the maximum possible drawdown of hydraulic heads. The authors concluded that by utilising the unused surface water during the transition period from the wet to dry season for groundwater recharge and by proper apportioning of this groundwater for conjunctive water use, the water scarcity problem in the study area could be resolved.

The distribution of canal water may not be fair in most of the command areas. Usually, the head-end farmers over utilized the surface water, which in turn forced the tail-end farmers to withdraw groundwater from the unconfined aquifer to meet their irrigation demand. An appropriate scientific tool for evaluating various scenarios is necessary before making decisions on water distribution. With this objective, an integrated numerical simulation model was developed by Biswas *et al*. (2017) considering various processes involved in a basin irrigated canal command area. According to the study, even distribution of surface water through a dense network of canals will reduce groundwater withdrawal by tail-end farmers and address water logging issues in the head reaches.

Simulation optimization models

Most of the conjunctive water management systems are large and quite complex systems to be modelled by either an optimization model or a simulation model. Combination models are necessary in this case, such as the simulation-optimization model. Within this combination, a simulation model predicts the consequences of management and an optimization model computes the mathematically best management strategy. The simulation model produces near-

optimal solutions and the optimization model refines these solutions to get an optimal solution. Thus, the simulation model reduces the size and complexity of the optimization model. Simulation-optimization models are nowadays common in dealing with conjunctive water management problems (Vedula and Mujumdar, 2005; Peralta and Shulstad, 2004; Mohan and Jyothiprakash, 2003).

A simulation-optimization model was developed by Raul and Panda (2013) to predict the maximum permissible groundwater pumping from the Hirakud canal command area for conjunctive management of surface and groundwater. Simulation analysis was done by developing a conceptual three-dimensional groundwater flow model with Visual MODFLOW software. An optimization model was also developed for determining the optimal cropping pattern for the command area that maximises net annual benefits. The study concluded that the optimal cropping pattern derived by the model can increase net benefits from the command area by around 51.3-12.5% for 10-90% PERC (probability of exceeding rainfall and canal water availability) when compared to the existing cropping pattern. In a similar study, Khan *et al.* (2014) compared three strategies for conjunctive water use in the Ganges basin. The efficacy of these strategies was determined using numerical models based on MODFLOW. The strategies have been tested for a wide range of scenarios and the study concluded that the actual efficacy of conjunctively managing different water resources in the basin would vary depending on aquifer characteristics, river characteristics, the topography of the region and other hydrologic and anthropogenic factors. Hence, before implementation of conjunctive use policies, testing of pilot projects is required in a limited area.

Chen *et al.* (2016) integrated a simulation and optimization model for scheduling irrigation in a multi-crop command area to alleviate the effect of seasonal drought using combined operation of reservoirs and ponds. The integrated model has two components: an operating policy model, which optimises the releases from reservoirs and ponds and an allocation model that determines irrigation allocations from the reservoirs and ponds. To solve the complex integrated problem, an artificial bee colony algorithm was incorporated with a differential evolution algorithm and a particle swarm optimization algorithm. The integrated model is applied at the Zhanghe Irrigation District in China and compared with the other three simulation models. The results indicated that the integrated model is efficient in reducing the impact of drought and increased the average annual return by 7.9, 7.0 and 3.1 per cent compared to the other three simulation models, respectively. Another integrated simulation-optimization model was developed by Chang *et al.* (2017) to minimise the shortage of water for irrigation in a reservoir-pond system in China by using conjunctive management of these resources. This model also had two components: an optimal model, which optimises the reservoir release and a simulation model that simulates the water supply from ponds and reservoirs. The model was applied in the Yarkant River Basin (YKB), China. From the study, the authors found that conjunctive operation of reservoirs can maintain the ecological flow of the river.

Economic optimization models

The use of groundwater in conjunction with surface water is able to increase crop production and income compared to the use of a single source. During drought periods, groundwater acts as a secure source against uncertain surface water. However, groundwater use increases production costs due to the cost involved in pumping. Sometimes, the poor quality of groundwater may affect crop yield. Many studies have been carried out to analyse the economics involved in planned conjunctive water use with the help of a modelling approach.

Water resource allocation options were assessed by Khare *et al.* (2007) for planning the combined operation of surface and groundwater resources in the command area of a link canal with an economic optimization model. The linear programming technique was used for optimization to work out a suitable cropping pattern that maximises net benefits considering various hydrological and management constraints. The model has been run for both the existing and proposed cropping patterns under different scenarios and the proposed pattern has been found suitable for the link canal command with a considerable saving of surface water.

Bharathi *et al.* (2008) developed an economic hydrologic simulation-optimization model to help in decisions for successful management of land and water resources in a small reservoir-based irrigation system. The study used WaSiM-ETH, a physical hydrology model that combines surface, subsurface and groundwater hydrology and was developed by the Swiss Federal Institute of Technology for simulation. The economic optimization model was written in GAMS (General Algebraic Modelling System) with the objective function of maximising the net profit. Time series of surface runoff, groundwater levels and other hydrologic parameters were the major outputs of the WaSiM-ETH model. The outputs from this model provide the boundary conditions for the economic optimization model. After obtaining an optimum solution, values of decision variables were conveyed to the WaSiM-ETH model to reexamine boundary conditions. If boundary conditions have been violated by restricting groundwater extractions, the optimization model has been re-executed. Results showed that WaSiM-ETH is a successful hydrologic simulation model. Using the data from the hydrologic model GAMS, the optimum cropping pattern was determined using nonlinear optimization.

Models to handle water quality issues

Conjunctive water management often faces water quality issues along with water scarcity problems. Many scientists have tried to find a solution to this problem using the modelling approach.

Sethi *et al*. (2002) developed a conjunctive water use model with two components: the groundwater balance model and an optimization model, to get an optimum cropping pattern suited for a coastal river basin. The groundwater balance model shows the regulated groundwater flow to avoid severe water table fluctuations. The second component of the model maximises the economic benefits by selecting the optimum cropping pattern and providing proper groundwater management. The developed model was applied in a coastal river basin in Orissa and an optimum cropping pattern suited for the region was worked out for various scenarios. The authors advise practicing conjunctive use of surface and subsurface water to control further depletion of groundwater levels.

In coastal and deltaic regions irrigation with surface water faces two major issues- uneven distribution, both temporal and spatial and seawater intrusion. Excessive irrigation may lead to water logging conditions and excess withdrawal of groundwater may lead to intrusion of seawater. Rao *et al*. (2004) developed a conjunctive use model to solve irrigation issues of a coastal deltaic region using the simulated annealing method. The flow simulation was achieved using the SHARP interface model. The spatial and temporal variations of major water resources form the constraint for the management model. Quality of water can be maintained by placing well screens above the interface of freshwater and seawater. The management model has to achieve two conflicting objectives, that is, minimizing operational cost and maximizing groundwater reserve. The methodology adopted was combined simulation-optimization with SA algorithm (optimizer) and SHARP model (simulator). To reduce the computational burden, the SHARP model was replaced later by the ANN model.

Lari *et al*. (2009) developed a conflict resolution model considering water quality issues in conjunctive water use. Improving groundwater quality is conflicting with reducing the cost of wastewater collection and purification systems. In such a region, the authors developed a model using Non-dominated Sorting Genetic Algorithm II (NSGA II) and Yung Conflict Resolution Theory (YCRT). The groundwater quantity and quality were simulated by using MODFLOW and MT3D. These simulation models were interconnected with the NSGA-II optimization model to get a set of good solutions. Among these solutions best were selected using YCRT. Results showed that based on the optimal solution, both objectives were satisfied.

Heydari *et al.* (2016) developed a multi-objective simulation-optimization model to handle quantity-quality issues in water allocation. Two evolutionary models, an Artificial Neural Network model for simulating groundwater levels and a Genetic Programming model for predicting TDS concentration were combined with NSGA-II. Minimizing water shortage, the drawdown of the groundwater level and groundwater quality changes were the multi-objectives of the model. MODFLOW was used to simulate groundwater flow. The model was applied to Najaf Abad plain in Iran. The application of the simulation-optimization model showed that the model could generate satisfactory solutions to increase the quality and quantity situations of the aquifer.

Use of evolutionary algorithms

For planning conjunctive water management optimization, simulation and simulation-optimization models are widely used. Classical optimization methods have a disadvantage in that it needs a large number of numerical computations to get an optimal solution. Evolutionary techniques like genetic algorithm (GA) are efficient in solving the optimum conjunctive management models and identifying global optimal solutions.

In simulation-optimization models, the simulation model represents the physical nature of the system and the optimization model represents the conjunctive water use characteristics of the system. Linking between simulation and optimization models often faced difficulty due to computational load. Researchers often overwhelmed this problem, by using an approximate simulator of the physical Processes. Artificial neural networks (ANNs), support vector machines (SVMs), relevance vector machines (RVMs), *etc*. are some examples. These types of estimation models are based on machine-learning theory (Safavi and Esmikhani, 2013).

Genetic algorithms

Genetic algorithms are used to solve complex optimization problems. It is a search technique based on the theory of biological evolution. The evolution starts from a random population and optimization occurs in generations. A fitness function formulated in the model evaluates all the individuals in the population, in each generation, for their fitness. Several individuals are selected from one population and modified to form a new population (Singh, 2014). Genetic Algorithms are nowadays used in various conjunctive water management models.

Chowdhary *et al.* (2012) developed an optimization model for conjunctive use of surface water and groundwater using both genetic algorithm and linear programming and applied it for the multipurpose Mahanadi Reservoir Project (MRP) in Chhatisgarh. Optimum canal release, pumping quantity from groundwater and water allocation for each crop, *etc*. were the outputs obtained from the model with the objective function of maximizing the total relative yields of all individual crops. The authors compared the results obtained from GA and LP and found that both are reasonably close and hence proved the suitability of GA for modelling conjunctive water use.

A multi-objective optimization model based on inter-basin water resources and restoration of outer-basin water resources was developed by Tabari and Yazdi (2014) with the objectives of reducing the water scarcity, water leaving out of the boundary of Iran and increasing the water transferred to an unused lake for remediation. Since the

decision variables were plenty and nonlinear relations were existing between water resources, NSGA-II was used for optimization. Promising results were obtained from the study.

Artificial neural network

The artificial neural network resembles the biological neural network mainly in two aspects. It can acquire knowledge through a learning process and is able to store and retrieve it through interconnections known as synaptic weights. An ANN is able to perform a number of tasks like classification, data clustering, optimization, pattern-matching and approximation that are challenging for ordinary computers. Thus, using a supervised learning process, a trained ANN could act as a good simulator. It is able to use ANN successfully in conjunctive water management models (Vedula and Mujumdar, 2005).

Karamouz *et al*. (2007) developed a multi-objective simulation-optimization model using artificial neural network (ANN) and genetic algorithm (GA) to effectively reduce the computational time for the conjunctive water use. Sufficient water to meet irrigation demands, while minimising the pumping charges and fluctuations in the groundwater table, were the objective functions. The MODFLOW-PMWIN model by Chiang and Kinzelbach (1999) was used as a simulator which simulates the aquifer characteristics. The results obtained from the groundwater model were utilised to train an ANN. The results of the ANN-based groundwater simulation model were then combined with a GA-based optimization model to get a monthly allocation of canal water and groundwater in a conjunctive management system.

Fuzzy optimization

While developing conjunctive water management models, various uncertain natural parameters are involved, like rainfall, surface water availability and groundwater recharge. By including the uncertainty of such parameters, the perfection of the model could be improved. Application of fuzzy logic is a method for this. Vagueness in events is represented as a membership function. Several models have been developed for conjunctive water management in which fuzzy logic is used for optimization (Louks and van Beek, 2005; Vedula and Mujumdar, 2005).

An irrigation planning model was formulated by Regulwar and Pradhan (2013) for the conjunctive water management. In the study, major water resources were represented in a fuzzy set. A Fuzzy Linear Programming (FLP) model was formulated with the objective function of maximising the net profits and it was applied in a case study of the Jayakwadi Project in Maharashtra. Optimization resulted in a satisfaction level of up to 0.546 when the uncertainty involved in the availability of water resources has been taken into consideration.

CONCLUSION

Conjunctive water use is an efficient method to solve water scarcity as well as water quality issues in arid and semi-arid regions. Without proper planning, it would have become a failure due to the over-extraction of groundwater. Mathematical models support the decision makers in planning the optimum allocation of surface and groundwater. Various types of models, from simple optimization models to complex multi-objective simulation optimization models, are used for conjunctive water management. Some researchers developed models to plan cropping patterns to suit the available water from both surface and groundwater resources. Optimization models are developed using different methods by different scientists. Linear programming, non-linear programming, dynamic programming, *etc*. are some of the methods.

A simulation study provides information about river-aquifer systems under different conditions. Some simulation models alone may suggest solutions to conjunctive water use issues. However, a combination of simulation optimization models can be recommended as most suited to that particular area or system. It can take into account the stochastic nature of inputs to some extent. But, simulation increases the computation burden while running the model. To reduce this burden in the modern era, some evolutionary algorithms are used along with simulation optimization models for planning conjunctive water management. In a nutshell, computer-aided mathematical models reduce the efforts of decision-makers involved in planning the appropriate allocation of surface water and groundwater for solving water quantity and quality problems.

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Conflict of interest

All authors declared that there is no conflict of interest.

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