2.1 INTRODUCTION

Conjunctive use of surface water and groundwater has been adopted as a means of optimal utilization of the available water resources since a long time. Extensive studies have been conducted in the past to evolve various conjunctive use plans and policies for efficient management of the irrigation system. Efforts are still on to develop more practical solutions to problems involving conjunctive irrigation management.

Groundwater flow models are the essence of modern conjunctive use models. The mathematical groundwater models are linked to the management models by various means to develop simulation-optimization models.

In this chapter, a brief review of the previous works on groundwater flow modeling, conjunctive use modeling and other relevant topics is presented.

2.2 GROUNDWATER FLOW MODELS

Groundwater models have developed from the physical laboratory models that were used until the early 1970s, to the numerical computer models used today (Bear and Verruijt, 1987). According to Anderson and Woessner (1992), there are three main types of applications of groundwater models:

- Predictive: the most common type of application used to predict the future.
- Interpretive: used for studies of the system and/or organization of field data
- Generic: used to analyze flow in hypothetical system, which can be useful in framing regulatory guidelines for a specific region.
The mathematical groundwater models can be solved either analytically or through application of numerical techniques. With the advent of computers, numerical models have become the preferred type of models for analyzing the groundwater flow and transport processes.

Two numerical techniques are generally used for modeling the groundwater flow process— the finite difference method and the finite element method. Wang and Anderson (1982) described the detailed modeling procedures using these two techniques. A number of models have been developed for study of the groundwater flow and transport phenomena, applying both finite difference and finite element methods.

Voss (1984) developed the computer program SUTRA (Saturated- Unsaturated Transport) for simulating fluid movement and the transport of either energy or dissolved substances in a subsurface environment. The original program was developed by using finite element method for two dimensional flow and transport modeling. The upgraded version of the model (Voss and Provost, 2008) has the ability to use irregular 3D meshes, conveniently incorporate input data from separate files, define schedules to control time stepping and observation output, interpolate observations in time and space and store observations in an alternative format. The code employs a 2D or 3D finite-element and finite-difference method to approximate the governing equations that describe the two interdependent processes being simulated.

MODFLOW (McDonald and Harbaugh, 1988) is one of the most widely used numerical groundwater flow models. It is a three-dimensional model for flow and transport modeling, originally developed by the U.S. Geological Survey. It uses block-centred finite difference scheme for the saturated zone. The advantages of
MODFLOW include numerous facilities for data preparation, easy exchange of data in standard form, extended worldwide experience, continuous development and availability of source code.

ASM (Aquifer Simulation Model) is a 2D groundwater flow and transport model using finite difference scheme (Chiang et al., 1998). The first version of ASM was published in 1989 and ran under MS-DOS environment. ASMWIN is the Windows version provided with a professional Graphical User Interface (GUI).

FEFLOW is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media (Trefry and Muffels, 2007). The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including the fluid density effects and the chemical kinetics for multi-component reaction systems. Originally developed in 1979, FEFLOW has been developed continuously and is now available as a commercial simulation package.

2.3 CONJUNCTIVE USE MODELS

The modeling approaches used in the development of conjunctive use management plans and strategies have seen a great deal of change since their beginning in the 1960’s. Karamouz et al. (2004) described the various stages of evolution in the system approach and techniques used in conjunctive use modeling. In the early development stages of conjunctive use models, groundwater was considered as a separate source of water and actual interaction between the surface and groundwater resources was mostly neglected. In the second stage of the evolution of these models, the partial differential equations of the interaction between surface and groundwater resources, the physical and economic constraints and pollution transport were considered in descriptive conjunctive use models. In the third stage, the nonlinear differential
equations of groundwater flow were considered in optimization models in order to estimate the groundwater table and quality variations. The uncertainties in discharge and recharge parameters have also been taken into account in stochastic conjunctive use optimization models.

In general, conjunctive use models may vary from simplified lumped models to sophisticated simulation-optimization models. Conjunctive use models can also be categorized on the basis of different optimization techniques applied.

2.3.1 Simplified Conjunctive Use Models

In the early stages of development of conjunctive use modeling, some studies used simplified lumped parameter systems, where the actual surface water–groundwater interaction was not reflected in the modeling approach.

Burt (1964) proposed a conjunctive use model for maximizing the net agricultural revenues by optimizing the water use from a surface reservoir and a single-cell groundwater basin.

Tsur and Tomasi (1991) analyzed the optimal withdrawals under a conjunctive use system with stochastic surface supplies. The possibility of recharge of surface supplies to the aquifer was, however, not taken into consideration.

Provencher and Burt (1994) considered a three-cell model for three interrelated aquifers in Madera County, California applying a policy iteration dynamic programming approach, where the value function was estimated by Monte Carlo simulation. They compared this approach with a Taylor series approximation to the functional equation of dynamic programming.

Khare et al. (2007) analyzed the feasibility of conjunctive use management in the Sapon irrigation command area of Kulon Progo Regency, Yogyakarta province, Indonesia using a simple economic-engineering optimization model.
When the groundwater system is treated as a single cell, the inherent simplifications and assumptions should be taken into account while analyzing the results obtained from such models (Bredehoeft et al., 1995).

2.3.2 Simulation-Optimization Models

Simulation-optimization forms the basic framework for representing the surface water-groundwater interactions and their combined effect on the water demand. Many simulation and optimization models have been proposed for effective conjunctive use plans and strategies, including approaches with detailed representation of physical stream-aquifer interactions.

Young and Bredehoeft (1972) developed a management model that incorporated aquifer behaviour through a simulation model to analyse problems associated with unrestricted development of groundwater hydraulically connected to a stream. By using this model, the spatial and temporal interaction of the stream-aquifer system was analysed through various excitations such as river flows, stream diversion and well pumping.

Maddock (1974) combined groundwater management models and policy evaluation models to include surface water allocation and stream-aquifer interaction in addition to well pumpage where the stream stage was assumed to be time invariant (i.e. when withdrawals or losses from a stream to an aquifer do not affect the stream stage through response functions). This assumption is usually valid only along large rivers.

Illangasekare and Morel-Seytoux (1982) presented an analytical procedure to derive response equations of the physical components of a stream-aquifer system to simulate the behaviour of the system when subjected to different excitations.

Willis et al. (1989) developed a conjunctive groundwater-surface water planning model to maximize net revenue obtained from various agricultural products in the
North China plain. They developed hydraulic response equations of the conjunctive system using the finite element method and the matrix exponential, which became part of the constraint set of the nonlinear optimization model.

Matsukawa et al. (1992) presented a simulation-optimization model to develop planning and operational strategies for the Mad river basin, California. The river basin consisted of a single multipurpose reservoir and an unconfirmed aquifer system that hydraulically interacted with the river in the basin.

Dandy and Crawley (1992) modeled the operation of a multiple reservoir system to determine optimal water supply to Adelaide, Australia, with consideration of the effects of water salinity.

Mehrez et al. (1992) described a network optimization model for real-time operation of the water system in the Avra Rift Valley, Israel. Economically optimal allocation from multiple sources with varying salinity was made to a number of demand points with varying quantity and salinity requirements.

Garcia et al. (1995) introduced a model for the design and management of conjunctive irrigation and drainage systems. This model was used to estimate the growth response of a crop to its soil water-air-subsurface environment as influenced by drainage design and management practices such as irrigation and cropping pattern.

Reichard (1995) proposed a simulation-optimization modeling approach for regional groundwater-surface water management that explicitly incorporated the uncertainty of surface water supplies. The economic, technical and institutional feasibility of obtaining additional surface water was not considered in the analysis. In essence, the problem considered efficient strategies for meeting demand and controlling a regional water quality problem (e.g. seawater intrusion). The model was applied to the Santa Clara- Calleguas basin in southern California.
Philbrick and Kitanidis (1998) identified real time control policies and the benefit of capacity expansion in a hypothetical conjunctive-use system with an uncertain supply, using characteristics of a water system in Oakland, California.

Belaineh et al. (1999) presented a simulation-optimization model that integrated linear reservoir decision rules, detailed simulations of stream-aquifer system flows, conjunctive use of surface and ground water and delivery via branching canals to water users. State variables, including aquifer hydraulic head, stream flow and surface water/aquifer interflow, were represented through discretized convolution integrals and influence coefficients. Reservoir storage and branching canal flows and interflows were represented using embedded continuity equations.

Basagaoglu and Marino (1999) developed a coupled simulation-optimization model for a hypothetical river basin to determine optimal operating policies for joint use of surface and groundwater supplies by considering their temporal and spatial hydraulic interaction. The system involved a multipurpose reservoir, a hydraulically connected stream and aquifer, agricultural plots, water supply and observation wells and an artificial recharge zone. The model minimized deviations from a set of rule curves defined for storage in the reservoir and along the stream course, so as to consider possibilities for storage of excess water in the wet periods and its distribution in the subsequent dry periods. The management model could be used for developing and improving target levels, exploring the best strategies in the case of droughts and wet periods and testing various possibilities for changing the water elements, including reservoirs, groundwater wells, surface water streams and canals.

Basagaoglu et al. (1999) proposed a nonlinear coupled simulation and optimization model to find optimal operating policies with a minimal cost for the conjunctive management of hydraulically interacting surface and groundwater supplies. Both
nonlinear and linear management models were formulated. The nonlinear problem was solved by coupling the solver with a random number generator to provide the model with a different initial guess each time. In contrast, the linear problem was formulated as a linear mixed integer programming model. Optimal operating policies and the operation costs obtained from both models were found to be in good agreement.

Azaiez and Hariga (2001) developed a conjunctive use model for a multireservoir system with stochastic inflow and irrigation demand. High penalty was imposed for pumping groundwater in order to avoid the risk of aquifer depletion. The non-linear stochastic problem was illustrated through a hypothetical example.

Barlaw et al. (2003) developed a conjunctive management model for numerical simulation along with linear optimization to maximize the total annual ground water withdrawal from an alluvial aquifer with the stream flow depletion constraints.

Karamouz et al. (2004) developed a simulation-optimization model for optimal allocation of available water resources to agricultural areas in Tehran, Iran. The specific objectives of this model were to minimize the shortages of irrigation supply, to minimize the groundwater pumping cost and to control the average groundwater table fluctuations in the agricultural zones.

Rao et al. (2004) presented a regional conjunctive use model for a near real deltaic aquifer system, irrigated from diversion system, with some reference to hydrogeoclimatic conditions prevalent in the coastal deltas of India.

Gorantiwar and Smout (2006) developed a simulation-optimization model considering alternative schedules based on full or deficit irrigations for irrigation schemes of central and south India.

Schoups et al. (2006) developed optimal conjunctive use water management strategies for the irrigated agricultural system of the Yaqui Valley, Mexico considering
two potentially conflicting objectives- sustaining irrigated agriculture during droughts and minimizing unnecessary spills and resulting water losses from the reservoir during wet periods. Optimal strategies were identified using multiobjective interannual optimization for sustainability and spill control, combined with gradient-based annual profit maximization.

Marques et al. (2010) developed a model to optimize conjunctive use operations of groundwater pumping and artificial recharge with farmer’s expected revenue and cropping decisions. A two-stage programming approach was used for modeling of water allocations and permanent crop production decisions, with recourse for uncertain conditions of hydrology, annual crops and irrigation technology decisions.

Safavi et al. (2010) proposed a simulation-optimization framework for conjunctive use of surface water and groundwater on a basin-wide scale at the Najafabad plain in west-central Iran. The main goal of this simulation-optimization model was to minimize shortages in meeting irrigation demands for three irrigation systems subject to constraints on the control of cumulative drawdown of the underlying water table and maximum capacity of surface irrigation systems.

Fayad et al. (2012) presented a simulation-optimization model for application in water resource planning and mini hydropower system development. The model simultaneously addressed all significant flows including reservoir-stream-diversion-aquifer interactions in a detailed manner.

The stream-aquifer interactions in simulation-optimization models are represented in three different ways- embedded technique, response matrix approach and linked simulation-optimization method.
In embedded technique, the nodal heads are treated as additional decision variables and the finite difference or finite element groundwater flow equations are embedded as constraints to the optimization model.

Aguado and Remson (1974) introduced LP based management models embedding the finite difference approximation of the governing differential equations as constraints in the formulation. They obtained solutions for example cases of confined and unconfined aquifers, one- and two-dimensional flow fields and steady state and transient flow conditions.

Gorelick and Remson (1982) incorporated the steady state finite difference form of solute transport equation as embedded constraints. They maximized waste disposal at two locations while protecting water quality at supply wells and maintaining an existing waste disposal facility.

Mahar (1995) proposed a methodology for identifying unknown source of groundwater pollution. The governing equations of flow and transport were discretized using finite difference technique. These discretized equations were embedded as constraints to his optimization model.

Peralta et al. (1995) developed a simulation-optimization model with embedded groundwater flow equations to calculate optimal water-use strategies. Their model was run for different scenarios, each characterized by time series of upper and lower bounds on water use.

Mahar and Datta (2001) presented optimal source identification methodologies based on embedded optimization models considering simultaneous estimation of aquifer parameters and identification of unknown pollution sources under transient flow conditions.
Vedula et al. (2005) used embedded technique for representing the aquifer response to groundwater withdrawal or recharge in their conjunctive use model. The finite element groundwater flow equations were embedded as constraints to the management model.

Gorelick (1983) reviewed the computational complexities associated with using embedded method and concluded that the method’s applicability to large scale systems is limited. Tung and Kolterman (1985) suggested that the embedded technique was useful for small management problems, but had numerical difficulties with large real world problems. Bhattacharjya (2012) suggested that incorporation of the non-linear partial differential equations of groundwater flow into the constraint set made the embedded approach numerically inefficient especially when applied to large aquifer systems with considerable heterogeneity.

In response matrix (also called kernel function or influence function) approach, an independent simulation model is utilized for generating the system response to groundwater withdrawal or recharge in order to create response matrices, which are then incorporated as constraints to the management model.

Maddock (1972) developed algebraic technological functions (response equations or discrete-kernel approach) that allowed the coupling of simulation and optimization models. The algebraic form allows the behaviour of the groundwater system to be explicitly included in a management model.

Willis (1976) presented a planning model for the optimal conjunctive use of groundwater and surface water resources. The steady state solute transport simulation model was first formulated as a finite difference coefficient matrix. The inverse of this matrix was then computed and relevant portions were then included in the management model as constraints.
Illangasekare and Morel-Seytoux (1982) presented an analytical procedure to derive response equations of the physical components of a stream-aquifer system to simulate the behaviour of the system when subjected to different excitations.

Ratzlaff et al. (1992) used a finite element procedure to generate the response matrix for piezometric head and velocities for a two-dimensional flow field to determine the best well locations and pumping rates in order to achieve advective containment of contaminant plumes.

In the conjunctive use model proposed by Belaineh et al. (1999), a finite difference simulation model was linked to an optimization model via influence coefficients to form a simulation-optimization model.

Shirahatti and Khepar (2007) proposed a chance constrained linear programming model for the Upper Krishna Project irrigation command area in the south Indian state of Karnataka, where the groundwater flow model was coupled to the management model using response matrix approach.

Afshar et al. (2010) used the groundwater flow and transport model MODFLOW to simulate the stream aquifer system for deriving the response function coefficients.

Ghosh and Kashyap (2012) presented a linked kernel function-optimization model for planning the groundwater development for irrigation in canal command areas. The objective of this model was to optimize the cropping pattern subject to the constraints on two most crucial state variables of the groundwater system viz the maximum water table depth and the stream-aquifer interflow.

Although the response matrix approach has been widely used in simulation-optimization models, this method is based on the principle of superposition and linearity and hence is not suitable for application in non-linear systems (Das and Datta, 2001).
The third approach known as linked simulation-optimization (LSO) technique, directly links a groundwater flow simulation model with the optimization model. This approach has no restrictions as to the dimensionality or linearity of the system. However, the application of this approach is limited by the computational effort required to complete the optimization process, as the simulation model is required to be run several times during optimization. Various approaches have been suggested to reduce the computational time in the LSO models.

Datta and Chakrabarty (2003) proposed the use of linked simulation-optimization approach where a simulation model was externally linked to a classical nonlinear optimization model for identification of groundwater pollution sources.

Singh and Datta (2003) proposed an Artificial Neural Network (ANN) based methodology and a genetic algorithm (GA) based linked simulation optimization methodology that would facilitate optimal identification for unknown groundwater pollution sources using concentration measurement data.

Karamouz et al. (2004) applied linear regression technique to develop a simplified model from MODFLOW, which was linked to a management model for irrigation planning.

Bhattacharjya and Datta (2005) applied ANN as a simulator for connecting a simulation model with an optimization model for a groundwater remediation problem.

Curtis and Willis (2012) proposed a multi-objective LSO model for a three dimensional saltwater intrusion problem with the objective of determining the optimal pumping rates that would minimize the saline concentration at the well sites, while satisfying an exogenous water demand.
2.4 OPTIMIZATION TECHNIQUES APPLIED IN CONJUNCTIVE USE MODELING

On the basis of techniques used, the optimization models for conjunctive use may be classified as the LP models, the DP models, the NLP models and others. Different combinations of these modeling techniques have also been applied. Of late, various non-conventional search methods like GA, Simulated Annealing (SA) and Particle Swarm Optimization (PSO) have seen their applications in conjunctive use modeling.

2.4.1 Linear Programming Models

Linear Programming (LP) has been the most widely used optimization technique in conjunctive use modeling.

Castle and Linderborg (1961) made one of the earliest studies of conjunctive use optimization applying linear programming for allocation of ground water and surface water in two agricultural areas. The assumption made in this study was that application of other crop inputs would depend on the irrigation water supplied.

Rogers and Smith (1970) formulated a conjunctive use model using linear programming with a lumped groundwater response, applying ground water budget concept.

Lakshminarayana and Rajagopalan (1977) studied the problem of optimal cropping pattern and water releases from canals and tube wells in the Bari Doab basin, India, using a linear programming model. The model was a deterministic model and the dynamic response of the ground water aquifer was not considered.

Bredehoeft and Young (1983) applied a sequence of linear programs to assess optimal groundwater capacity to reduce income variability by simulating conjunctive use of surface water and groundwater and crop planting decisions.

Latif and James (1991) presented a linear programming-based conjunctive use
model for application in the Indus basin in Pakistan to maximize the net income of irrigators.

Raman et al. (1992) proposed a methodology for development and application of an expert system for drought management. A linear programming model was used to generate optimal cropping patterns from past drought experiences as also from synthetic drought occurrences. These policies together with the knowledge of the experts were incorporated in an expert system.

Peralta et al. (1995) developed a linear programming-based simulation-optimization model to obtain the sustainable groundwater extractions over a period of five decades, under a conjunctive water use scenario.

Sethi et al. (2002) proposed a Linear programming model for conjunctive use operation in a coastal river basin in India. The ground water response was incorporated using mass balance approach.

Devi et al. (2005) presented a linear programming model for optimal water allocations in a large river basin system. They applied the model to the transboundary Subernarekha River in India.

The conjunctive irrigation management developed by Vedula et al. (2005) was a deterministic linear programming model that integrated a linear reservoir operation, soil moisture balance and groundwater pumping.

Raul et al. (2012) developed a linear-programming optimization model for optimal crop planning and management of the available water resources from surface water and groundwater in the Hirakud canal command, India under uncertainty of hydrologic events, such as rainfall, canal release and net irrigation requirement. An irrigation scheduling model (ISM) was used to predict the actual crop yields under different irrigation strategies i.e. full depth as well as deficit irrigation.
2.4.2 Dynamic Programming Models

Dynamic programming can be applied to linear and non-linear systems and they also take into account the stochasticity of the hydrologic process. But the only limitation of dynamic programming is the curse of dimensionality.

Buras (1963) applied dynamic programming for deriving conjunctive use policy for two agricultural areas to find hydraulic design criteria of the conjunctive use system.

Jones et al. (1987) used a DP algorithm to reduce computational burden for unsteady, nonlinear, ground water system management problems.

Onta et al. (1991) proposed a long term conjunctive use policy guideline using stochastic dynamic programming, which was evaluated using a lumped simulation model. The model was applied in a case study of Bagmati river basin in Nepal.

Philbrick and Kitanidis (1998) applied a gradient based dynamic programming technique in their conjunctive use model to mitigate the "curse of dimensionality" that prevents the application of dynamic programming to stochastic problems with numerous state variables.

The conjunctive irrigation management model developed by Karamouz et al. (2004) applied dynamic programming for optimal allocation of available water resources to different agricultural areas.

Safavi and Alijanian (2011) developed a fuzzy dynamic programming model for optimal crop planning and conjunctive use of surface water and groundwater resources in Najafabad Plain, a part of the Zayandehrood river basin located in west-central Iran. The goal of optimization was to minimize shortages in supplying the irrigation demands, subject to certain constraints, such as the control of groundwater withdrawals and the capacity of irrigation systems.
2.4.3 Non-Linear Programming Models

Many conjunctive use management models involve non-linearities in the objective functions and constraints. These non-linear problems can be solved by using NLP algorithms. However, the applications of the NLP algorithms are limited by the complexity, the slow rate of convergence and the possibility of getting a local instead of global optimal solution (Yeh, 1992).

Maddock (1972) developed a quadratic programming model to minimize the present value of pumping cost in the operation of a stream-aquifer system under stochastic demand and supply.

Noel and Howitt (1982) formulated an optimal linear-quadratic control model for a multibasin conjunctive management problem, comparing the results of mathematical programming with analytical solution.

Datta and Peralta (1986) presented a multi-objective optimization procedure using quadratic programming for developing a regional conjunctive water management strategy for an important rice production area in Arkansas, U.S.A. The objectives considered were the minimization of the total cost of water use and maximization of groundwater withdrawal.

Matsukawa et al. (1992) applied non-linear optimization technique for conjunctive management of Mad river basin in California, U.S.A.

Basagaoglu and Marino (1999) proposed a nonlinear coupled simulation and optimization model to find optimal operating policies with a minimal cost for the conjunctive management of hydraulically interacting surface and groundwater supplies.

Schoups et al. (2006) presented a gradient based non-linear optimization procedure for sustainable conjunctive irrigation management. The model was applied to a real-
world conjunctive surface water-groundwater management problem in the Yaqui Valley, an irrigated agricultural region in Mexico.

Marques et al. (2010) applied two-stage stochastic quadratic programming to optimize conjunctive use operations of groundwater pumping and artificial recharge along with modeling of water use and permanent crop production decisions.

Montazar et al. (2010) coupled a non-linear optimization model to a soil moisture balance model for deriving optimal conjunctive use policy for an irrigation command and demonstrated how the river–aquifer equilibrium could be maintained by their approach.

Apart from the conventional optimization techniques discussed above, various non-conventional search methods are being used to derive efficient management plans for the irrigation system including conjunctive use optimization. A brief account of the various non-conventional optimization methods applied in water resources management is presented separately in the following section.

2.5 APPLICATION OF NON-CONVENTIONAL OPTIMIZATION TECHNIQUES IN WATER RESOURCES MANAGEMENT

Due to the difficulties in modeling of the water resources system using the conventional optimization methods, the research attention has now shifted towards developing new methodologies for efficient management of water resource system.

Among the various non-conventional search methods, GA has already been established as a superior method for application in various water resources management problems. Other techniques like PSO and SA algorithms have also been used in water resources management. Fuzzy based programming methods and artificial neural networks have been utilized to improve the performances of the management
models. More recently, AIS has been introduced as an optimization method for application in water resources management.

### 2.5.1 Genetic Algorithms

Genetic algorithm derives its principle from Darwin's theory of Survival of Fittest and natural genetics. GA is an evolutionary search method, which many advantages over traditional search techniques, as elaborated by Goldberg (1989).

Esat and Hall (1994) compared the performances GA and dynamic programming for deriving reservoir operation rules. Advantages of GA over standard dynamic programming techniques in terms of computational requirements were demonstrated through a case study of a four reservoir problem.

Otero et al. (1995) applied GA for determining minimum storm water detention storage capacities and optimal operating rules for managing freshwater runoff into the St. Lucie Estuary along the southeast coast of Florida.

Oliveira and Loucks (1997) used a GA to derive operating rules for multi-reservoir system and evaluated this method as a practical and robust method for estimating the operating policies of complex reservoir systems.

Wardlaw and Sharif (1999) compared different GA formulations for application in reservoir systems. They concluded that a real-value representation, incorporating tournament selection, uniform crossover and modified uniform mutation would operate most efficiently and produce the best results.

Hilton and Culver (2000) compared an additive penalty method with a multiplicative penalty method in a GA for minimizing the cost of groundwater remediation.

Morshed and Kaluarachchi (2000) employed three GA enhancement methods to a nonlinear groundwater problem with objective of minimizing the costs of pumping.
Sharif and Wardlaw (2000) presented a GA approach to the optimization of a multireservoir system. Results of the GA compared well with those obtained by discrete differential dynamic programming.

Yoon and Shoemaker (2001) applied a real-coded genetic algorithm with directive recombination and screened replacement, for in situ bioremediation of groundwater.


Raju and Nagesh Kumar (2004) applied a GA for evolving an optimum cropping pattern utilizing surface water resources in the command area of a multipurpose reservoir system.

Wardlaw and Bhaktikul (2004) evaluated the performances of LP model and GA in a canal scheduling problem and demonstrated GA approach to be robust and very efficient in application to lateral canal scheduling problems.

Karamouz et al. (2007) developed a monthly conjunctive model using GA. Water supply to agricultural demands, reduction of pumping costs and control of groundwater table fluctuations were considered in the objective function of the model.

Momtahen and Dariane (2007) employed GA for finding optimal reservoir operating rules having a variety of predefined forms. They compared these rules with the ones obtained from conventional methods such as Stochastic Dynamic Programming (SDP) and Dynamic Programming and Regression (DPR) and concluded that GA operation rules proved far more effective than other methods.

2.5.2 Fuzzy Based Models

Fuzzy management models are based on unwritten experiences and personal judgments. Fuzzy Interface System (FIS) when used in irrigation system management,
takes into account farmers’ experience and knowledge as well as expert judgments to
develop an optimal crop planning and to predict a trusty demand for irrigation on the
basis of climate conditions.

Leung (1988) used Fuzzy Linear Programming (FLP) to study the allocation of
water to three farming areas. The goal was to optimize water consumption to enhance
profitability.

Bender and Simonovic (2000) used the fuzzy-compromise method for water
resources programming under uncertainty.

McPhee and Yeh (2004) studied simulation and optimization of groundwater usage
based on fuzzy logic.

Raju and Nagesh Kumar (2005) adopted two fuzzy logic-based Multi Criteria
Decision Making (MCDM) methods, namely similarity analysis and decision analysis
and applied to a case study of the Sri Ram Sagar Project (SRSP), Andhra Pradesh,
India, for selecting the best performing irrigation subsystem. They found the fuzzy
logic methodology for real-world decision-making problems to be very effective.

Abolpour et al. (2007) developed a fuzzy based model for the allocation of water
resources in a large basin.

Ozger (2009) used a genetic algorithm (GA) for training the fuzzy rules and
developed if-then rules with linguistic expressions. He also developed two different
FIS models to predict the discharge of the Euphrates River in Turkey.

Fuzzy regression technique was used by Safavi and Alijanian (2011) as a means
reducing computational complexity in conjunctive use planning. Groundwater flow
modeling and interaction between surface water and groundwater was simulated using
MODFLOW-2000 and fuzzy regression was used to consider the uncertainty in the
data required for estimating the simulation model.
2.5.3 Artificial Neural Networks

Artificial neural networks have mostly been used in combination with other methods for reducing modeling complexities in water resources management. ANNs have been utilized to derive efficient operation rules for reservoirs. They have also been used for simplifying simulation-optimization models of conjunctive irrigation management. Mustafa et al. (2012) analyzed the various ANN models applied so far in water resources engineering and concluded ANN to be a robust technique for modeling water resources engineering parameters.

Raman and Chandramouli (1996) derived a general operating policy for a reservoir using ANN, which was compared with results from a Stochastic Dynamic Programming (SDP) model, Standard Operating Policy (SOP) and the operating policy produced by multiple linear regressions from the Deterministic Dynamic Programming (DDP) results. The performance of the ANN model was reported as better than that of the other models.

Campolo et al. (2003) forecasted River flood by using feed forward neural network approach with standard back propagation training algorithm. They used the information of rainfall, hydrometric data and dam operation at the Arno River basin, Italy, to predict the hourly water level variations.

Sudheer and Jain (2003) established stage discharge relationship through the modeling of rating curves, using radial basis function neural network.

Singh et al. (2004) applied ANN in conjunction with GA for optimal identification of unknown groundwater pollution sources.

Deka and Chandramouli (2009) proposed a Fuzzy Neural Network (FNN) model of reservoir operation. The FNN was used to study the behavior of optimal release operating policy on the proposed reservoir in Pagladiya river of Assam.
Demirel et al. (2009) forecasted flow by using two different techniques which include ANN and Soil and Water Assessment Tool (SWAT). Authors used the daily flow data of the Pracana basin in Portugal. ANN was found to produce a better forecast than the other method.

Fernando et al. (2009) forecasted combined sewerage overflow using Multilayer Perceptron neural network with standard back propagation training algorithm. Two ANN models with different number of inputs, one containing antecedent rainfall and antecedent discharge data and the other having only antecedent rainfall data, were developed and compared.

2.5.4 Artificial Immune Systems

AIS is a new field of evolutionary optimization technique inspired by the biological immune system. AIS has seen few applications in water resources management in the recent years.

Chu et al. (2008) proposed an optimization procedure based on AIS framework to optimize the designs of water distribution networks.

In a comparative evaluation of different evolutionary algorithms for parameter estimation of a hydrologic model, Zhang et al. (2008) found the performance of AIS to be at par with other evolutionary algorithms.

Luo and Xie (2010) used a Clonal Selection Algorithm (CSA), which is a category of AIS, for parameter estimation of non-linear Muskingum model for stream flow routing.

AIS was used as an statistical model by Xi et al. (2011) for data analysis in a dam displacement problem and this model was found to give higher degree of accuracy in comparison to stepwise regression model for predicting future behaviour of dam.
Wang et al. (2011) employed Artificial Immune Recognition System (AIRS) as a new approach of data mining to extract operating rules on a water-supply reservoir and reported that AIRS could effectively extract water-supply operating rules and enrich the reservoir operation researches.

2.5.5 Other Non-Conventional Methods

Efforts are being made to apply various non-traditional search techniques for deriving efficient management plans for the water resources system.

Rao et al. (2004) applied SA algorithm to obtain near-optimal solution in their conjunctive use management model developed for a near-real deltaic aquifer system, irrigated from a diversion system, with some reference to hydrogeoclimatic conditions prevalent in the east coastal deltas of India.

Nagesh Kumar and Reddy (2007) used PSO technique to derive operation policies for a multipurpose reservoir system. They presented an efficient and reliable swarm intelligence-based approach, namely Elitist-Mutated Particle Swarm Optimization (EMPSO) technique, which was found to perform better than GA.

Li et al. (2010) presented a multi objective Frog Leaping Algorithm (FLA) as a new effective alternative for solving the complex reservoir operation problems.

Meenal and Eldho (2012) developed a simulation model using mesh free Point Collocation Method (PCM) for confined groundwater flow and transport and a PSO based single objective optimization model and coupled them to get an effective simulation-optimization model for groundwater remediation.

2.6 CONCLUSION

The literatures reviewed in the preceding sections have revealed the amount of thrust given on mathematical modeling of the conjunctive use system. The range of research
reviews include simplified conjunctive use models to state of the art simulation-optimization models that include complete interaction among reservoir-stream-aquifer systems. Although the present study is limited to conjunctive irrigation management, literatures related to other aspects of conjunctive use system modeling have also been included in the review so as to have broader view of the research in the relevant fields.

Groundwater flow models are indispensable parts of modern conjunctive use modeling. A few literatures regarding flow modeling and different developed flow and transport models have been described in this chapter.

Among the different modeling techniques used in conjunctive use system modeling, LP, NLP and DP techniques have mostly been used. Research is still on and various non-conventional methods are being applied to arrive at efficient conjunctive plans and policies. Among the different non-conventional search methods, GA has mostly been utilized in conjunctive use system modeling. ANN has also been applied to aid in the search process. Another new field of optimization techniques with potential application in conjunctive use modeling is the AIS. However, due to lack of adequate literatures regarding the applications of the non-conventional methods in conjunctive use system modeling, the relevant literatures describing the applications of these methods in the broader field of water resources management have been included in the review.