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# Review: Computer-based models for managing the water-resource problems of irrigated agriculture

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**Abstract** Irrigation is essential for achieving food security to the burgeoning global population but unplanned and injudicious expansion of irrigated areas causes waterlogging and salinization problems. Under this backdrop, groundwater resources management is a critical issue for fulfilling the increasing water demand for agricultural, industrial, and domestic uses. Various simulation and optimization approaches were used to solve the groundwater management problems. This paper presents a review of the individual and combined applications of simulation and optimization modeling for the management of groundwater-resource problems associated with irrigated agriculture. The study revealed that the combined use of simulation-optimization modeling is very suitable for achieving an optimal solution for groundwater-resource problems, even with a large number of variables. Independent model tools were used to solve the problems of uncertainty analysis and parameter estimation in groundwater modelling studies. Artificial neural networks were used to minimize the problem of computational complexity. The incorporation of socioeconomic aspects into the groundwater management modeling would be an important development in future studies.

**Keywords** Groundwater management · Simulation · Optimization · Agriculture · Waterlogging

## Introduction

Irrigated agriculture faces serious threats of waterlogging and salinization in arid and semiarid regions of the world, where more than 75 % of the global population live (Boumans et al. 1988; Wolde-Kirkos and Chawla 1994; Chowdary et al. 2008; Han et al. 2011; Singh 2012a, 2015a). The continuous expansion of the irrigation system, seepage from unlined canal networks, percolation from irrigation fields, under-utilization of poor quality groundwater, rolling topography, low-lying areas, inadequate drainage, and poor water management practices are the major factors contributing to this phenomenon (Shah 1988; Brahmabhatt et al. 2000; Hillel 2000; Hodgson et al. 2002; Alam and Bhutta 2004; Manjunatha et al. 2004; Guganesharajah et al. 2007; Ritzema et al. 2008; Wang et al. 2008; Quan et al. 2010; Singh 2011). Waterlogging and salinization reduce the quality of soils and associated crop productivity (Swamee et al. 2000; Dai and Labadie 2001; Upadhyaya and Chauhan 2002; Oster and Wichelns 2003; Sharma and Tyagi 2004), affect groundwater quality, and also limit the use of groundwater for agriculture and community supply (Nulsen 1989; Kirchner et al. 1997).

Waterlogging and salinization of irrigated lands are coinciding processes because prolonged irrigation in arid and semiarid regions, where evaporation largely exceeds rainfall, causes salt accumulation in the soil profile. The groundwater quality in these regions is generally poor and the substrata may contain considerable geochemical salt deposits (Kovda 1973). Strong climatic aridity is a prerequisite for salinization. Irrigation development in moderate climates and in the humid tropics has normally not lead to salinization of the land (Smedema 1990). Waterlogging and salinization have direct and indirect effects on plant growth and productivity and reduce the usability of the fields (Tsubo et al. 2006; Boling et al. 2007; Dinka 2010). Waterlogging also causes huge environmental damages in the form of damaged roads, buildings and other structures, and spread of endemic diseases. The waterlogging problem is particularly serious in areas underlain by poor quality groundwater. The direct damage of waterlogging is experienced in reduced physiological activity, while indirectly it causes reduction in nutrient availability and gaseous exchange.

Considering the importance of food security and environmental conservation, the water and salt balance studies have been receiving due attention at various research institutions around the world (e.g., Williams 1987; Peck and Hatton 2003; Cartwright et al. 2004;

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Kitamura et al. 2006). Askri et al. (2010) reported that the waterlogging and salinization of irrigated lands are of great concern for the sustainability of irrigated agriculture in the modern oases of South Tunisia. A similar concern of waterlogging and salinization was also expressed by Ibrakhimov et al. (2011) for the Khorezm region of Uzbekistan, where water supply exceeded the crop water requirement, a condition that led to a rise in the water table. West and Taylor (1980), Barrett-Lennard (2002), and McFarlane and Williamson (2002) reported that the combined effect of waterlogging and salinity are more harmful to crop yields than the individual effects of waterlogging and salinity. Wichelns (1999) examined farm-level and project-level models of crop production for identifying appropriate policies, which include water markets, volumetric water pricing, and incentives for farmers to use irrigation methods that reduce waterlogging and salinization of irrigated areas.

The aforementioned water-resources problems of irrigated agriculture have been solved by using a large number of simulation, optimization, and simulation-optimization models during the last few decades (Cheng et al. 2000; Haouari and Azaiez 2001; Mantoglou et al. 2004; Katsifarakis and Petala 2006; Konukcu et al. 2006; Azamathulla et al. 2008; Li et al. 2011; Gaur et al. 2011; Xie and Cui 2011). As far as the author is aware, there has not been a review of the individual and combined applications of simulation and optimization modeling for the management of groundwater resources associated with irrigated areas. This paper, therefore, presents a review of the individual and combined applications of simulation and optimization modeling.

First, the paper provides an overview of the water resources problems of irrigated agriculture and the significance of the study. The applications of simulation modeling for the management of water resources problems are provided. Optimization modeling applications are then discussed. The last sections deals with the combined applications of simulation-optimization modeling and some conclusions are presented.

## Simulation modeling

There are various solutions that could be considered to address the problems of waterlogging and salinization associated with irrigated agriculture; however, the effectiveness of all the solutions and their combinations cannot be verified with field experiments (Singh 2014a). Simulation models are widely used for the management of waterlogging and salinization problems (Zhao et al. 2004; Xie and Cui 2011; Morway et al. 2013) because these models usually help to find an answer to 'What if?' due to their predictive capability (Singh 2014b). The use of simulation models is also necessary because many problems and prospects associated with a particular water management option are often not recognized until they are well advanced (Singh 2010). In the recent past, a large number of simulation models (Wesseling and Van den Broek 1988; Singh and Singh 1996; Xu 1996; Khouri 1998; D'Urso et al. 1999; Droogers et al. 2000; van Walsum and Veldhuizen 2011; Xu et al. 2011; Maanjhu and Kumar 2012) have been used for groundwater and salinity management. These models have gained inclusive acceptance as effective tools to evaluate the impact of agriculture on the groundwater level and quality. Almost all the previous researchers, except Konikow and Bredehoeft (1992), suggest validation of the model (Sorooshian and Gupta 1995; Ting et al. 1998) before it is used for simulation. A successfully validated model could aid as a decision-making tool to obtain quantitative and qualitative guidance in developing and evaluating management strategies.

Simulation models play a major role in field water balance, since they improve the understanding of the most important physical processes and may be used to predict the impact of irrigation scheduling on water balance with conventional irrigation by surface flooding (Ji et al. 2007). Mathematical simulation of waterlogging and salinization is a powerful tool for managing affected soils (Garcia et al. 2006). Warrick et al. (1971), Bresler (1973), and van Genuchten (1982) provided the theoretical basis for many computer programs designed to run numerical simulations of water and salt movement in the vadose zone. A number of models have been developed to predict waterlogging and salinity, based on the spatial properties of soil (Soderstrom 1992). Some of these models have been presented by Manguerra and Garcia (1995) and Zhang (1996). This is useful to identify critical areas responsible for the disproportionate amount of groundwater recharge and to implement best water management practices to control the waterlogging and salinity problems.

Advanced soil water flow simulation models have been used to solve relatively complex problems in groundwater, irrigation, and drainage management (Schoups et al. 2006; Bastiaanssen et al. 2007); however, Thayalakumaran et al. (2007) concluded that these models require many data and their application is complicated. They are not applicable at larger spatial scales or for long-term forecasting of groundwater levels and salinity. These models are also not suitable for the accurate determination of the groundwater flow which has to be estimated indirectly or approximated from additional saturated groundwater flow models (Hollanders et al. 2005; Sinai and Jain 2006). Tyagi et al. (1993) applied the model SGMP (Boels et al. 1996; Boonstra 1999) for analyzing the groundwater balance of an irrigated area located in Lower Ghaggar Basin in the command of Bhakra Canal System in Haryana State of India. The model SGMP was later utilized by Boonstra and Bhutta (1996), Anchal et al. (2002), and Kumar and Singh (2003) for the groundwater balance analyses of different regions. Recently, Singh (2013) applied the model SGMP for evaluating the impacts of potential policy changes on the management of waterlogging problems in an irrigated area of Haryana State of India.

The agro-hydrological model SWASALT, which is an extended version of SWATRE (Feddes et al. 1978;

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Belmans et al. 1983), was utilized by Singh (2010) for managing the problems of waterlogging and salinization in Hisar district of Haryana State, India. The simulation revealed that in most agro-hydro-climatic conditions, saline water of up to 7.5 dS/m can be used safely on a long-term basis for mustard-based cropping systems. Gates and Grismer (1989), Gates et al. (1989), and Schoups et al. (2005) have also used simulation models to carry out waterlogging and salinity studies in a number of regions of the United States. Garcia et al. (2006) introduced a simulation model to predict relative reductions in crop yield due to waterlogging and salinity at a field-scale by incorporating spatially and temporally variable crop, climatic, and irrigation data to simulate crop yields. This model utilizes soil and water data normally collected in field-scale studies. Chandio et al. (2012) presented a three-dimensional (3D) finite element model, based on Galerkin weighted residual techniques. The model was applied in a waterlogged area of the lower Indus Basin, Pakistan, for groundwater simulation.

A spatial-agro-hydro-salinity model, SAHYSMOD (Oosterbaan 2005; Akram et al. 2009), was applied by Rao et al. (1995) for analyzing the water and salt balances of a waterlogged area of northwest India. Later, Singh and Panda (2012a,b) used SAHYSMOD in an area located in the Haryana State of India, where the groundwater level has risen during the last few decades. After successful calibration and validation, they used the model for studying the long-term effect of different management scenarios on the future groundwater behaviour. They considered the socio-economic issues in groundwater simulation. Xu et al. (2010) used a lumped model in Yellow River Basin of China to examine management and infrastructure rehabilitation options to cope with water scarcity, waterlogging, and salinization problems in the upper part of the basin. A wide range of management options were investigated through the model and it was concluded that a combination of interventions is quite effective in controlling the problems of water resources. Several studies have analysed the spatial variability of waterlogging and salinity and the significance of these variabilities when applied toward the identification and management of these problems (Castrignano et al. 1994; Thokal et al. 1996; Alvarez-Rogel et al. 1997; Thiam and Singh 1998).

Konukcu et al. (2006) proposed a sustainable solution for waterlogging and salinity problems in the irrigated Lower Indus Basin of Pakistan. They used dry drainage in the selected area, developed a simulation model and used it to solve the problems of the area where saline groundwater, shallow water tables, intensive irrigation, high evaporative demand and natural dry drainage exist. Kitamura et al. (2006) studied the causes of farmland salinization in the arid area of Aral Sea basin, Japan. They suggested to avoid mixed cropping with rice and upland crops. The study also suggested to combine either upland crops or rice in an irrigation block to control salinity and the water table problems because this strategy would decrease the conveyance and field application losses by the introduction of canal lining and improved land-leveling. Recently, Chandio et al. (2013) carried out a simulation study along the Rohri Canal in Khairpur District of Pakistan. They evaluated the impacts of a horizontal drainage system, a vertical drainage system, and a combination of horizontal and vertical drainage on waterlogging control under different flow levels in Rohri Canal. They concluded that a combined drainage system, i.e., horizontal plus vertical drainage system, is more effective and beneficial in controlling the waterlogging problem.

Most of the existing models require inputs which are not easy to measure and also they use short time steps and need at least a daily database of hydrologic phenomena. Keeping aforementioned reservations in view, Singh (2012b) used an agro-hydro-salinity model, SaltMod (Oosterbaan and de Lima 1989; Srinivasulu et al. 2004; Oosterbaan 2008), to analyze water and salt balances of an irrigated semi-arid area located in the Haryana State of India where the groundwater level has risen in the last few decades (Singh et al. 2010, 2012; Singh 2015b). Improved and efficient irrigation methods along with better cropping pattern, canal lining, and reduced canal water use and increased groundwater use were suggested to manage the waterlogging and salinization problems of the area. Earlier, Rao et al. (1992) used the model SaltMod for a hydrologic unit of 1580 ha in the Tungbhadra irrigation project, India. The objective was to predict groundwater level and salinity behavior in the root zone and to delineate areas prone to waterlogging and soil salinity. A similar model was used by Kumar et al. (1996); the model was verified with the data set of Rao et al. (1992) and with the limited data from the Ukai-Kakrapar Command in Gujarat, India. Scenario building exercises revealed that average annual water release is more than the demand; therefore, some arrangements to reduce its release may help in solving waterlogging and salinization. Later, the model SaltMod was used by Bahceci et al. (2006) for the study of water and salt balances and to improve subsurface drainage design in the Konya-Cumra Plain, Turkey. The simulated soil salinity results showed that most crops theoretically have no yield reduction when the depth to the water table is 1 m.

## Optimization modeling

The development of irrigated agriculture in arid and semiarid regions is contained by the availability of good quality water and land resources (Singh 2012c). Furthermore, unplanned utilization of these resources leads to problems of waterlogging and salinization. The planned and optimal allocation of natural resources can be determined by employing an optimization model (Maknoon and Burges 1978; Maji and Heady 1978; Loucks et al. 1981; Afshar and Marino 1989; Tsakiris and Kiountouzis 1984; Saruwatari and Yomota 1995; Wardlaw and Barnes 1999; Li et al. 2008; Singh 2012d). Numerous optimization models have been used during the

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last few decades for the management of water-resource problems in irrigated areas (Chavez-Morales et al. 1987; Smout and Gorantiwar 2005; Khare et al. 2006; Seifi and Hipel 2001; Karamouz et al. 2009; Yang et al. 2009; Li et al. 2011; Huang et al. 2012). These models help to identify the best management strategy to achieve a given set of objectives under particular constraints (Singh 2014c).

Various optimization techniques have been used to solve the problems of water resources (Morel-Seytoux 1975; Yaron and Dinar 1982; Ahlfeld et al. 1988; Azaiez et al. 2005; Katsifarakis and Petala 2006; Gaur et al. 2011; Singh 2014d). The techniques used include linear programming (LP) (Castle and Lindeborg 1960; Vedula and Roger 1981; Feinerman and Yaron 1983; Peralta et al. 1995; Mantoglou 2003), non-linear programming (NLP) (Rydzewski and Rashid 1981; Takahashi and Peralta 1995; Montazar et al. 2010; Shamir et al. 1984; Mantoglou and Papantoniou 2008), dynamic programming (DP) (Burt 1970; Yakowitz 1982; Lee and Kitanidis 1991; Datta and Dhiman 1996; Philbrick and Kitanidis 1998; Shangguan et al. 2002; Tran et al. 2011), quadratic programming (QP) (Lefkoff and Gorelick 1986), and genetic algorithm (GA) (Holland 1975; Sharif and Wardlaw 2000; Maskey et al. 2002; Wardlaw and Bhaktikul 2004; Haq et al. 2008; Wu et al. 2007; Liu et al. 2008; Rana et al. 2008; Safavi et al. 2009).

Because of easy formulation and application, the use of LP-based optimization models is very common in the management of water-resource problems (Bender et al. 1984; Suryavanshi and Reddy 1986; Kumar and Pathak 1989; Ahlfeld and Heidari 1994; Vedula and Kumar 1996; Khare et al. 2007; Azamathulla et al. 2008; Lu et al. 2011; Singh 2014e). However, NLP models have not been widely used because of rigorous mathematics involved in its development and the high computation time and memory required. Latif and James (1991) employed an LP-based optimization model in the Indus Basin in Pakistan to maximize the net income of irrigators through wet-year and dry-year cycles over the long-term. The model determines the optimal groundwater extraction for supplementing canal water to avoid adverse effects of waterlogging or groundwater depletion and high pumping cost. Recently, an LP-based optimization model was formulated and applied by Singh and Panda (2012c) in an irrigated area of Rohtak-Jhajjar districts of Haryana State, India. Crop yield, price, unit costs of canal water and groundwater, quality of the mixed canal water and groundwater; and net irrigation requirement of crops were the economic and hydrologic factors used in the model. A groundwater balance constraint was imposed on the model, which mitigated the waterlogging problems, while making optimal allocation of land and water resources.

An optimization model was developed for the optimal allocation of good quality surface water and poor quality groundwater (Tyagi 1986). It was applied in a waterlogged saline area of Western Yamuna Canal Command, India. The results showed that progressive development of groundwater would assist in the reclamation of waterlogged saline lands and increase farm income. Later, Afzal et al. (1992) developed an LP model for the optimal allocation of different quality waters by alternative irrigation methods rather than by blending, in order to maximize the net return. They used the model in an area of Pakistan where groundwater quality was poor and good quality canal water was limited. The area under different crops and the amount of water applied to each crop were decided by the model. The model presents a solution for the scenarios wherever low rainfall and different quality waters are the constraints for the agricultural development. Similarly, Shyam et al. (1994) utilized an LP-based optimization model for devising an improved method of water allocation to different canals in a canal command in India. They compared the results of the model with the existing and three alternate operation policies in which optimal allocation took place at different stages of water distribution.

Tyagi and Narayana (1984) developed a deterministic LP model for the allocation of surface water and groundwater for irrigation in order to determine optimal water use in alkali soils under reclamation. Optimal cropping pattern over a period of 20years at five discrete stages of reclamation were determined and parametric analysis was done to determine the optimal water-resources-management policies with regard to canal water diversion and groundwater mixing. Similarly, Easwaramoorthy et al. (1989) suggested the optical cropping pattern for the lower Bhawani project of India, using an LP model. The objective of the model was to maximize net return from all crops, considering the land, groundwater, and crop-water-requirement constraints. A regional LP model was developed by Yamout and El-Fadel (2005) to assist decision makers in the planning and setting of policies for optimal water resources allocation by taking economic, environmental, and social implications into consideration.

To assist in planning and management of surface water and the saline groundwater in a typical waterlogged saline area of northwest India, Tyagi (1988) formulated and applied a decision model. The model determines optimal land and water allocation and the resulting salt and water balances. The study revealed that increased groundwater withdrawal would mitigate the waterlogging and salinization problem and also increasing the net farm benefit. Earlier, Tyagi and Narayana (1981) applied an LP model for allocating surface water and groundwater for irrigation of agricultural crops in a semi-arid area of India where alkalization was a problem. The net farm return was increased by 14% under the optimal allocation of land and water resources. Malek-Mohammadi (1998) developed a mixed integer LP model for planning an irrigation system considering a reservoir, underlying aquifer, supply system capacity, and candidate cropping patterns as constraints.

An LP model was applied by Khepar and Chaturvedi (1982) to make decisions on optimal cropping pattern and groundwater management alternatives in a canal-irrigated area of India. Sun et al. (2011) utilized an optimization model for sustainable groundwater use in a semiarid

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region located in North China Plain. The model optimizes yield and water-use of different cropping systems. The study revealed that the irrigation water productivity can be improved for the double cropping system under optimized water management. Recently, Singh (2012c) developed an LP model for optimal land and water resources allocation in order to maximize net annual returns and to manage the waterlogging problem of a command area located in the Jhajjar District of Haryana, India. Under the optimal land and water allocation, the groundwater use was increased, which in turn mitigated the waterlogging and salinity problems of the command area. The net annual return from the command area increased by more than 20 % under optimal allocations.

## Simulation-optimization modeling

As mentioned in the preceding, the separate applications of simulation and optimization models have been practiced extensively for the solution of water resource problems of irrigated agriculture; however, it is highly unlikely to get a suitable management option with simulation or optimization models alone (Singh 2014f). Because these models address two different questions, i.e., a simulation model examines 'What if?' scenarios, while an optimization model answers the question of 'What is the best?' under a specific set of constraints (Singh 2014g, 2015c); therefore, combined use of simulation and optimization models is essential (Maddock 1972, 1974; Gorelick 1983; Willis and Yeh 1987; Hallaji and Yazicigil 1996; Ayvaz and Karahan 2008; Das and Datta 2001; Mantoglou et al. 2004; Lu et al. 2012; Yazdi and Salehi Neyshabouri 2012; Singh 2014h; Das et al. 2015). Barlow et al. (1996) used a simulation-optimization approach to identify groundwater-pumping strategies for control of the shallow water table in the western San Joaquin Valley, California (USA), where shallow groundwater threatens continued agricultural productivity. The approach combines the use of groundwater flow simulation with optimization techniques to build on and refine pumping strategies identified using flow simulation. The model results showed a 20 % reduction in the area subject to a shallow water table.

In the simulation-optimization modeling framework, a simulation model is used to check the constraints of the problem that are based on state variables, i.e., groundwater level. The objective function is evaluated using the optimization model, which in turn utilizes the simulation model to satisfy the constraints. The simulation-optimization approach is attractive because it can account for the complex groundwater flow behaviour and identify the best management option for a particular condition. In the simulation-optimization approach, a simulation model accounts for the physical behavior of groundwater systems, while the optimization model accounts for the optimal allocation aspects. Ahlfeld et al. (1986); Gorelick (1990); Dougherty and Marryott (1991); Yeh (1992), Emch and Yeh (1998), Wang and Zheng (1998), Das and Datta (1999), Cheng et al. (2000), Bhattacharjya and Datta (2005), Vedula et al. (2005), Uddameri and Kuchanur (2007), Qin et al. (2009), Safavi et al. (2010), and Srivastav et al. (2011) have utilized various simulation-optimization models for the solution of resources management problems during the last few decades. A GA-based simulation-optimization approach was utilized by Sedki and Ouazar (2011) for the optimal groundwater exploitation strategies in Rhis-Nekor Plain, Morocco. The objective of the study was to maximize the groundwater withdrawals to meet current and future water needs while efficiently controlling seawater intrusion, excessive drawdowns, and waterlogging and salinity problems in the aquifer.

A simulation-optimization model was developed by Nishikawa (1998) for the optimal management of water resources in the city of Santa Barabara, USA. An LP optimization model was formulated to minimize the cost of water supply subject to water demand constraints, hydraulic head constraints, and water capacity constraints. The decision variables were monthly water deliveries from surface water and groundwater, and the state variables were hydraulic heads. Singh and Panda (2013) developed a unique and simple technique in which an LP model was first developed that allocates available land and water resources in order to maximize net annual returns by mitigating the waterlogging problems. A finite-difference two-dimensional (2D) simulation model was then used to evaluate the long-term impacts of various water management strategies on the water table with the optimal land and water use parameters which were obtained through the optimization model. The model was used to solve the waterlogging and salinity problem of an area located in the Haryana State of India. Reduced rice area, increased groundwater withdrawal, and canal lining were suggested to mitigate the problems of waterlogging, whereas earlier, Onta et al. (1991), Tracy (1998), and Psilovikos (1999) also used simulation-optimization models for managing the resources problems.

A simulation-optimization model was presented by Ejaz and Peralta (1995) to address the conflicts between water quantity and quality objective. The response matrix approach was used to link the simulation and optimization models. Maximizing waste loading from a sewage treatment plant to the stream was the water quality objective, while maximization of conjunctive use of surface water and groundwater was the water quantity objective in the model. The model was used to solve a groundwater management problem of the upper San Pedro River Basin, southeastern Arizona (USA). The response matrix approach was also utilized by Danskin and Gorelick (1985), Karatzas and Pinder (1993), McKinney and Lin (1994), Keshari and Datta (1996), and Shen et al. (2004) for the solution of water resources problems. Karamouz et al. (2004) developed a dynamic programming-based simulation-optimization model with the objective of meeting the agricultural water demands by reducing the pumping costs and controlling groundwater level fluctuations in the Tehran metropolitan area (Iran).

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The long-term impacts of different management scenarios on the conjunctive use policies and water table fluctuations were assessed by the model. Earlier, a similar approach was adopted by Willis et al. (1989) and Basagaoglu et al. (Basagaoglu and Marino 1999).

A simulation-optimization model was used by Safavi and Esmikhani (2013) for the conjunctive use of two water sources in the Zayandehrood River basin of west central Iran. Maximum capacity of irrigation systems and maximum cumulative groundwater drawdown were the model constraints. A similar approach was also adopted by Jones et al. (1987), Willis and Finney (1988), Ibanez-Castillo et al. (1997), and Karterakis et al. (2007) for the management of water resources. Mohan and Jothiprakash (2003) utilized a simulation-optimization model to develop and assess the alternate priority-based policies for operation of surface water and groundwater resources. An optimization model was first used to get the optimal cropping pattern and then a simulation model was employed to evaluate the conjunctive operation of the system using the optimal cropping.

A decision support system was constructed by McPhee and Yeh (2004) for solving a groundwater management problem of upper San Pedro River basin, south-eastern Arizona. The study treated the case as a multi-objective optimization problem in which environmental objectives were explicitly considered by minimizing the magnitude and extent of drawdown within a pre-specified region. Garg and Ali (2000) revised their model (Garg and Ali 1998) and used it in Dadu Canal command of the lower Indus Basin, Pakistan, to address the problem of waterlogging. The simulation result suggested that waterlogging can be managed by operating the existing tubewells at their maximum capacity and installing more tubewells. The study concluded that an additional 130 % tubewells could be installed in the command area for mitigating the waterlogging problem. An LP-based simulation-optimization model was presented by Belaineh et al. (1999). The model integrates linear reservoir operation rules, conjunctive use of surface and groundwater, and delivery to water users via branching canals. Groundwater flow was simulated using the MODFLOW program, which solves the quasi 3D groundwater flow equations.

## Conclusions

Irrigation is essential for achieving food security to the burgeoning global population because a properly managed irrigated agriculture will provide more food in the future; however, without proper planning and management, irrigated agriculture can be detrimental to the environment and lead to waterlogging and salinization problems. A literature review revealed that simulation and optimization models have been widely used for the management of waterlogging and salinization problems associated with groundwater resources. The simulation models were used to find the answer of 'What if?', while the optimization models provide the answer of 'What is the best?' under a given set of conditions; however, to get a suitable management alternative, the combined use of simulation and optimization models is essential. It can be seen from the review that most studies on simulation-optimization modeling of the management of water-resource problems of irrigated agriculture are concentrated on the development and linking of simulation and optimization models and their applications to real-world problems. Embedding technique and response matrix are the two methods generally used to integrate the simulation and optimization models. The discretized flow equations are included in the linear program as constraints in the embedding approach, while these are computed separately in the response matrix method. The response matrix approach produces good results for linear or slightly nonlinear systems and it is generally preferred for unsteady-state optimization because an embedding technique may require a large computer memory for unsteady flow situations. In earlier studies of simulation-optimization modeling, the objectives were to minimize the rise of the water table, to minimize costs, or to maximize the well production by taking into account the constraints like drawdown, pumping rates, salinity of the pumped water etc.

It is clear from the review that the combined use of simulation-optimization modeling is very suitable for achieving an optimal solution of groundwater-resource problems even with a large number of variables. The uncertainty analysis and parameter estimation are the major problems in modelling studies; however, the applications of independent model tools such as PEST and UCODE have solved these problems. The computational complexity in the groundwater modeling is another problem associated with the management and modeling of these processes, although the recent use of artificial neural networks has minimized this problem to some extent. Very few studies reported so far have considered the determination of optimal cropping patterns that can maximize the net benefit and the corresponding pumping schedule by taking into account the groundwater level within the desired limits so as to mitigate the waterlogging and salinization problems. Socioeconomic factors have not been included as a modeling component in the earlier studies. The interdisciplinary nature of groundwater problems requires the integration of technical, economic, environmental, social, and legal aspects into a coherent analytical framework. However, in developing countries these objectives are difficult to achieve because of the lack of observation infrastructure and economic aspects; thus, future research will be directed toward improving the long-term hydraulic assessment by collecting and analyzing widespread spatial data, which can be done by increasing the observation and monitoring networks. Incorporating socioeconomic aspects into the groundwater management modeling would be another aspect which could be included in future studies.

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