Optimization Modeling for Conjunctive Use Planning of Surface Water and Groundwater for Irrigation

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Abstract: The continuous increase in global population and simultaneous decrease in good-quality water resources emphasize the need of conjunctive use of groundwater and surface-water resources for irrigation. The optimal allocation of water resources can be achieved by employing an appropriate optimization technique. This paper presents an overview of the different programming techniques used for the conjunctive use planning and management of irrigated agriculture. Past papers on the applications of different programming techniques for the conjunctive use of different water sources are grouped into four categories: linear programming, nonlinear programming, dynamic programming, and genetic algorithms. Conclusions are provided based on this review, which could be useful for all stakeholders.
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Introduction

The global population is growing continuously and it needs about 60% more food to feed the 9.5 billion people projected for 2050 (United Nations 2012; FAO 2013; Singh 2014b, a, f). The provision of irrigation is very important for achieving food security (Singh 2012a) and it will remain vital as its share in world food production will rise to over 45% by 2030 (Faures et al. 2007) from the current level of 40%. However, without proper planning and management, the intensification of irrigated agriculture can result in biodiversity degradation and other ecological problems in agro-ecosystems (Krebs et al. 1999; Foley et al. 2005; Singh 2010, 2011, 2015a). For example, more than 33% of the world's irrigated land is affected by waterlogging and/or secondary salinization (Heuperman et al. 2002) and these conditions poses threats to food security and environmental conservation (Wichelns and Oster 2006; Singh et al. 2010; Singh and Panda 2012h, i, 2013; Singh 2012b, 2013, 2015b).

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The conjunctive use of groundwater and surface-water resources is necessary because the availability of one source of water over time and space may not be sufficient to fulfill all irrigation requirements (Tyagi et al. 2005; Harmancioglu et al. 2013). Generally the conjunctive use of water resources improves water use efficiency and the regional environment of irrigated areas (Cosgrove and Johnson 2005; Liu et al. 2013; Singh 2014g, 2015c; Das et al. 2015). The specific objectives of conjunctive use are to increase yield and reliability of supply by combining two water sources. Burt (1964) introduced the concept of conjunctive water use and suggested that surface water and groundwater should be considered as two elements of an integrated water system. Fredericks et al. (1998), Ruud et al. (2004), and Islam et al. (2011) evaluated the conjunctive use of two water sources in water-scarce semiarid regions.

The increase in agricultural production by minimizing the crop stress is the major benefits of conjunctive water use. A properly-managed conjunctive use system will yield more water than separately-managed groundwater and surface-water systems (Wrachien and Fasso 2002). Conjunctive water use can also solve the problems of groundwater resources (Singh and Panda 2012j; Singh 2014d). Small farm sizes and the spatially scattered landscape are the constraints in large-scale implementation of conjunctive use in Asia (Rao et al. 2004). Safavi et al. (2013) concluded that evaluation of conjunctive use in some developing countries is difficult because of limited data availability. Winter (1995), Garcia-Lopez et al. (2009), Venot et al. (2010), Karimov et al. (2012), and McCallum et al. (2013), and Nikoo et al. (2013) have reported the various aspects related to conjunctive use of groundwater and surface-water resources.

The optimal allocation of available groundwater and surface-water resources is crucial in conjunctive use planning and management, and this can be achieved by using an optimization model (Pathumnakul et al. 2011; Singh 2012c; Stray et al. 2012). Different programming techniques have been used in optimization modeling during the last five decades (e.g., Castle and Lindebor 1960; Mylopoulos et al. 1999; Chen and Huang 2001; Reca et al. 2001; Khare et al. 2006; Li et al. 2011; Singh 2014c). These models compare different permutations of groundwater and surface-water sources and select an optimal permutation based on certain constraints (Maknoon and Burges 1978; O'Mara 1988; Vincent and Dempsey 1991). As far as the authors are aware, there has not been a review on the applications of various optimization techniques for conjunctive use planning of different water sources for irrigation. This paper, therefore, presents an overview of different programming techniques used for conjunctive use planning and management of groundwater and surface-water resources for sustainable irrigated agriculture. Past papers are grouped into four sections: linear programming, nonlinear programming, dynamic programming, and genetic algorithms.

Linear Programming

Linear programming (LP) based optimization models have been widely used for conjunctive use planning and management in irrigated agriculture owing to LP's easy formulation and use (Hallaji and Yazicigil 1996). A conjunctive surface-water and groundwater management model was solved by Morel-Seytoux (1975) using LP. The discrete kernel generator (Morel-Seytoux and Daly 1975) was used in the model to develop the response matrix. An LP-based optimization model was developed by Tyagi and Narayana (1981) to allocate surface water and groundwater for irrigation of agricultural crops in a semiarid area of India where alkalization was a problem. Later, Tyagi and Narayana (1984) developed a deterministic LP model for allocation of two water sources for irrigation in order to determine optimal water use in alkali soils under reclamation. An LP-based conjunctive management model was presented by Barlow et al. (2003) to evaluate the tradeoffs between groundwater withdrawal and stream flow depletion for alluvial-valley stream aquifer systems of the northeastern United States. The objective function maximizes the sustained yield from the aquifer in a specified month for the given standard of stream depletion.

A decision model was formulated by Tyagi (1988) for the conjunctive use planning of limited surface water and saline groundwater. It was applied in a waterlogged saline area of Western Yamuna Canal Command in Haryana State of India to determine optimal land and water resource allocation and analyze the resulting salt and water balances. The results showed that progressive development of groundwater would assist in the reclamation of irrigation-induced saline lands and increase farm income. Earlier, Tyagi (1986) formulated and used a similar management model for the conjunctive use planning of an area underlain by poor quality groundwater. Lu et al. (2011) developed and applied an inexact rough-interval fuzzy LP model to generate conjunctive water-allocation strategies in agricultural irrigation systems. Suryavanshi and Reddy (1986), Gaur et al. (2011), and Kashyap and Chandra (1982) have also used similar models for management and planning of surface-water and groundwater resources.

Smith (1973) formulated a CCLP (chance-constrained linear programming) model for studying complex hydrologic and economic interactions on conjunctive use of two water sources in an irrigation project in Bangladesh. Two CCLP models were formulated by Maji and Heady (1978) for intertemporal allocation of irrigation water in the Mayurakshi Project in India. Mishra (1975), Lakshminarayana and Rajagopalan (1977), and Panda et al. (1985) also used the similar approach for conjunctive use planning and management of water resources. An LP-based optimization model was developed by Moradi-Jalal et al. (2007) for the optimal allocation of water resources in a reservoir-irrigation system in Iran. The model objective was to maximize the annual benefit of the system for a proposed multicrop pattern over the planning period. An LP-based optimization model was developed by Singh (2012a) for the optimal allocation of available resources. The model was applied in a canal command of a semiarid region of India, which is underlain by poor quality groundwater. Model results suggested practicing conjunctive use of canal water and groundwater for maximizing the farm income.

An LP-based optimization model was developed by Peralta et al. (1995) to obtain sustainable groundwater extractions over a period of five decades under a conjunctive water use scenario. A multilevel optimization technique was used by Paudyal and Gupta (1990a) to solve the complex problem of irrigation management in a large heterogeneous basin. A similar approach was adopted by Karmarkar (1984), Easwaramoorthy et al. (1989), Ponnambalam et al. (1989), Shyam et al. (1994), and Yamout and El-Fadel (2005). An LP-based optimization model was developed by Latif and James (1991) to maximize the net income of irrigators through cycles of wet and dry years over a long period. The model was applied in the Indus Basin of Pakistan for determining the optimal groundwater and canal water uses to avoid adverse effects of waterlogging or groundwater depletion and high pumping cost.

A deterministic LP-based conjunctive model was developed by Kaushal et al. (1985) to determine the optimal cropping pattern and optimum use of saline groundwater in a canal command area in India. Similarly, Khare et al. (2007) used an LP-based optimization model to investigate the scope of conjunctive use of surface water and groundwater for a link canal command in Andhra Pradesh, India, while, Saruwatari and Yomota (1995) presented the results of a study on a forecasting system of irrigation water requirements using the fuzzy theory. Panda et al. (1983) developed and applied an LP model for conjunctive use of surface water and groundwater in a canal command area of Punjab in India. A water-allocation model that incorporates deficit irrigation for optimizing the use of water for irrigation was presented by Smout and Gorantiwar (2005). They developed the model for surface irrigation schemes in semiarid regions under rotational water supply. The model used for the optimal allocation of available land and water resources. Later, Gorantiwar and Smout (2005) applied the model to a medium irrigation scheme in India to obtain land and water allocation plans. A similar LP-based optimization model was also used by Khanjani and Busch (1983) for optimizing the conjunctive use of surface water and groundwater sources for irrigated agricultural systems.

Nonlinear Programming

LP models are easy to formulate and apply, however, they are unable to handle nonlinear problems and do not attain the global optimal solution of other algorithms (Gorelick et al. 1984; Sedki and Ouazar 2011; Singh 2014e). This inability of LP models necessitates the use of nonlinear programming (NLP) models in conjunctive use planning and management of surface-water and groundwater resources (Yeh 1985; Shang and Mao 2006). Furthermore, most conjunctive use management problems are nonlinear in nature (Vedula et al. 2005). Despite this fact, the application of NLP-based models has been fairly limited in conjunctive use planning and management because of the complexity and the slow rate of convergence of the NLP algorithms and difficulty in considering stochasticity (Willis et al. 1989; Matsukawa et al. 1992). Haimes and Dreizin (1977) developed a methodology for solving the problems of conjunctive use of a large-scale complex groundwater system. They formulated a sample problem in which the available surface water and groundwater supply were conjunctively used to meet the water needs of several water users in a basin.

Chiu et al. (2010) formulated a conjunctive use planning model with a linear objective function and nonlinear constraints.

The model was formulated by considering an optimal pumping and recharge strategy with the objectives of removing the high-nitrate concentration while maintaining groundwater levels at desired elevations at specified locations as well as meeting water demand. Gupta et al. (1987) formulated an NLP model for conjunctive use planning through mixing poor-quality groundwater and good-quality canal water. The nonlinear objective function of the model was solved by using generalized geometric programming. An NLP-based optimization model was developed by Khan (1982) for managing irrigated agriculture with different quality waters. The model maximizes the net benefits under the constraints of water supply, water blending, land availability, and root-zone salinity. LP and NLP models were used by Ghahraman and Sepaskhah (2004) for the investigation of irrigation optimization using an irrigation interval of 10 days.

A groundwater–surface water management model was developed by Danskin and Gorelick (1985). It was applied to a complex, real-world water-allocation problem in California using the response matrix approach. The groundwater system was analyzed using a transient, quasi-three-dimensional finite-difference model that considered nonlinear behaviour of the unconfined aquifer. Montazar et al. (2010) developed an integrated soil–water balance algorithm and coupled it with an NLP model. The model was applied in a command area in Iran to develop an optimal allocation plan of surface-water and groundwater resources for irrigation of multiple crops and enhance overall farm incomes. Earlier, similar conjunctive use planning models were utilized by Paudyal and Gupta (1990b), Takahashi and Peralta (1995), Mainuddin et al. (1997), and Raju and Kumar (2004) for irrigation systems management.

An integrated two-stage interval-quadratic programming model was developed by Huang et al. (2012). It can deal with nonlinearities and uncertainties expressed as probability density functions and discrete intervals and can also support the analysis of policy scenarios that are associated with economic penalties when the promised targets are violated. The model was used to analyze different water resources based scenarios in the Tarim River Basin, northwest China. A crop water benefit function-based NLP optimization model was formulated by Benli and Kodal (2003). It was utilized for the determination of irrigation water needs and farm income under adequate and limited water supply conditions in the southeast Anatolian Region of Turkey. A similar approach was adopted by Ghahraman and Sepaskhah (1997) and Carvallo et al. (1998). Rastogi (1989) used NLP for the simulation of a groundwater management model. The model was applied in the Blue Lake aquifer in Northern California with the objective of minimizing pumping costs. The study concluded that huge savings can be possible by implementing an annual optimal pumping policy as compared to a nonoptimized policy. Austin et al. (1998) and Shang and Mao (2006) also used NLP-based models for conjunctive use planning and maximization of farm income.

Genetic Algorithms

The conventional LP-based and NLP-based optimization models have been extensively used for the solution of conjunctive water-allocation problems. However, their inability to handle nonlinear non-convex problems and difficulty in attaining global optima generate demand for other types of algorithms. Genetic algorithms (GA) have been shown to be a valuable tool for solving complex optimization problems during the recent past (Van Laarhoven and Aarts 1987; Oliveira and Loucks 1997; Wu et al. 2007; Liu et al. 2008; Safavi et al. 2009; Nicklow et al. 2010). A genetic algorithm is an optimization technique based on the process of biological evolution (Holland 1975). This technique has been used by researchers worldwide to deal with a wide range of optimization problems (Goldberg 1989; Mckinney and Lin 1995; Haupt and Haupt 1998; Reed et al. 2000). The GA-based optimization approach is particularly suitable for externally linking a numerical simulation model within an optimization model.

The GA can yield much better results than traditional optimization techniques (McKinney and Lin 1994; Huang and Mayer 1997), and it has gained popularity in many fields because it does not require differentiability of objective function or/and constraint. Despite the wide utilization of GA-based optimization models for the solution of many optimization problems, its application in conjunctive use planning and management is relatively new, picking up pace only during the last two decades (East and Hall 1994; Hilton and Culver 2005; Espinoza et al. 2005). Karamouz et al. (2009) used a GA model to optimize a water-allocation scheme considering the conjunctive use of surface-water and groundwater resources. The objective function of the model aimed at maximizing the net benefit, considering the water pumping cost, crop cultivation cost, and benefit of total crop production during the study's time horizon. The performance of the model was successfully field-evaluated to determine the optimal crop mix and water allocation from surface water and groundwater. A similar approach was also used by Dariane and Hughes (1991), Mujumdar and Ramesh (1997), and Nixon et al. (2001) for the multicrop irrigation planning.

Morshed and Kaluarachchi (2000) applied three GA enhancement methods to a nonlinear groundwater problem of minimizing the costs of pumping for meeting a specific demand. The time block approach and GA was used by Wardlaw and Bhaktikul (2004) for solving an irrigation scheduling problem. They demonstrated how the time block model may be formulated as a GA. However, the approach used by Wardlaw and Bhaktikul (2004) was criticized by Haq et al. (2008), who demonstrated that this algorithm did not have a dual goal of minimizing both discharge and earliness/tardiness. Furthermore, they have emphasized the need for thorough testing of GA, before any conclusion about its performance and application can be made (Haq and Anwar 2010). Afshar et al. (2010) developed and applied a hybrid two-stage GA model for optimizing the design and operation of a nonlinear, nonconvex, large-scale semidistributed, cyclic reservoir system in an irrigated area.

An irrigation allocation model was presented by Kumar et al. (2006) for determining the relative yield from a specified cropping pattern for various states of reservoir inflows and rainfall in the irrigated area using a GA approach. The model was applied in the Malaprabha single-purpose irrigation reservoir in Karnataka State, India. The optimal operating policy obtained using the GA was similar to that obtained by linear programming. The proposed model can be used for optimal utilization of the available water resources of any reservoir system to obtain maximum benefits. Mohamed Azamathulla et al. (2008) formulated an integrated LP and GA model to obtain an optimal reservoir operating policy that incorporates field-level decisions. The integrated model was applied to real-time reservoir operation in an existing reservoir system in India. The study revealed that the performance of the GA model was superior to the LP model. A GA-based management model was formulated by Karamouz et al. (2008) to optimize the cropping pattern of irrigation networks. They considered water allocation priorities with surface water and groundwater availability as constraints. Wardlaw and Sharif (1999), Wu and Simpson (2001), Maskey et al. (2002), Archibald et al. (2006), and Moghaddasi et al. (2010) have also used GA-based optimization models for the planning and management of irrigation systems.

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Dynamic Programming

The use of dynamic programming (DP) technique is very common in irrigation planning and management because of its intrinsic advantages, i.e., ability to model sequential decision-making processes and nonlinear systems, together with its ability to incorporate stochasticity of hydrological processes and global optimality even for complex policies. DP is the most appropriate and popular method of dynamic optimization in water resources (Yakowitz 1982). The DP approach has been extensively used in conjunctive use planning of irrigated agriculture (Hall et al. 1968; Burt 1970; Rao et al. 1992; Umamahesh and Sreenivasulu 1997; Naadimuthu et al. 1999; Abdallah et al. 2003; Tran et al. 2011). Kennedy (1986) and Benedini (1988) reported the key developments in the area of the DP application in conjunctive use planning and management. Karamouz et al. (2004) developed and applied a DP-based optimization model for fulfilling the objectives of meeting agricultural water demands, reducing pumping costs, and controlling groundwater fluctuations in the Tehran metropolitan area.

Generally the DP approach has been limited to problems with few periods and two or three state variables. But, Philbrick and Kitanidis (1998) applied a second-order gradient DP method, which had five state variables. The model identified the efficient real-time control policies that utilized surface water and groundwater in an uncertain supply environment. An optimization model was developed by Rao et al. (1990) for an optimal weekly irrigation scheduling policy for two crops by considering both seasonal as well as intraseasonal competition of water. They used DP for solving the problems based on a heuristically-derived seasonal crop water production function. Earlier, Jones et al. (1987) developed and applied a differential DP algorithm for unsteady and nonlinear groundwater management problems. The study concluded that the computational efficiencies were most strongly influenced by the dimension of the state vector.

A DP-based optimization model was developed and applied by Panda (1992) for conjunctive use planning and management in a semiarid region of India through the irrigation of surface water and gypsum treated sodic groundwater. A deterministic DP optimization model was developed and applied by Prasad et al. (2006) for obtaining optimal irrigation planning strategies by allocating land and water resources in a multicrop and multiseason environment in Nagarjuna Sagar right canal command of India. Stochastic dynamic programming (SDP) is widely used for deriving operating policies for irrigation systems. Because incorporation of the stochastic nature of supply and demand is easy and satisfactory in these models (Protopapas and Georgakakos 1990). The stochastic irrigation need of paddy was modeled by Gupta and Chauhan (1986). They assumed the irrigation requirement time series by an additive model. The developed model superposes a periodic–deterministic process and a stochastic component. Earlier, the SDP models were used by Dudley et al. (1971) and Dudley and Burt (1973) for determining the optimal irrigation planning of agricultural systems.

A chance constrained model was developed by Azaiez et al. (2005) for optimal multiperiod operation of a basin operating under a conjunctive use of surface water and groundwater resources. A system analysis approach was presented by Yaron and Dinar (1982) for water allocation to crops during the peak seasons. They used soil–moisture response functions for the key crops using an LP model for maximizing farm income and a DP model for generating new irrigation scheduling activities. A model for designing a groundwater quality-monitoring network was developed by Datta and Dhiman (1996). The model linked a groundwater pollution transport simulation model and an optimization model. The model produced the optimal location of the monitoring wells. Bertsekas and Tsitsiklis (1996) used fuzzy theory within the proposed stochastic dynamic programming to deal with descretization. Duldley (1988) and Dudley and Musgrave (1993) have also used SDP-based optimization models for the solution of irrigation management problems.

A three-variable SDP model was developed by Vedula and Mujumdar (1992) for obtaining an optimal steady-state reservoir operating policy. They integrated the reservoir release and field allocation decisions in a single model that took into account soil–moisture dynamics and crop growth at the field level. They first used a DP to optimally allocate the available water among all crops within a given period and then evaluated the system performance using SDP to optimize the benefits over a full year. Huang et al. (2002) developed a GA-based SDP model to cope with the dimensionality problem of a multiple-reservoir system. Paul et al. (2000) proposed an optimal resources allocation strategy for a canal command in India's Punjab region. The strategy was divided into two modules using a multilevel approach. The first module was a single crop intraseasonal model that used SDP algorithm. The second module was a single crop SDP intraseasonal model that takes the output of the first module and gives the optimal weekly irrigation allocations for each crop by considering the stress sensitivity factors of crops. Stedinger et al. (1984), Rao et al. (1988), and Sunantara and Ramirez (1997) also utilized SDP approach for addressing the problems of optimal resources allocation for irrigation of several crops.

A fuzzy-learning disaggregation method was developed by Saad et al. (1996) to decompose monthly optimal policies of an aggregated reservoir obtained by deterministically optimizing a large number of stream flows using DP. Ghahraman and Sepaskhah (2002) developed an intraseasonal allocation model by using NLP and a seasonal allocation model by using SDP. The model was used for optimal allocation of water from a single-purpose reservoir to an irrigation project with predetermined multiple cropping patterns in Ardak reservoir dam (Khorasan Province, I.R. Iran) in an arid region. Hsiao and Chang (2002) used an integrated GA-CDDP (constrained differential DP) model for obtaining the optimal solutions of water resources problems. They considered both fixed costs and time-varying pumping rates for achieving optimal solutions. They concluded that the application of conventional optimization algorithms, i.e., LP and NLP, was difficult due to the discontinuity of the fixed-cost function in the objective function. They also concluded that the use of conventional discrete algorithms such as integer programming or discrete DP was hampered by the large computational burden caused by varying pumping rates over time. A GA algorithm was presented by Sharif and Wardlaw (2000) for the optimization of a multireservoir system in Brantas Basin in Indonesia. They concluded that GA is able to produce solutions very close to those produced by DP. Alaya et al. (2003) developed a stochastic DP model for determining the various optimal rules for the water resources management of the Nebhana dam (Tunisia), in order to satisfy the irrigation water demand and ensure minimal water storage in the dam.

Conclusions

The continuous increase in global population and simultaneous decrease in good-quality water resources emphasize the need of conjunctive water use of surface-water and groundwater resources for irrigation. The proper allocation and planning of water resources can be achieved by employing an appropriate optimization model. The literature review revealed that the optimization models used in the past for conjunctive use planning mainly considered the objectives of maximization of net farm income, stabilization of groundwater at a safe level, and minimization of groundwater rises/falls. The linear programming (LP) technique was extensively used because of its easy formulation and application. However, the inability of LP-based models to handle nonlinear problems motivated the use of nonlinear programming models (NLP). Despite this fact, the application of NLP-based models has been fairly limited in conjunctive use planning and management because of the complexity and the slow rate of convergence of the NLP algorithms and their difficulty in considering stochasticity. Chance constrained linear programming is one of the approaches of LP under risk wherein parameters of the problem are considered as random variables. Genetic algorithms have been used to solve complex nonlinear nonconvex optimization problems as they could yield better results than traditional optimization techniques. This approach is mainly suitable for externally linking the numerical simulation model within the optimization model. The use of dynamic programming technique was very common in conjunctive use planning of irrigated agriculture because it is able to undertake sequential decision-making and can incorporate stochasticity of hydrological processes.

Reviews of the different programming techniques used for the conjunctive use planning and management for irrigated agriculture were conducted and presented in this paper. Theses reviews provide the basis for the selection of appropriate programming techniques for researchers, planners, and policymakers. Though the study has looked at all possible literature sources, it appears to be virtually impossible to include all publications in a single review. This paper highlights an overview of the selected topic. It is likely that some aspects of some of the subjects have either been overlooked or only briefly referred to. The topics covered in this paper deserve a more comprehensive and separate review. It is anticipated that these gaps could be filled by successive contributions and that there is possibility for further debate about the subjects covered in this review.

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