Cyclic storage design and operation optimization; hybrid GA decomposition approach

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Abstract: *In a large scale cyclic storage system ,as the number of rule parameters and/or number of operating period increase, general purpose gradient-based NLP solvers and/or genetic algorithms may loose their merits in finding optimally feasible solution to the problem. In these cases hybrid GA which decomposes the main problem into two manageable sub-problems with an iterative scheme between GA and LP solvers may be considered as a sound alternative This research develops a hybrid GA-LP algorithm to optimally design and operate a nonlinear, non-convex, and large scale lumped cyclic storage system. For optimal operation of the system a set of operating rules are derived for joint utilization of surface and groundwater storage capacities to meet a predefined demand with minimal construction and operation cost over a 20 seasonal planning period. Performance of the proposed model is compared with a non-cyclic storage system. The management model minimizes the present value of the design and operation cost of the cyclic and non-cyclic systems under specified and governing constraints, employing the developed GA-LP hybrid model. Results show that cyclic storage dominates non-cyclic storage system both in cost and operation flexibility.*

Keywords: *conjunctive use, cyclic storage, hybrid GA, decomposition method.*

Introduction

Construction of large dams in many proposed sites in different parts of the world may not be the best solution for irrigation water supply purposes because of being economically inefficient, socially regressive, and environmentally infeasible (Lund, 1993). Restricted suitable dam sites, large people rehabilitation and other social impacts, increased evaporation losses especially in arid and semi arid regions, reservoirs sedimentation, and problems with dam heightening, are some of the major problems with large dams.

In recent years, integrated water resources planning and management (IWRPM) that concentrates on conjunctive use of surface and ground water resources has received great attention. According to Coe, 1990, usually lower costs, lack of sedimentation and evaporation, fewer water quality problems, and lack of social and cultural problems can be regarded as advantages of groundwater use comparing to surface impoundments. Ignoring potential capacity of aquifers as a competitive storage and regulating system in any surface water resources system development may lead to technical, economical, and social problems.

To diminish the major problems associated with large scale surface impoundment system developments, conjunctive use of surface and groundwater may be considered as a challenging alternative. As stated in Wang et al., 1995 the concept of conjunctive use seems quite simple; however, its correct implementation is a real challenge. Generally a successful conjunctive use project has to be functionally feasible, environmentally sound, institutionally acceptable, and cost effective. According to Basagaoglu et al., 1999 a coordinated joint operation of surface and subsurface water resources enhances the reliability, efficiency, and cost-effectiveness of water use in river basins.

Conjunctive use emphasizes the mechanics of stream-aquifer interaction and related

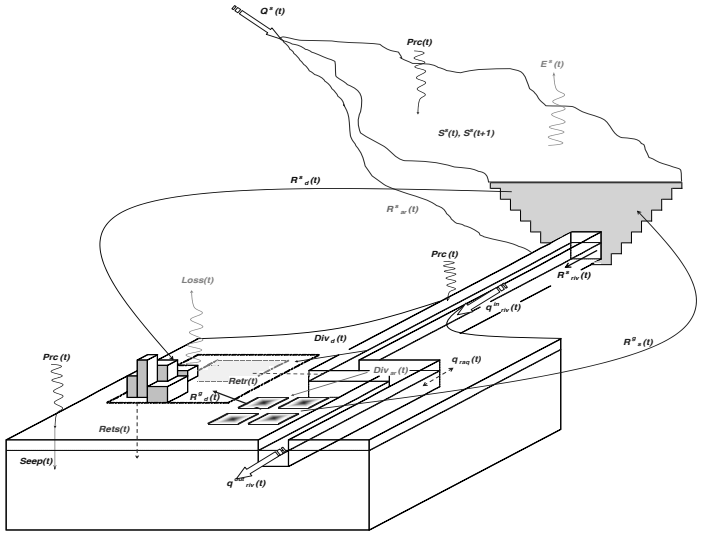


Fig. 1 Typical scheme of Cyclic Storage (CS)system.

management strategies or operating policies which exploits synergisms between stream flow and groundwater gradients for such objectives as maximizing reliability or minimizing costs of a surface reservoir and groundwater pumping (Latternmaier and Burges, 1982; Wang et al., 1995; Reichard, 2003; Barlow et al., 2003; Bredehoeft and Young, 1983; and Basagaoglu et al., 1999).

Potential use of cyclic storage was described in detail by Thomas, 1978. Nevertheless, it is worth to realize that there are not many instances where cyclic storage is being used currently on a large scale. It is surprising that, especially in developing countries, most of the existing dynamic storages are provided in the form of surface impoundments, in spite of the fact that subsurface storage potential far exceeds that of surface impoundment systems. Hence, a thorough evaluation of cyclic storage approach has not received particular interest in recent years.

Cyclic storage as proposed and defined by Alimohammadi and Afshar, 2005; refers to physically integrated and operationally interconnected surface water and groundwater subsystems with full direct interactions between the subsystems. This definition may be somehow different than provided by Lettenmaier and Burges, 1982.

This new definition, treats groundwater aquifer and surface impoundment subsystems as competing and potentially interconnected parallel storage facilities which will minimize most of the problems with large scale surface impoundments for water supply purposes. According to Alimohammadi and Afshar, 2005; as illustrated in Figure 1, a cyclic storage system (CS) may be recognized as an integrated interactive surface water storage subsystem (reservoir) and a groundwater subsystem developed to jointly satisfy the predefined demand in a long-term planning horizon. Thus, the desired level of development of systems' components, the amount of water transfer between elements of the two subsystems, and their conjunctive operating rules, should be determined as CS characteristics. Moreover, the amount of water transfer between system components should be considered as decision variables in various periods of planning horizon.

Defining the natural interactions between the groundwater and surface water subsystems along with providing physical means for operational interconnections between the two subsystems will promote the performance criteria such as reliability, vulnerability, and recovery period. Artificial groundwater recharge on a large scale

with regulated water from the surface reservoir and possibility of refilling reservoir from groundwater resources is the key element of a cyclic storage system which distinguishes it from conjunctive use of surface and groundwater as usually practiced.

This research decomposes a large scale cyclic storage system into a GA-LP structure for solution of the system with extende planning period. The research emphasizes on the development of a hybrid GA-LP algorithm to optimize design and operation of a nonlinear, nonconvex, and large scale lumped cyclic storage system. in an irrigable area. It is also intended to develop an optimal operating rules for the joint utilization of surface and ground water storage capacities in a cyclic system to meet a predefined irrigation demand with minimal construction and operational costs over a planning horizon including wet and dry periods.
The rest of the article is structured as (2) Problem setting, (3) Mathematical and conceptual representation of the management model (4) Proposed Ga-LP decomposition model (5) Model Application and Results, which follows by (6) concluding remarks.

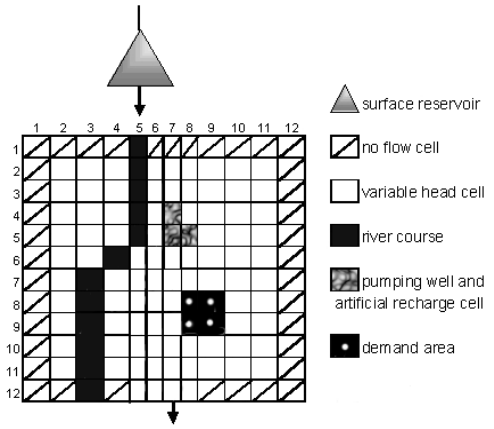
Problem setting

Consider a hypothetical system consisting of a surface reservoir, a hydraulically connected stream-aquifer system, demand zone, a recharge basin, observation and supply wells as originally defined by Alimohammadi and Afshar, 2005. Aquifer may be approximated by a 8×10 km in dimensions surrounded impermeable boundaries. Simplified presentation of the system to be modeled is illustrated in Figure 2a. Spatial variation of aquifer's hydrodynamic coefficients are illustrated in Figure 2b. River's cross-section is approximated by a rectangle with 20 meter width and 10 meter depth. Manning coefficient and longitudinal slope of the river assumed to be 0.02 and 0.0001, respectively. River has been divided into two upstream and downstream reaches. The thickness of the semi-pervious stream bed layer is 1 meter with hydraulic conductivity of 5×10^{-6} m/s in upstream and 7×10^{-6} m/s in downstream reach. It is assumed that 10 percent of the total water delivered to the demand area deep percolates into the aquifer and 10 percent returns to the second reach of the river as irrigation return flow. Field studies revealed that the vicinity of the pumping wells is the best place for the recharge purpose. Therefore, the same cells are also considered as possible recharge cells. Maximum pumping and recharge rates are determined to be 3 MCM per season. The area is located in a semi-arid region with annual precipitation of 300 mm. Proposed system consists of 10 excitation elements with 6 point elements units (i.e., 3 pumping wells and 3 recharge cells), 2 linear excitation elements (i.e., 2 river reaches), and 2 surface excitation elements (i.e., rainfall on the aquifer and deep percolation from the irrigated area). Employing the well known groundwater simulation model (MODFLOW, McDonald and Harbough, 1998) and unit excitations in all excited elements, the unit response coefficients for the components of the system were developed.

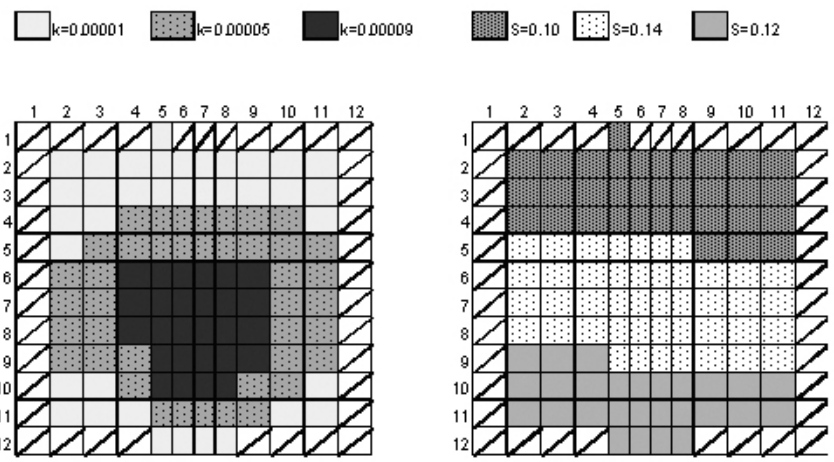
Theoretically speaking, it is possible to embed a distributed groundwater simulator into the optimization module to form a complete, embedded simulation- optimization model. However, solution to that model for a large scale real-world cyclic storage system may not practically be possible. Therefore, it was decided to replace the simulation model by unit response matrix (URM) method. The quasi-three-dimensional groundwater modeling (MODFLOW) is used to simulate the stream aquifer system for deriving the response function coefficients. The proposed cyclic storage optimization model employs modified unit response method (MURM) to approximate the interaction between surface and groundwater subsystems (Alimohammadi and Afshar, 2005).

Management model

A CS system may includes: (1) surface storage subsystem (reservoir), (2) groundwater storage subsystem (aquifer), (3) water course subsystem



(a)



(b)

Fig. 2 (a) Simplified hypothetical system - (b)Spatial characteristic of aquifer

(river), (4) pumping wells, (5) recharge wells (or basins), (6) water transfer and/or diversion systems, and (7) demand area. As illustrated in Figure 1, the surface flow $Q_s(t)$ is stored in the reservoir as $S(t)$. Part of the release from surface reservoir will be directly transferred to demand area $R^s_d(t)$ and to artificial recharge site, $R^s_{ar}(t)$, ,(if needed). Another part of reservoir release to the river is $R^s_{riv}(t)$. $Sp(t)$ is the spilled water in wet periods and E^s is evaporation from reservoir. In this system, water may be transferred from aquifer to surface reservoir $R^g_s(t)$,if needed, and justified. System demand could be met through direct release from the surface reservoir and/or combination of river diversion to demand area $DivD(t)$, and aquifer pumping $R^g_d(t)$. $DivAr(t)$ represents water diverted from river to recharge wells for future use of regulation of groundwater as required by the derived long-term operating policy. Some fraction of the total water conveyed to demand area, $y(t)$, will percolate to the aquifer, $Seep(t)$, and/or returned to the river as irrigation return flow $Retr(t)$. Along the river, there is hydraulic interaction between river and aquifer causing seepage from river to aquifer and vice versa $q_{raq}(t)$.

The management model minimizes the present value of design and operation cost for meeting the predefined demand during a finite planning horizon, where any deficit will be penalized by defined penalty function.

Reservoir capacity ($CapD$), as well as design

capacity of conveyance systems from: reservoir-to-demand area (*CapCD*), reservoir-to-artificial recharge (*CapCAR*), and aquifer-to-reservoir (*CapP*), and aquifer to demand point (*CapARD*), and river diversions to: demand area (*CapDivD*), and artificial recharge area (*CapDivAR*) have been considered as decision variables. In this formulation it is assumed that the recharge lots and pumping wells exist, hence, only their operational costs have been considered as depicted in Alimohammadi and Afshar, 2005. In a general form the model structure may be presented as:

$$Minimize\ PVC \tag{1}$$

$$PVC=CC+PVC(OC) \tag{2}$$

$$CC=C(D)+C(CAR)+C(divD)+C(DivAR)+C(P) \tag{3}$$

$$PVC(OC)=C(W)+C(AR)+C(DEF)+OMR \tag{4}$$

$$OMR=OMR(D)+OMR(CD)+OMR(CAR)+OMR(DivD)+OMR(DivAR)+OMR(P) \tag{5}$$

In which, *CC* : system construction cost, *C(D)* : dam construction cost, *C(CD)* and *C(CAR)* : conveyance system cost from reservoir to demand and artificial recharge areas respectively, *C(DivD)* and *C(DivAR)* : Diversion system cost from river to demand and artificial recharge areas respectively, and *C(P)* : conveyance system cost from aquifer to reservoir. *PVC(OC)* is the sum of present value of the pumping operational cost *(CW)*, groundwater recharge cost *(CAR)*, deficit costs for not meeting the predefined demands *(CDEF)*, and operation, maintenance and replacement costs *(OMR)* of the system elements. It is assumed that construction cost of all elements of the system can be defined as:

$$C(X_i)=f(CapX_i)=a_{Xi}(CapX_i)^{b_{Xi}} \tag{6}$$

Where $C(X_i)$ and $CapX_i$ are the construction cost and design capacity of the ith component of the system respectively, a_{Xi} and b_{Xi} are predefined cost function parameters.

The proposed model is subject to the following constraint.

a. Constraints on mass balance and capacity

$$F_1(S^s,Q^s,R_s^g,E^s,R_d^s,R_{ar}^s,\ R_{riv}^s,\ Sp,\ CapD,\ CapC,\ CapP)=0 \tag{7}$$

b. Constraints on demand:

$$F_2(R_d^s,\ R_d^g,\ DivD,\ ANY,DEF)=0 \tag{8}$$

In which, *DEF* and *ANY* stand for seasonal deficit and demand, respectively.

c. Constrains on pumping and recharge balance:

$$F_3(q_w,R_d^g,R_s^{g)})=0 \tag{9}$$

$$F_4(q_w,R_{ar}^s,DivAr,q_{raq},rets,seep)=0 \tag{10}$$

In which *rets* is the fraction of water that percolates into the aquifer from transferred water to the demand area. Equation 9 says that pumped water must either be transformed to the demand area and/or back to the reservoir. Along the river, there is hydraulic interaction between river and aquifer ($q_{raq}(t)$) causing seepage from river to aquifer and vice versa. Equation 10 balances the input to and output from the aquifer in planning horizon for CS model. For NCS model equation 10 must be modified to exclude the possibility of artificial recharge with regulated water from reservoir:

$$F_5(q_w,DivAr,Sp,q_{raq},rets,seep)=0 \tag{11}$$

d. Constraints on river-aquifer interactions

$$F_6(q_{raq},C_{riv},h_{riv}^s,h_{riv}^g,h_{riv}^{bot})=0 \tag{12}$$

In which, C_{riv} is the river conductance, h_{riv}^s is water level in the river, h_{riv}^g is aquifer water table elevation, h_{riv}^{bot} is elevation of semi-pervious streambed bottom.

e. Constraints on river hydraulics:

$$F_7(q_{riv}^{in},\ ql_{riv},\ q_{riv}^{out},\ \Delta S_{riv},\ h_{riv}^{in},\ h_{riv}^{out},\ h_{riv},\ dh_{riv},h_{riv}^{out,min},\ h_{riv}^{out,max})=0 \tag{13}$$

In which q_{riv}^{in}, and q_{riv}^{out} are river inflow and outflow respectively, ql_{riv} is the net lateral inflow

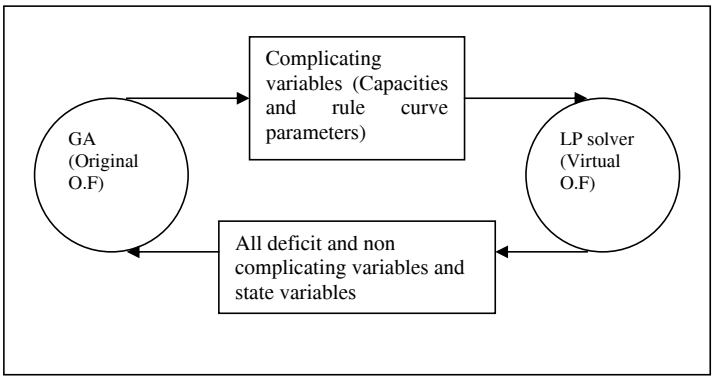


Fig.3 GA-LP general scheme

or outflow along river, dh_{riv} and ΔS_{riv} are river stage and storage changes respectively, h_{riv}^{in} and h_{riv}^{out} are river stage for inflow and outflow respectively, $h_{riv}^{out,min}$ and $h_{riv}^{out,max}$ are minimum and maximum outflow stages respectively, and h_{riv} is the initial stage of the river. Equation 14 is needed for mass balance, continuity of flow along the river, converting the inflow and outflow into related stages, changes in river stage and storage, and discharge limitations.

f. Operational rule curves:

To formulate the design and operation CS model one must define the releases and/or withdraws from the system components as functions of selected state variables. It is very common to define these rules as linear function of selected and easily monitored state variables. For this purpose $R_d^s(t)$, $DivD(t)$, $DivAr(t)$, R_d^g , R_{riv}^s are defined as:

$$R^s{}_d(t) = a_{rsd}(S(t)+Q_s(t)) + b_{rsd}(\sum_{k=1}^{NK} s_w(k,t-1))/3 + c_{rsd}ANY \quad (14)$$

$$DivD(t) = a_{rdivd}(S(t)+Q_s(t)) + b_{rdivd}(\sum_{k=1}^{NK} s_w(k,t-1))/3 + c_{rdivd}ANY \quad (15)$$

$$DivAr(t) = a_{rdi\,var}(S(t)+Q_s(t)) + b_{rdi\,var}(\sum_{k=1}^{NK} s_w(k,t-1))/3 \quad (16)$$

$$R^g{}_d(t) = a_{rgd}(S(t)+Q_s(t)) + b_{rgd}(\sum_{k=1}^{NK} s_w(k,t-1))/3 + c_{rgd}ANY \quad (17)$$

$$R^s{}_{riv}(t) = a_{sriv}(S(t)+Q_s(t)) + b_{sriv}(\sum_{k=1}^{NK} s_w(k,t-1))/3 \quad (18)$$

in which $a,b,$ and c are rule curves parameters and $S_w(k,t-1)$ is the groundwater drawdown at the previous period for k^{th} pumping well.

In non cyclic system regulated water may not be used for artificial recharge. In fact, regulated water is only employed to meet the predefined irrigation and/or other demands. Spill from the reservoir and/or natural flow from the tributaries may be diverted to the artificial recharge sites. Therefore, in NCS modeling, release from the reservoir is either transferred to the demand area and/or used to satisfy the downstream environmental requirement. Depending on the capacity of river diversion system to the artificial recharge site, total or fraction of natural spill from the reservoir maybe diverted to recharge the aquifer and operating rules are accordingly revised.

Proposed Hhybrid GA _LP algorithm

The basic concept with the proposed hybrid GA is to decompose a large scale highly nonlinear optimization problem into a GA solver and a large scale LP(Linear programming) model. General inter-relation between the two sub-modules are depicted in Figure 3. In this formulation, the NLP problem is broken into two separate modules. The approach employs a two-

step optimization procedure to minimize the objective of the original problem considering the imposed constraints while trying to satisfy the demand or accept the assigned penalties.

The general mathematical statement of the problem follows. Let X and Y be the vectors of noncomplicating and complicating variables with k elements, respectively. Let P and N be vectors of positives and negative deviations from the constraints with *m* elements, respectively. The original problem may be expressed as:

$$Minimize\ PVC \tag{19}$$

$$Subject\ to\ F(X,Y)=0 \tag{20}$$

Keeping complicating variables in the original model, a virtual LP model will be formed with noncomplicating variables as decision variables. This model treats complicating variables as known parameters whose values will be imported to the virtual LP model from solution to the original GA model. Therefore, the virtual LP model may be formulated as:

$$Minimize\quad G=[P]+[N] \tag{21}$$

$$Subject\ to\ f_i(x,y)-p_i+n_i=0 \quad \forall\ i=1,...,m \tag{22}$$

$$x\in X,\ y\in Y,\ p_i\geqq 0,\ n_i\geqq 0, \tag{23}$$

The original GA model will now be formulated as:

$$Minimize\quad PVC+w*G \tag{24}$$

Where *G* is the vector of constraints violations which results from solution to the virtual LP model and w is a positive penalty assigned for constraints violations. Iterative solution to the two stages hybrid GA-LP model results in near optimum values of the original objectives function of minimum present values of total cost while satisfying the system constraints by minimizing the sum of positive and negative constraints violations with the virtual LP model.

Embedding rule curves with unknown rule parameters into the cyclic model makes the problem highly nonlinear. Nonconvex cost function makes the solution strategy more and more difficult. As the number of rule parameters and/or number of operating period increase, general purpose gradient-based NLP solvers may loose their merits in finding optimally feasible solution to the problem. In these cases hybrid GA which decompose the main problem into two manageable sub-problems with an iterative scheme between GA and LP solvers may be considered as a sound alternative.

For the proposed cyclic storage model, operating rules parameters have the most contribution in complicating the model's structure. Therefore, in addition to the design capacities of the system components, they were also considered as complicating decision variables to be solved by GA optimizer.

Having defined the lower and upper bounds on the capacities and operation rule parameters between {-1,1}, a random generator is employed to generate the trial solutions to be used as the original initial chromosomes. The trial chromosomes are then imported into the main nonlinear model to give it a linear structure. Solution of the LP model with objective of minimizing a measure of violation from the constraints (equation 21) will be imported into the GA solver to evaluate the fitness of the trial solutions. New GA solutions for complicating decision variables will be imported to the main program to have a new linear model with objective of minimizing total constraints violations in the linearized model. This process continues until the termination criteria come true. Detailed of the proposed hybrid GA structure are depicted in Figure 4. The proposed structure for hybrid GA is somehow different than was recommended by Cai et al., 2001; in which the key idea is to identify a set of complicating variables in the model which, when fixed, render the problem into a linearized model. Only a one-step procedure including linearized model estimates the constraints violations and objective values simultaneously. Conducting few test examples it was concluded that for the defined

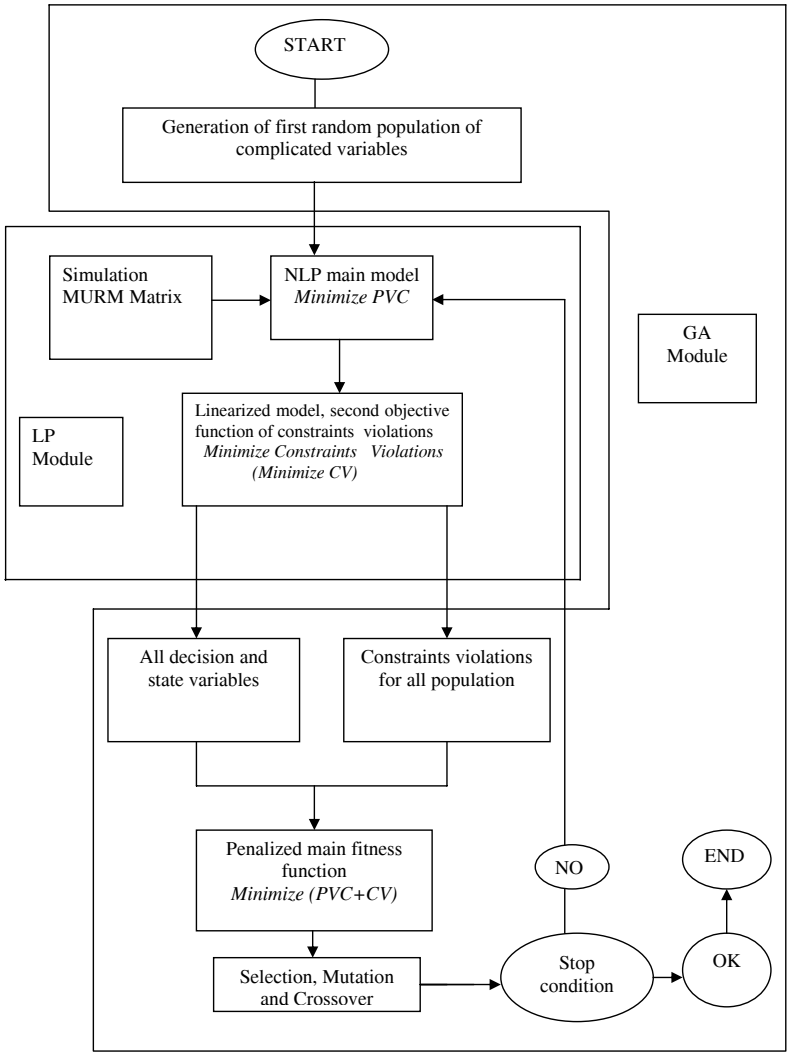


Fig.4 Flowchart of hybrid GA algorithm including two separate modules of LP and GA.

cyclic storage system structures, the proposed hybrid GA formulation may be superior.

According to Gen and Cheng, 2002; there are two important issues with respect to any search strategies: exploiting the best solution and exploring the search space. The genetic algorithms provide a directed random search in complex landscapes. Genetic operators perform essentially a blind search; selection operators hopefully direct the genetic search toward the desirable area of the solution space. One general principle for developing an implementation of genetic algorithms for a particular real-world problem is to make a good balance between exploration and exploitation of the search space. To achieve this, all the components of the genetic algorithms must be examined carefully.

The proposed hybrid GA benefits from roulette wheel (Holland, 1992) as the main selection mechanism with one-point crossover and standard mutation are used to generate progressive iterations (Goldberg, 1989; and Gen and Cheng, 2002).

Model application and results

The developed hybrid GA-LP cyclic system optimization model was used to generate optimum design capacities and operating rules

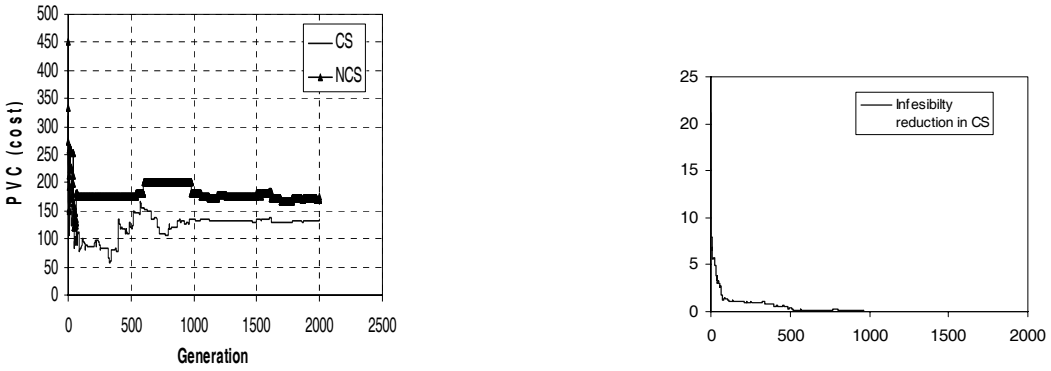


Fig. 5 GA procedure (a) Convergency curves in CS and NCS for best computed run (b) Infeasibility accompanied in CS

Table 1 Average rates of many important decision variables and capacities related to designing phases resulted from the CS and the NCS models.

	Average release MCM/Season		Capacity-MCM	
	CS	NCS	CS	NCS
Dam release to demand area(Rsd)	1.36	2.68	2.48	5.44
Dam release to art.rech (Rsar)	1.98	0.00	4.05	0.00
Aquifer pumping to dam(Rgs)	0.20	0.00	1.90	0.00
Aquifer pumping to demand area(Rgd)	3.76	2.15	0	0
River diversion to demand area (rDivd)	1.31	1.57	2.28	3.88
River diversion to art.rech (rDivar)	0.57	0.75	1.27	1.90
Dam release to river (Rs,riv)	5.31	5.79	-	-
Dam spilled water (Spill)	1.01	1.44	-	-

for a full cyclic system and a noncyclic system which is more or less similar to commonly practiced conjunctive use systems. Full cyclic system was defined previously. In noncyclic system (NCS), it is assumed that aquifer may only be recharged through natural interaction between river and the aquifer and water diverted from the river to the recharge cells. Flow to be diverted from the river comes from reservoir spill when it overflows. In cyclic system, however, water releases from reservoir to the river according to operating rules which are optimally determined with two stages hybrid (GA-LP) modeling approach.

Five different runs were conducted for cyclic storage (CS) and non-cyclic storage (NCS) structure. The best solution found by hybrid GA for CS and NCS resulted is 131 and 170 cost units respectively. Figure 5a presents the typical progressive evolution of the main objective function. With a population size of 100, nearly 2000 generations were required to obtain a desirable solution with zero infeasibility. The virtual objective function is a measure of non-feasibility which is the summation of constraints violations as depicted in figure 5b. The fluctuation in convergency procedure may associate to the dynamic penalty coefficient. The coefficient was increased gradually according to a stepwise function. Reduction of infeasibilities as the number of generation increases is depicted in figure 5b. Practically speaking, after almost 1000 generations near feasible solution with near zero (insignificant) infeasibility was obtained.
Five different seasonal rule curves with unknown rule parameters were defined to account for the rate of water transfer between different components of the system. Moreover, some nonlinear variables accounting for system components capacities were added to rule cure parameters to constitute a real coding chromosome. The rule curves parameters were bounded between -1 and 1, whereas the design capacities were bounded by physical and technological limitations. The complicated form

of nonconvex cost functions and nonlinear rule curves were the main reason to choose GA as a solver.

Both cyclic system (CS) and no cyclic (NCS) system were solved using the same hybrid GA. Components' design capacities as well as average rate of water transfer between the system components are presented in table 1. Reservoir capacity in the CS model is about 24 percent lower than NCS; that is, the dam size is reduced from 27.5 to 22.2 MCM from NCS to CS.

Allocating more water for artificial recharge through reservoir (R^{s}_{ar}) and river diversion (DivAr) enhance aquifer's contribution in demand satisfactions. More efficient utilization of the potential aquifer storage volume and reduced reservoir capacity results from this strategy. As is clear from Figure 6 variation of groundwater level in CS model is highly intensive than NCS model. Negative values in groundwater fluctuation graph discloses that more water is recharged into aquifer during wet periods in cyclic system compared to NCS model to stabilize the total system's storage for next dry seasons. The total quantity of water evaporated in the CS and NCS systems are almost 6 and 7 MCM respectively. Results reveal that in cyclic system 44 and 55 percent of the total available water were stored in the aquifer and surface reservoir, respectively. These percents for NCS are determined as 40 and 59 percents, respectively, showing more efficient utilization of aquifer potential storage capacity in dry seasons for CS.

Results of optimal operating policy derived from application of the model to cyclic and non-cyclic systems are presented in Figure 7. As might be expected, in cyclic storage system groundwater must have more contribution in satisfying the demand. This is presented in figure 7b in which 54 and 47 percent of the total demand are met through groundwater storage for CS and NCS, respectively. On the other hand, average rate of water transferred from surface reservoir to demand nodes in non-cyclic system exceeds that of cyclic system by 1.3 MCM for each period

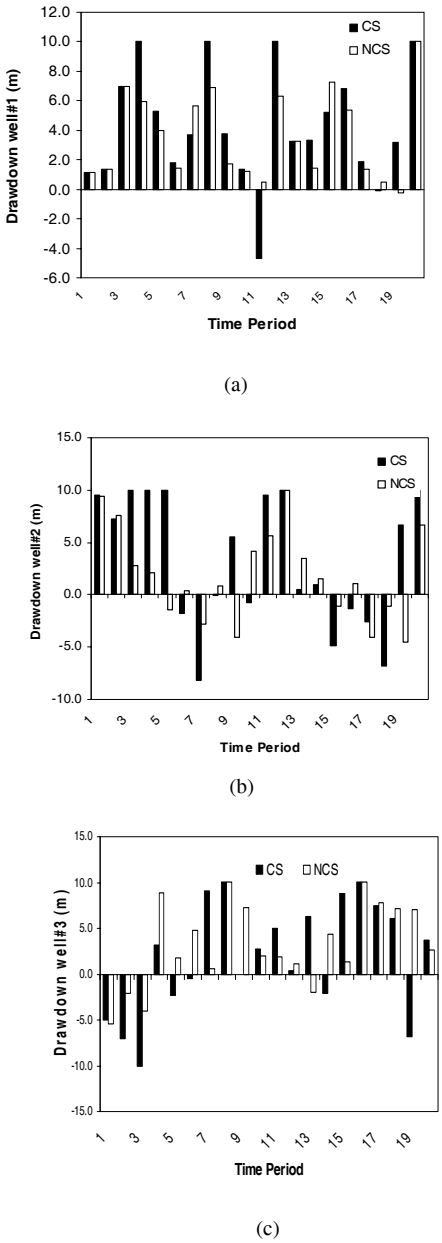


Fig.6 Groundwater level fluctuation (positive values for drawdown). (a) well number (1) (b) well number (2) (c) well number (3)

(Fig. 7a). Diversion from river to the artificial recharge area in cyclic system highly dominates that of non-cyclic as presented in figure 7d. This is justified by the fact that river diversion to the artificial recharge area in non-cyclic system is only effective when there is natural spill from the reservoir. Although not common, the input to the model was so selected to make water transfer from aquifer to the reservoir become feasible and justified. This was done to emphasize on the

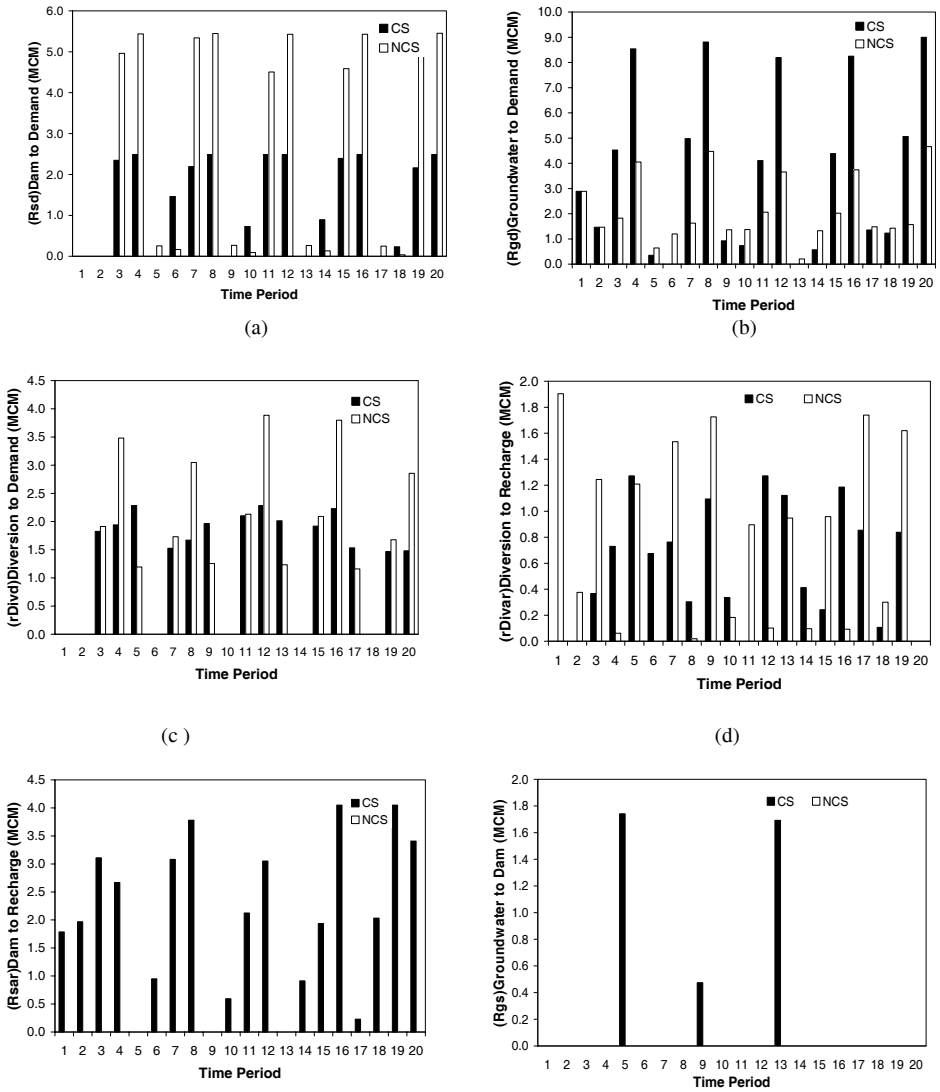
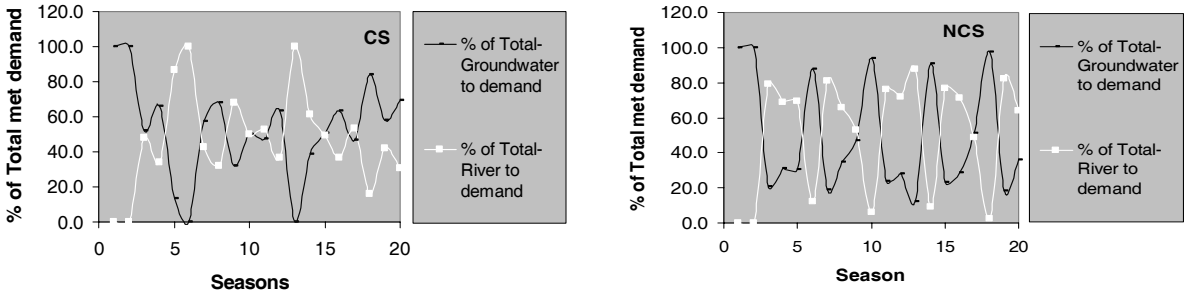


Fig. 7 Optimal operating policies from the CS and NCS models. - (a) Direct transfer from dam to demand (b) Direct transfer from aquifer to demand (c) Diversion from river to demand recharge wells (d)Diversion from river to artificial (e) Transfer from the dam to artificial recharge wells (f) Transfer from the aquifer to dam

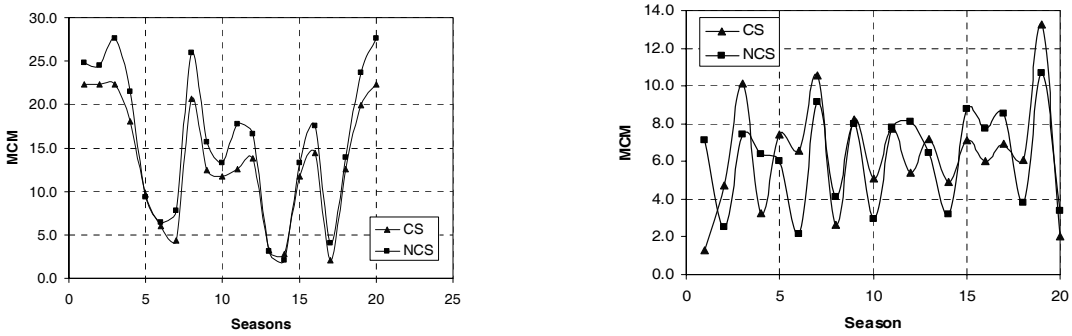
capability of the model to consider all possible cases as might come true. In fact, to make use of all available resources with highest possible efficiency and recognizing the constraints on groundwater level as well as minimum environmental requirement in the downstream river reaches, limited water transfer from the aquifer to the reservoir is recommended (Fig. 7f). It is quite clear that periods with positive water transfer from aquifer back to the reservoir coincide with those of high groundwater level where the constraint on maximum allowable level might be violated. It is interesting to note that even in periods with normal inflow to the reservoir, part of the surface water is allocated to recharge the aquifer for coming dry periods.

The normalized rate of average availability of water in groundwater storage sub-system to that of surface reservoir is 0.65 for CS and 0.55 for NCS. Lower availability of water in surface reservoir, compared to aquifer in cyclic system, emphasizes on the more efficient use of groundwater storage potential in cyclic system compared to non-cyclic system. Hybrid GA following the NCS modeling admits larger deficits (2.1 MCM) as compared to those obtained through CS (1.1 MCM) modeling. In other words, CS modeling approach performs



(a) (b)

Fig. 8 Normalized percentages of preparing water for demand node to total satisfied demand. (a)Cyclic storage system (b)Non-cyclic storage system



(a) (b)

Fig. 9 (a) Variation of water storage in dam (b) Variation of water released from dam

better in dry periods as a result of long-term storage provided through groundwater recharge. Percent of the demand satisfied through groundwater and surface reservoir (i.e. direct transfer or diverted from river), for cyclic and non-cyclic systems are presented in figure 8. This figure demonstrates the percent of each component including Rgd, Rsd, and DivD to prepare water needed in demand node in the CS and NCS model. There seems more and more proofs although the designed dam in the CS model has 23 percent lower capacity, the average rate of 47 percent of total demand in this model has been prepared by the dam by Rsd, and DivD. This rate in the NCS is about 49 percent. Moreover the average percent of water allocated by the aquifer in the CS model is about 53 percent. This rate in the NCS storage system is 51 percent. So the CS model can increase the conformity and arrangement between these two subsystems (aquifer and the dam) to satisfy the demand. In dry seasons for the CS and NCS models, about 65 and 32 percent of total demand has been supplied by the aquifer respectively. This discloses the importance of efficient utilization of groundwater potential through well defined joint operation of two sub-systems and their mutual interactions.

The case example shows that CS modeling is superior to NCS modeling in satisfying the predetermined demands. In fact, for the case considered in this study, the average values of unmet demand for CS and NCS modeling are 0.05 and 0.11 MCM per season. Moreover, number of seasons with shortage for CS and NCS are 2 and 4, respectively. The maximum number of successive periods with deficit are 1 seasons for CS and 2 seasons for NCS modeling scheme. To make the CS and NCS modeling approach quite comparable, the optimum total cost of the CS model was set as the maximum permissible cost of the NCS modeling approach. With the same cost, performance of the CS model was more superior to NCS modeling approach. As an example, average seasonal deficit increased from 0.05 to 0.11 MCM, number of successive periods with deficit increased from 1 to 2 periods.

As shown in figures 9a and 9b, in the CS model there is higher tendency for releasing water from the surface reservoir rather than storing it for later use; hence demanding higher reservoir capacity. This is mainly due to mutual and direct

interrelation between surface and groundwater sub-systems defined in CS modeling approach.

Conclusion

It was shown in this paper that the cyclic storage system as an approach derived from the typical conjunctive use system can result in many advantages such as lower construction and operation cost and higher reliability. A hypothetical model including a surface storage reservoir, an unconfined aquifer, and a set of hydraulically interconnected components of systems build a cyclic storage model. Results from this model are compared with a similar noncyclic storage system to demonstrate the ability of CS system to improve some important parameters such as reliability and average deficits. Moreover, the proposed hybrid GA algorithm approximating model can be used in practical applications for the solutions of nonlinear and nonconvex problems of water resources management with an explicit economic objective function like this. In this algorithm, the nonlinearity in terms of rule curves parameters and cost functions are eliminated by replacing the terms causing nonlinearity with imposed approximated GA coefficients in the main model. As a result, this model is freed from nonlinearity and will be linearized. Alternatively, this linearized model is solved with a virtual objective function to give penalty term to be returned into GA. Solutions shows the strength of method in solving such large scale problem instead of typical solvers usually converging to local optimum.

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Notations:

The most important notations are as follow:

$Q_s(t)$: Natural inflow in month t

$S(t)$: Storage in month t

$R^s_d(t)$: Release from surface reservoir to demand area.

$R^s_{ar}(t)$: Release from surface reservoir to artificial recharge site

$R^s_{riv}(t)$: Extra reservoir release to the river

$Sp(t)$: Spilled water

$E^s(t)$: Evaporation from reservoir

$R^g_s(t)$: Water transferred from aquifer to surface reservoir

$DivD(t)$: River diversion to demand area

$R^g_d(t)$: Aquifer pumping to demand area

$DivAr(t)$: Water diverted from river to recharge wells

$y(t)$: Fraction of the total water transferred to demand area which percolates into the aquifer or returns to the river.

$Seep(t)$:Fraction of the total water transferred to demand area which percolates into the aquifer - part of $y(t)$

$Retr(t)$: Fraction of the total water transferred to demand area which returns to the river as irrigation return

$q_{raq}(t)$: Seepage from river to aquifer and vice versa