Proceedings of the 5th WSEAS/IASME Int. Conf. on SYSTEMS THEORY and SCIENTIFIC COMPUTATION, Malta, September 15-17, 2005 (pp249-256)

Optimum Design of Cyclic Storage Systems; Distributed Parameter Approach: 1- System Definition and Model Formulation

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Abstract: A cyclic storage system is a conjunctive use system, containing two major sub-systems: surface water and groundwater, which could meet the guaranteed demands via an interactive trade-off cycle. Considering the literatures may lead us that, these kinds of systems neither has been of a great concern in general topics, nor in particular fields such as distributed optimization of design, and operating rules. In order to optimize these systems, one must consider the hydraulic interactions between all of the components. Unfortunately, it has been neglected in most studies. In these two companion papers (both have published in this issue); a distributed parameter approach has been implemented for optimum planning of cyclic storage systems. For this purpose the modified and generalized form of unit response matrix has been developed and used to connect the distributed parameter groundwater simulation model to the optimization model. The resulted optimization model has a form of a nonlinear programming. In order to validate the model, it has been implemented in a hypothetical simple cyclic storage system. The results show that the modified unit response matrix method is a robust and powerful method for optimum planning of cyclic storage systems.

Key Words: Cyclic Storage, Distributed Optimum Design, Modified Unit Response Matrix

1 Introduction

The desirability of providing streamflow buffering, both for reduction or elimination of drought effects and for altering seasonal runoff patterns had lead to construction of various size of surface impoundments. In recent years, however due to environmental restrictions, construction difficulties associated with remaining dam sites, and rapidly increasing construction and rehabilitation cost, surface storages have provide to be much more difficult to ever.

Nowadays, constructing large dams in many countries may not be the best alternative for water supplies, due to of major physical and environmental problems. Limitations in suitable dam sites, large people rehabilitation and other social impacts, increasing evaporation losses especially in arid regions, filling reservoirs with sediments and high cost of reservoirs desedimentation, and significant difficulties in increasing the dams heights, may be referred to as the major problems.

Integrated water resources management that focuses on conjunctive operation of surface and ground water resources is of a great concern for water supply authorities. In comparison with dam construction, groundwater has some advantages, which result from the fewer problems. Usually lesser costs, lack of sedimentation and evaporation, fewer water quality problems, and lack of social and cultural problems are some of these advantages [6]. Ignoring potential capacity of aquifers as a competitive resource for surface waters during the planning phase, leads to high amount of technical, economical, and social problems.

To minimize the major problems associated with large scale surface impoundment system developments, cyclic storage may be considered as a challenging alternative. It has been argued that cyclic groundwater- surface water storage may represent an attractive alternative which can reduce the necessity of surface storage volume for a given reliability and/or regulation capacity. Cyclic storage by our definition, refers to the joint development and use of two subsystems including an aquifer one or multiple surface impoundment, having direct interactions with each other and develop to satisfy defined demand with given reliability. This definition may be somehow different than provided by Lettenmaier and Burges [9]. The system as defined may offer possibilities for increasing system reliability, or for the same reliability, reduction the size of required surface storage and its associated environmental and other problems.

It is quite surprising that the research community has given little attention to cyclic storage system in favor of the related problem of conjunctive use. Although the boundaries between these two topics are not quite clear, yet, cyclic storage may be considered to refer to design and operational management of joint surface planning and their long-term performance considering resistance to drought, flood control, and even water quality management. On the other hand, conjunctive use emphasizes the mechanics of stream- aquifer interaction and related management strategies or operating policies which exploits synergisms between streamflow and groundwater gradients for such objectives as maximizing reliability or net benefits of a surface reservoir and groundwater pumping wells [9].

Potential for use of cyclic storage has been fully described by Thomas [18], and Ambroggi [1]. 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 storage is provided in the form of surface impoundments, in spite of the fact that subsurface storage potential for exceeds that of surface impoundment systems. It is now well recognized that surface impoundment system developments have further reduced the subsurface storage by natural recharge with a number of important groundwater basin withdrawal exceeding the natural recharge.

Artificial recharge on a large scale with even regulated water from the surface reservoir, in comparison to the direct withdrawals from a surface reservoir for demand satisfaction, is the key element of a cyclic storage system which distinguishes it from conjunctive use of surface and groundwater as usually practiced.

In these two companion paper (both in this issue), a distributed optimization model for design of a cyclic storage system has been presented. This model includes major interacting components of surface and ground water sub-systems with objective of maximizing the discounted net benefits of construction and operation of the system. For this purpose, the generalized and modified unit responses matrix method has been developed and used. The resulted model is a nonlinear programming model, which accounts for the interactions between the well defined interconnected elements of the system.

2 Literature Review

Previous studies in conjunctive use systems might be categorized in the lumped and distributed models. One of the first lumped parameter optimization models was developed by Buras [5]. Some earlier studies have been presented by Philbrick and Kitanidis [14], Pulido [15], and Syaukat and Fox [16].

A distributed parameter optimization of groundwater and conjunctive systems was initially presented by Bredehoeft and Young [4, 19]. They considered the optimization of a simple river-aquifer system using simulation-optimization approach to achieve the optimum pattern of wells pumping and river diverting. Maddock III [10] developed the unit response matrix (URM) method to optimize the operation of an aquifer system. Morel-Seytoux [12] implemented and extended the URM method in a river-aquifer system.

Richard [16] developed a distributed model to optimize the operation of a river-aquifer system, regarding the probability of surface flows, using URM method. Lall [8] presented a study about planning of a conjunctive system with the purpose of screening the alternative options. He used the modified sequential peak algorithm and URM method for surface reservoirs and groundwater modeling, respectively. Nishikava [13] conducted a similar Reichard's study [16], in order to optimize the conjunctive operation of coastal water resource system of Santa Barbara in California during droughts. He implemented URM method to simulate the behavior of groundwater, and used LINDO as optimizer to solve the resulted model. Basagaoglu et al. [3] developed a distributed model to optimize the operation of a conjunctive system (which is not far from the cyclic storage system) including surface reservoir, river, aquifer, pumping, and recharge wells, considering the interactions between the river and the aquifer.

Recently Barlow et al. [2] developed an optimization model for conjunctive operation of a river-aquifer system. They implemented MODFLOW as software to produce the unit response coefficients and LINDO to solve the optimization model. Czarencki et al. [7] developed a conjunctive operation model for an aquifer in Mississippi Valley in northeastern and southeastern regions of Arkansas. They used unit response matrix method in steady-state condition and implemented software called MODMAN to produce the response coefficients and system optimization. MODMAN uses MODFLOW simulation model to produce the response coefficients.

Considering the above mentioned and other studies show that all the lumped model studies, have been done with purpose of system operation optimization (or simulation). In fewer studies, the optimum operating rule of system has been considered. On the other hand, in distributed parameter studies, except Lall [8], couldn't find any study about optimum design of system based on distributed modeling approach.

3 Cyclic Storage System; Conceptual Model

By definition, a cyclic storage system (CYCS) is an integrated interactive surface water storage subsystem (reservoir) and a groundwater subsystem developed to jointly satisfy the predefined demand with assigned reliability at minimum sum of development and operational cost in a long-term planning horizon (Fig. 1). The main specific characteristic of the CYCS is that it would establish not only an interaction between surface water and groundwater subsystems, but also a close relation via implementing pre-planned operation rules. As depicted in Fig. 1 the surface and groundwater impounding subsystem behave more or less like to parallel reservoir with possibility of exchanging stored water while keeping their individual characteristics, they are so operated to satisfy the desired target. Thus, the desired level of development of system component, the amount of water transfer between two subsystems, and their conjunctive operating rule, should be determined as CYCS characteristics. Moreover, the amount of water transfer between two subsystems should be considered as decision variables in various periods of planning horizon.

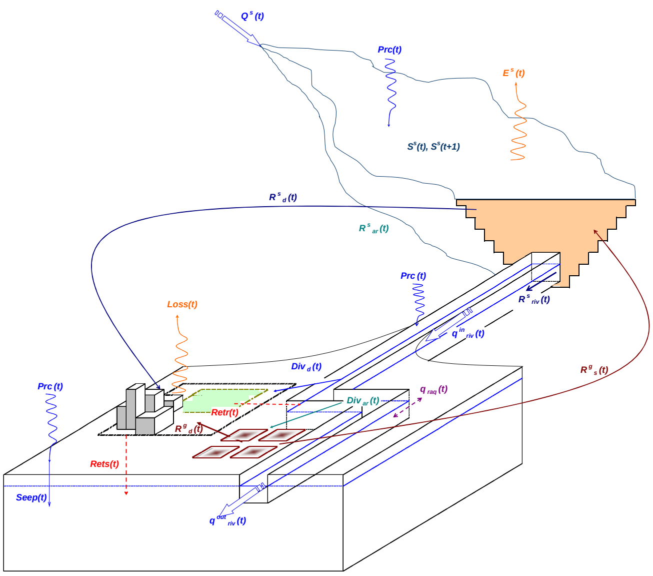

Fig. 1- A CYCS system with its major components

In detail, a CYCS system may include the following components: (1) surface water storage subsystem (reservoir), (2) river, (3) groundwater storage subsystem (aquifer), (4) pumping wells, (5) recharge wells (basins), (6) water conveyance and river diversion systems, and (7) demand area. In this system there is a hydraulic connection between the river and the aquifer. Joint operation of the aquifer and the reservoir will increase the reliability of the system in meeting the demands. As illustrated in Fig. 1, the surface flow ($Q^s(t)$) is stored in the reservoir as ($S^s(t)$). Part of the release from reservoir will directly be transferred to demand area ($R^s{}_d(t)$) and/or to artificial recharge site ($R^s{}_{ar}(t)$). Other part of reservoir release, is discharged to the river ($R^s{}_{riv}(t)$). In this system, water may be transferred from aquifer to reservoir ($R^g{}_s(t)$) if needed and justified. System demand could be met through surface reservoir, river diversion ($DivD(t)$), and aquifer pumping ($R^g{}_d(t)$). Some fraction of the water conveyed to demand area ($y(t)$), will be lost through evaporation ($Loss(t)$). The remained of it, percolates to the aquifer ($Seep(t)$), and/or returned to the river ($Retr(t)$). Along the river, there is hydraulic interaction between river and aquifer causing seepage from river to aquifer or vice versa ($q_{raq}(t)$). Unfortunately this term is usually neglected in conjunctive use or artificial recharge plans studies leading to optimistic results in system net benefits.

Based on the above mentioned notes, the conceptual representation of a CYCS system is illustrated in Fig. 2. The relation between components of each sub-system with un-numbered arrows, and the relation between components of different sub-systems with numbered arrows is illustrated.

4 Model Formulation

A distributed cyclic storage design model has been formulated which employs of the modified unit response matrix (MURM) as a tool which accounting for interaction between surface water

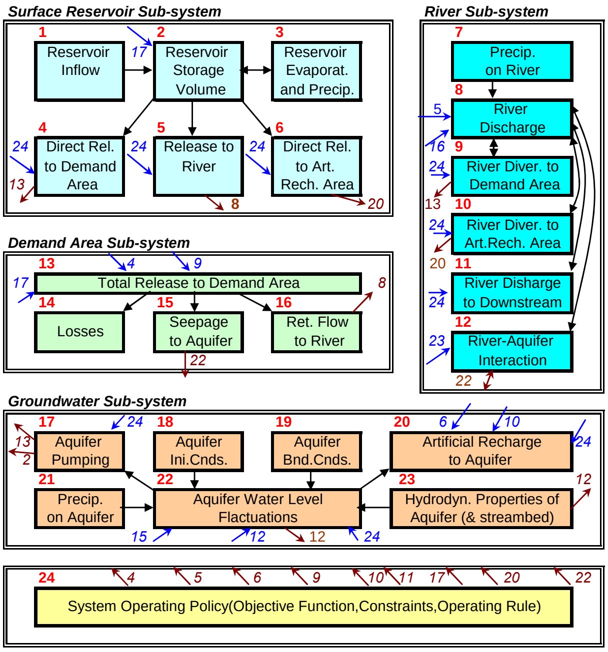

Fig. 2- Conceptual representation of CYCS systems

sinks, respectively. As explained later, annual body and ground water aquifer. The model treats recharge and discharge wells as point sources or guaranteed of water supply (*ANY*), design capacity of surface reservoir (*CapD*), dam-to-demand area water conveyance system (WCS) capacity (*CapCD*), dam-to-art.rech. *WCS* capacity (*CapCAR*), aquifer-to-dam WCS capacity (*CapP*), capacity of river diversion system (RDS) to demand area (*CapDivD*), capacity of RDS to art.rech. (*CapDivAR*) have been considered as decision variables. In a general form the model structure may e presented as:

$$Max\ PVNB = BENEFIT - COST \tag{1}$$

$$BENEFIT = f(ANY) \tag{2}$$

$$COST = CD + CCD + CCAR + CDivD + CDivAR + CP + CW + CAR + CDEF \tag{3}$$

In which, BENEFIT is the annual benefit of the water supplies and *COST* is the annual costs of the system include *CD*: annual construction and OMR (ACOMR) costs of the dam, *CCD*: ACOMR costs of the dam-to-demand area WCS, *CCAR*: ACOMR costs of the dam-to-artificial recharge area (art.rech.) WCS, *CP*: ACOMR costs of the aquifer-to-dam WCS, *CDivD*: ACOMR costs of the river diversion system (RDS) to the demand area, *CDivAR*: ACOMR cost of the RDS to the art.rech. *CGW*: ACOMR costs of pumping from wells, *CAR*: ACOMR costs of artificial recharge to aquifer, and finally *CDEF*: annual costs (penalties) of shortage in meeting the guaranteed demands. Except pumping and artificial recharge costs other system components costs, may be considered as a function of associated capacity. For simplicity it has assumed that the water supply benefits and above mentioned costs functions has the general following forms:

$$BENEFIT = f(ANY) = a_y (ANY)^{b_y} \tag{4}$$

$$CX_i = f(CapX_i) = a_{Xi} (CapX_i)^{b_{Xi}} \tag{5}$$

Where Xi is the design capacity of i^{th} component of the system, a_y, b_y, a_{xi} and b_{xi} are predefined benefit and cost function parameters. On the other hand the pumping from aquifer and artificial recharge costs may be calculated through multiplying the pumping or recharging flow by the water pumped or recharged height [3]:

$$CW = CRF \cdot \left\{ \sum_{t=1}^{NT} \sum_{k=1}^{NK} \frac{m_w(t)}{(1+r_s)^t} \left[l_w(k) + s_w(k,t) \right] \cdot q_w(k,t) \right\} \tag{6}$$

$$CAR = CRF \cdot \left\{ \sum_{t=1}^{NT} \sum_{l=1}^{NL} \frac{m_{ar}(t)}{(1+r_s)^t} \left[l_{ar}(l) + s_{ar}(l,t) \right] \cdot q_{ar}(l,t) \right\} \tag{7}$$

$$m_w(t) = (uelif \cdot ucen / efp / 1000)(Q2V(t)) \tag{8}$$

$$m_{ar}(t) = (ueinj \cdot ucen / efi / 1000)(Q2V(t)) \tag{9}$$

In which, NT: number of time periods, NK: number of pumping wells, NL: number of recharge wells, $l_w(k)$ and $l_{ar}(l)$: initial drawdown (initial lift) in pumping and recharge wells, respectively, $s_w(k,t)$: change in groundwater table in pumping well k in period t, and $s_{ar}(l,t)$: change in groundwater table in recharge well l in period t, $q_w(k,t)$: pumping rate in pumping well k in period t, $q_{ar}(l,t)$: recharge rate in recharge well l in period t. Also *uelif* and *ueinj* are necessary unit energy to pumping a unit volume of water to a unit height and pressure recharge of unit volume of water to unit depth, respectively, ucen: unit cost of energy, *efp* and *efi* are pumping and recharge efficiencies, respectively. The model so structured to the following constraint that present in vector form (for more details refer to *alimohammadi@iust.ac.ir*):

a- Constraints on mass balance and capacity:

$$G1(S^s, Q, R_s^g, E^s, R_d^s, R_{ar}^s, R_{riv}^s, CapD, CapC, CapP) = 0 \quad (10)$$

In which S^s: initial reservoir storages volume, Q^s: river inflow to surface reservoir, $R^g{}_s$: inflow from aquifer to reservoir, E^s: evaporation from reservoir, $R^s{}_d$: dam release to demand area, $R^s{}_{ar}$: dam release for art.rech. and $R^s{}_{riv}$: dam release to river.

b- Constraints on demand:

$$G2(R_d^s, R_d^g, DivD, ANY, DEF, EXE) = 0 \quad (11)$$

In which, $R^g{}_d$ and $DivD$ are groundwater allocation and river diversion to meet demands respectively, and DEF, and EXE are the deficit and excess water supply respectively.

c- Constrains on pumping and recharge balance:

$$G3(q_w, R_d^g, R_s^g) = 0 \quad (12)$$

$$G4(q_{ar}, R_{ar}^s, DivD) = 0 \quad (13)$$

$$G5(q_w, q_{ar}, q_{raq}, rets, seep) = 0 \quad (14)$$

In which *rets* is the fraction of water yield that percolate to aquifer, and *seep* is the fraction of precipitation that seepage to aquifer. Equation 14 balances the input and the output discharge of aquifer.

d- Constraints on water table fluctuations in aquifer and river:

$$G6(R_x, m_j, .\beta_j, E_j) = 0 \quad (15)$$

In which R_x is response of the excited component x to the exciting component j, m_j is correction factor, β_j is unit response coefficient, and E_j is the value of excitation cause by exciting component j. Eq. 15 is a modified form of the unit response matrix method. Using this equation could lead us to derive the response of every component of the system (such as water table fluctuations in aquifer and river) to every excitation (such as pumping, recharge, river flow, etc.) for all kinds of sources including point sources (e.g. wells), linear sources (e.g. river) or distributed sources (e.g. infiltration or precipitation over an area). In the case study, responses include groundwater table fluctuations of pumping wells ($s_w(k,t)$), recharge wells ($s_{ar}(l,t)$), river reaches ($s_{riv}(r,t)$), and discharge flow between river to aquifer ($q_{raq}(r,t)$).

e- Constraints on river-aquifer interactions [11]:

$$G7(q_{raq}, C_{riv}, h_{riv}^s, h_{riv}^g, h_{riv}^{bot}) = 0 \quad (16)$$

In which, C_{riv} is the river conductance, $h^s{}_{riv}$ is elevation of river stage, $h^g{}_{riv}$ is elevation of aquifer water table in cells below of river, $h^{bot}{}_{riv}$ is elevation of semi-pervious streambed bottom.

f- Constraints on river hydraulics:

$$G8(q_{riv}^{in}, ql_{riv}, q_{riv}^{out}, \Delta S_{riv}, h_{riv}^{in}, h_{riv}^{out} \quad (17)$$

$$, h_{riv}, dh_{riv}, h_{riv}^{out,\min}, h_{riv}^{out,\max}) = 0$$

In which $q^{in}{}_{riv}$, and $q^{out}{}_{riv}$ are river inflow and outflow respectively, ql_{riv} is summation of lateral inflows or outflows along river, dh_{riv}, and ΔS_{riv} are river stage and storage changes respectively, $h^{in}{}_{riv}$ and $h^{out}{}_{riv}$ are river inflow and outflow stages respectively, $h^{out,min}{}_{riv}$ and $h^{out,max}{}_{,riv}$ are minimum and maximum river outflow respectively, and h_{riv} is the initial stage of the river. Eq. 17 is needed for mass balance, continuity of flow along the river, converting the inflow and outflow discharges into related stages, changes in the river stage and storage, and discharge limitations.

5 Model Application

To test the model performance in a medium size CYCS, a hypothetical example with a seasonal time step has been used (Fig. 1). The input data and characteristics of the system are presented in the companion paper. However the result of optimization model solution has illustrated graphically in Fig. 3. In this Fig. the system inflows and outflows have presented. It has seen that many terms have the general and long-term pattern of surface hydrology regime of the system. Also groundwater has the rule of backup of the surface water and especially in dry period this role is more highlighted. Considerable amount of water is discharge from river to aquifer or vice versa. Unfortunately this term often omitted in water resources development studies and this leads to optimistic results.

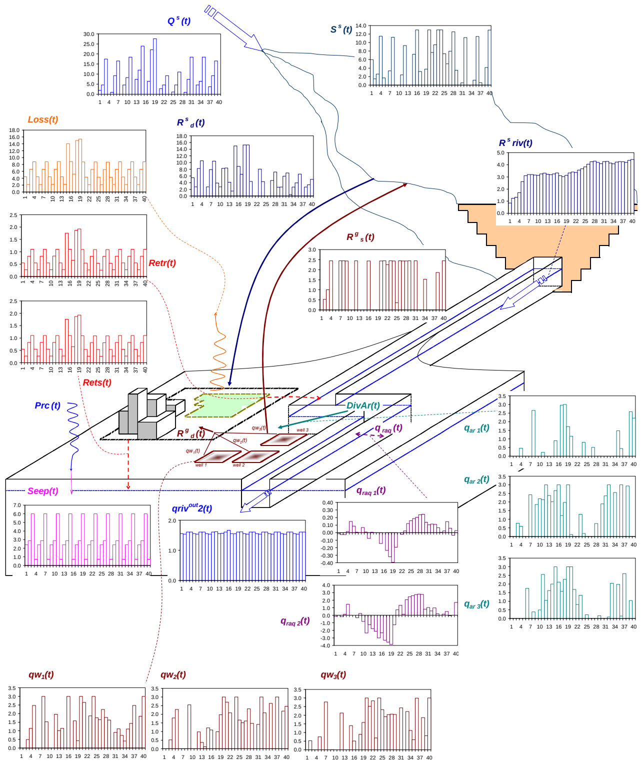

Fig. 3- The result of optimum design model

6 Summary and Conclusion

In this paper, an optimization model was developed for designing of cyclic storage systems. The model has a form of nonlinear programming. In order to evaluate the model efficiency, a simplified hypothetical system was considered as an example. Using its data, the optimization model was executed. The following conclusions have been resulted from this study:

1- The distributed parameter optimization model has been developed based on the modified and generalized unit response matrix method. Surveying the literature shows that there is a few studies such this one and the model addressed here is more efficient and free of constrains than the previous reported models.

2- Surface Hydrology regime of the system made an important role in the behavior of the system components, such as groundwater recharge and discharge.

3-The groundwater might be considered as a backup of surface water in meeting demands. In the problem analyzed here, it was seen the increasing and decreasing groundwater pumping in long term dry and wet periods respectively (Fig. 3).

4- The considerable amount of river discharge may seepage to aquifer or vice versa. Ignoring this volume of water (that unfortunately occurs in more studies) may lead to optimistic and rung decisions.

Acknowledgments

The authors do appreciate the Iran water resources management organization (IWRMO) for the financial support of this research.

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