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Optimum Design of Cyclic Storage Systems; Distributed Parameter Approach: 2- Model Solution Methodology and Analysis of Results

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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. 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. For verification and testing of model outputs, the results of optimization model evaluated for two purposes. First for global optimality of model solution, and second for validation of model structure. The first one is implemented with converting the nonlinear model to linear form and comparing of two model results. The second one is done with assessing of model results with a simulation model. The results show the model is valid both in global optimality and structure of it.

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

1 Introduction

In these two companion paper (both in this issue), a distributed optimization model for design of a cyclic storage system has been presented. In the first paper, the system definition, literature review, conceptual framework of the model, and optimization model formulation has been presented. In this paper the emphasis is on the method of model solution, verification, and results. The optimization 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. We don't repeat the model formulation in this paper. The readers refer to the first paper from authors in this issue [1].

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2 Problem Setting

To test the model performance in a medium size CYCS, a hypothetical example with a seasonal time step has been used. A simplified system also could be used as could be seen in Fig. 1. The aquifer has an impermeable boundary except the stream inlet and outlet. Aquifer has been divided to 1000 meters distant in vertical, and 1000, and 500 meters distant in horizontal directions. Spatial variation of the aquifer hydrodynamic properties has illustrated is Fig. 2. Pumping and recharge wells are also used as observation wells. Initial drawdown has been assumed to be 10 m all around the aquifer. The river has been considered as a rectangular channel with 20 meters wide, manning coefficient of 0.02 and slope of 0.0001. The river has been divided into upstream and downstream reaches, and either of reaches is finished with a cell which a gage station is located on it. The aquifer has been separated from the stream through a 2 meter semi-impervious streambed layer with hydraulic conductivity of 1×10^{-6} m/s. Demand area is in the middle part of the system. In each season 5% of precipitation and 10% of supplied water percolate into the aquifer. Also 10% of yield enters the second reach of the river. It is assumed that the system is initially at rest (groundwater table is equal to stream stage). For more simplicity, dead storage and evaporation of surface reservoir have been ignored. A 10 years seasonal flow has been considered. This area located in a semi-arid region with annual precipitation of 300 mm and mean annual river discharge of 30×10^6 m^3 (30 mcm). The seasonal variation of river discharge, precipitation and demand distribution have been given in table 1 and the other cost and technical data of the system are given in tables 2 and 3. An optimization model for system planning has been established, based on the given data.

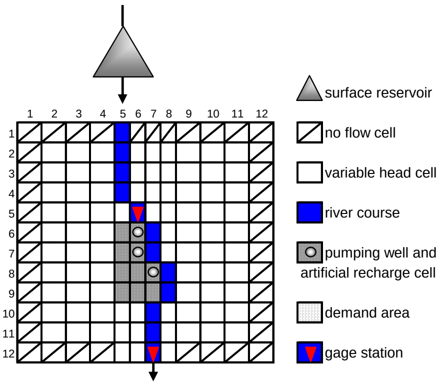

Fig. 1- Simplified hypothetical system

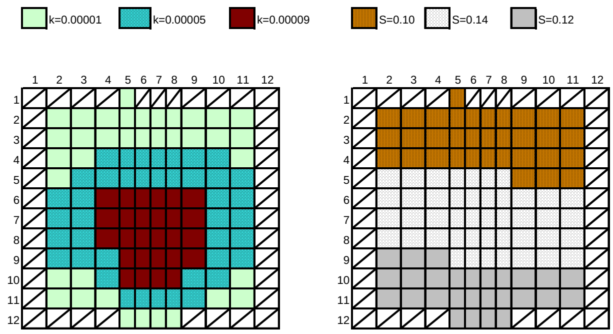

Fig. 2- Spatial characteristics of aquifer

Table 1- Seasonal variation of input data

Parameter	Fal.	Win.	Spr.	Sum.	Anl.
Inflow(mcm)	3.42	8.83	17.75	0.00	30.00
Precipit.(mm)	60.0	72.0	150.0	18.0	300.0
Dem. distrib.	0.20	0.10	0.30	0.40	1.00

Table 2- Benefit and costs input data

Term	*a*	*b*	*Term*	*a*	*b*
Benefit	*20.0*	*0.5*	*CP*	*0.1*	*0.5*
CD	*5.0*	*0.5*	*CDivD*	*1.0*	*0.5*
CCD	*1.0*	*0.5*	*CDivAR*	*0.5*	*0.5*
CCAR	*0.5*	*0.5*	*Cdef*	*20*	*2.0*

Table 3- Technological constraints input data

parameter	*value*	*parameter*	*value*
qw_{max}	*3mcm*	sw_{max}	*10 m*
qw_{min}	*0mcm*	sw_{min}	*-10 m*
qar_{max}	*3mcm*	$q^{outmin}riv$	*0.2 m3/s*
qar_{min}	*0mcm*	$q^{outmax}riv$	*1 m3/s*

3 Methodology of model solution and validation

The developed optimization model is a large-scale NLP design model. To solve the model two following methods have been used in this study: (1) solving NLP model using several initial guesses, and (2) changing the nonlinear model into the linear one using piecewise linearization and solving the resulted LP model.

The first method requires a short time to solve the model. Nevertheless, the result may be the local optimum. Thus one may solve the model several times with different initial values for the decision variables (unknown variables). Achieving the same result may ensure that it could be a global optimum. In the second method one must establish a linear version of NLP model. Solving this model would be result in a global optimum caused by linear model. Another advantage of such model is that while in the NLP model, the form of the functions must be identified, in the LP model every function in any form could be piecewise linearized, even if no specific function could be fitted with it. However, it should be noted that the run-time and accuracy of the result depend on the number of linear segments of the nonlinear functions. Although high number of segments would result in the model accuracy, it would highly increase the run-time of the model, especially in the large-scale models such as the above mentioned CYCS model.

In order to validate the model formulation, a simulation approach has been implemented. A simulation model was provided based on the optimization model results (such as wells pumping and artificial recharging and so on). After executing the model, the drawdown of the aquifer and the flow changes between the river and the aquifer was compared with those of the optimization model. If there is a little difference between them one may insure the model is valid in formulation.

4 Problem solution and model validation

The described NLP problem has been solved by two above mentioned methods. Table 4 shows the results of two models. It can bee seen that the two models have been reached to a unique global optimum. However it's been emphasized on the NLP results for the further analysis.

Table 4- Optimization result for NLP and LP models

Term \ Model type	Benefit-cost terms		Capacities**	
	NLP	LP	NLP	LP
Water supply	81.03*	81.31	27.61#	28.18
Dam	17.998	18.675	12.96&	14.37
Dam-dem. WCS	3.908	3.696	15.28	14.07
Dam-art.rech. WCS	0.000	0.000	0.00	0.00
Aquifer-dam WCS	0.156	0.155	2.44	2.80
RDS for demand	0.000	0.000	0.00	0.00
RDS for art.rech.	1.389	1.416	7.72	8.22
Pumping wells	0.256	0.284	9.00	15.25
Artificial recharge	0.007	0.008	7.72	0.00
Deficite	0.345	0.345		

Term \ Model type	Mean values (mcm)	
	NLP	LP
Dam release to demand area	20.97	20.51
Dam release to art.rech. area	0.00	0.00
Aquifer pumping to dam	4.66	5.39
Aquifer pumping to demand area	10.17	10.65
River diversion to demand area	0.00	0.00
River diversion to art.rech. area	10.53	11.49
River release to river	13.69	14.89
Deficite in water supply	0.20	0.21
Excess in water supply	3.73	3.18

* : net benefit ** : mcm/seaon # : mcm/year & : mcm

For model validation assess, the optimization model outputs (e.g. wells pumping and recharge volumes, river stage, and water supplies in overall time period), have been taken and given to simulation model as input data. Then the drawdown in wells and river-aquifer discharges has been taken from the simulation model. Figure 3 shows the typical resulted wells drawdowns and river reaches discharge to aquifer in optimization and simulation models. It could be seen that the two models yield same results and one could concluded that the optimization model is valid in formulation, and the accuracy of it is very high.

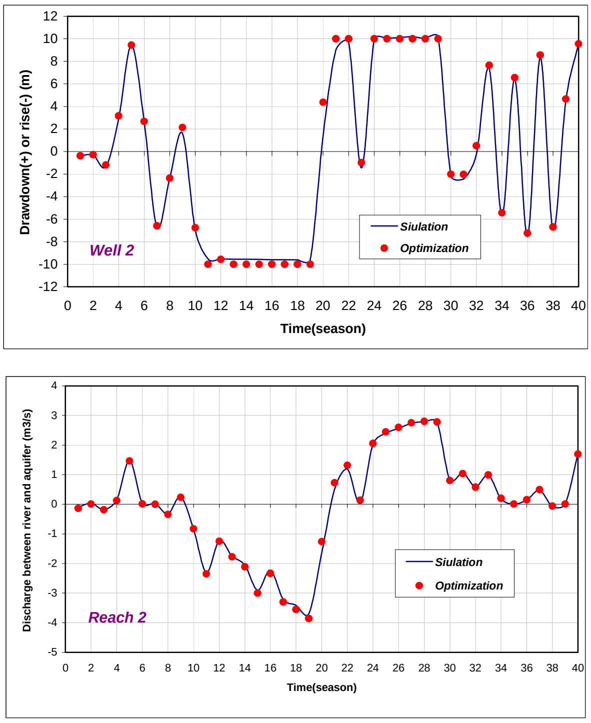

Fig. 3- Comparison of Typical wells drawdowns and river discharge to aquifer in optimization and simulation models.

5 Analysis of results

Figure 4 shows the seasonal variation of optimum design model outputs. In this figure, some results could be considered in more details. Reservoir storage fluctuation, inflow and release are depicted. As illustrated, reservoir has an important role in regulate the inflow. A wide range between 0 to 28 mcm has been reduced to a range between 3 to 18 mcm. In all years, some pumping volume from aquifer has been returned to reservoir especially in summers. It is because the downstream requirements have been taken constant in all seasons (table 3) and the aquifer transferred flow has an important role in meeting this demand. On the other hand, flow allocation to the demand area is about 60% of the entire release and the other 40% would release into the river. Some of these release diverted to artificial recharge sites and the remained of it has needed for downstream requirements.

Figure 4 shows that more of demand has been supplied from the reservoir. While the, 67% of supplied water has been provided by the reservoir, only 33% of it, has been pumped from the aquifer. In this example, the aquifer useful volume is proportionally small and the aquifer has the backup role for surface reservoir in meeting demands. Figure 4 also shows the temporal variation of river diversion to demand area (that is zero) and artificial recharge site. It could bee seen that the more of river discharge diverted in two wet years and the amount of diversion in dry years is low.

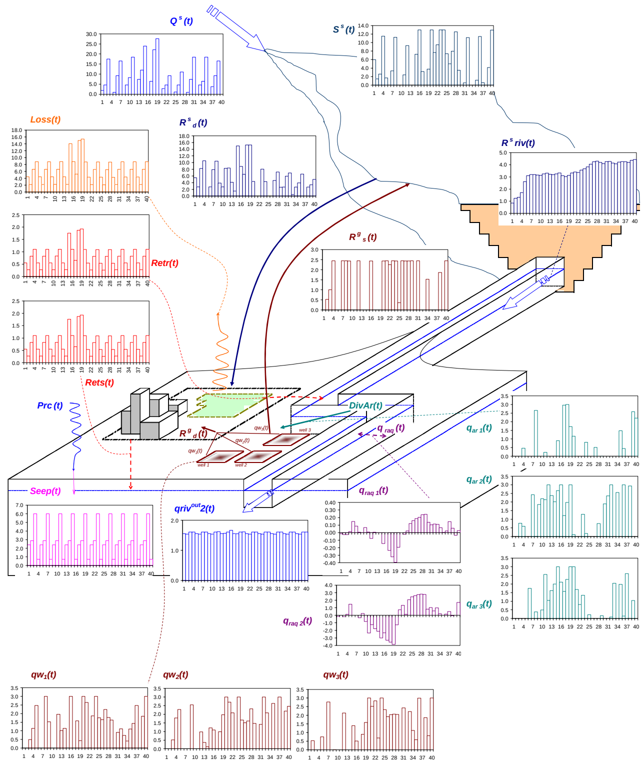

Fig. 4- Seasonal variation of optimum design model outputs

Seasonal variation of aquifer pumping, and recharging, in 3 wells, illustrated in the figure 4. As seen, the total amount of aquifer pumping has increased in the second half of the planning period. It is because decreasing of the surface water in this period. On the other hand in the two years wet period, the amount of pumping is decreased considerably. The average pumping from each well is close together, however the average pumped from well 1, is a little more, and well 2, a little less than two other wells because of their locations. The artificial recharge volume, is proportional to surface water and global pattern of it, is opposite to pumping as seen in figure 4. This cycle of pumping from and recharging to aquifer, is one of the main characteristics of CYCS that is separated it from other kind of conjunctive use systems. The seasonal fluctuations of groundwater table (not illustrated here), obey the hydrological regime of system, that it is maximum drawdown in dry and maximum rise in wet periods. Another reason of increasing artificial recharge in two year wet period is the rise of water table often is maximum in 3 wells, and the cause the cost of recharging would be low.

The discharge trading between river and aquifer also has been shown in figure 4. There is a considerable change in the second reach because of nearing this reach to the wells, river discharge diversion to artificial recharging, and returned flow form demand area. This component of the system usually could be ignored in conjunctive operation studies. However, this may be of a great concern in such systems and Ignoring of it may lead to optimistic results (rerunning the optimization model neglecting the river-aquifer interactions, resulted 11.5% increase in net benefits). Finally the outlet discharge of the river has been illustrated in figure 3. The amount of discharge in the first reach approximately is equal to river release of dam (not shown). On the other hand the amount of it in the second reach is set equal to downstream requirements.

5 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. Two methods were implemented to solve the model. In order to evaluate the model efficiency, a simplified hypothetical system was considered as an example. Using its data, the optimization model was executed and output results were checked with a simulation model for validation. 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- Solving the main NLP model and linearized version of it lead to the same results. Solving NLP model is straightforward and proportionally simple. However there is no guaranty about the global optimality of the solution. On the other hand the LP version of the model always tends to global optimum. But the time consuming for solution of this form, might be very long.

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

4- Water returned to reservoir from aquifer might be important in meeting downstream requirements, especially if the pattern of this demand differs from river natural discharge. In the assessed problem, as seen this volume of water usually sent to reservoir in dry periods.

5-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.

6- 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

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References

[1] Alimohammadi, S., and Afshar A., Optimum Design of Cyclic Storage Systems; Distributed Parameter Approach: 1- System Definition and Model Formulation, *WSEAS Transactions on Information Science and Application*, This Issue.