Spill-Minimizing Rules For Parallel Reservoirs: Quantity and Quality

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Abstract
This paper presents a spill-minimizing operating policy for refill of reservoirs in parallel for water supply considering water quality criteria. First a Linear Programming form of the New York City Rule is developed. Next, this formulation is extended to consider stratified water quality in the reservoirs and a requirement of water quality for the downstream demand. Both approaches are applied to an example of reservoirs in parallel: Shasta and Whiskeytown reservoirs in California. The results of these applications show the effect of the water quality consideration in the operation of the system.

Introduction

Historically, a distinct separation in the consideration of water quantity and water quality concerns has existed, with most of the attention given to the provision of required quantities (Azevedo at al. 2000). The traditional approach of water-quality management considers quantity and quality aspects of the problem independently. Considering both aspects in a common strategy is commonly advocated (Loucks 1987, Arnold and Orlob 1989, Strzepek and Chapra 1990).

Many approaches have tried to consider both aspects for specific problems. Loftis et al. (1985) studied different conjunctive water quantity and quality approaches for the management of a system of lakes. Mehrez et al. (1992) considered both aspects in a non-linear programming model for water supply operation. Hayes et al (1998) dealt with the management of a multireservoir hydropower system with water quality requirements downstream.

Moreover, several water management Decision Support Systems (DSS) have been modified to consider water quality. Dai and Labadie (2001) link the system simulation model MODSIM and the water quality model QUAL2E using a non-linear programming algorithm to incorporate constraints on conservative constituents. Willey et al. (1996)

modified the water allocation model HEC5 to accept user specified water quantity and quality requirements and manage reservoir systems under both criteria. Finally in many cases, such as in Azevedo et al (2000) and Wu et al. (1996), the same DDS is considered with classical water quality models in a trial and error linkage. However, in this approach the quality aspect remains separated from the water operation process.

In the approach presented here, water quality is central to the model and management. Stratification of the reservoirs is considered, with different pools having different water quality characteristics. This fragmentation is considered inside the objective function of the model. Moreover a water quality requirement is considered in the target demand.

Despite the development and growing use of optimization models (Labadie 1997), most reservoir planning and operation studies are based on simulation modeling and thus require intelligent specification of operating rules. Lund and Guzman (1996, 1999) review derived single-purpose operating rules for reservoirs in series and in parallel for different purposes, with derived rules supported by conceptual or mathematical deduction. In many practical situations, operating rules are established at the planning stage of the proposed reservoir, and these rules provide guidelines for reservoir releases to meet demands (Tu et al. 2003). Among the developed rules for reservoirs in parallel used for supply water are: The New York City Rule (Clark, 1956), the Space Rule (Bower et al 1966) and the LP-NYC rule (Lund & Guzman 1999). These rules typically apply to the refill season and mostly for seasonal and long-term studies. For the drawdown season Wu (1988) developed a rule that equalizes the probability of each reservoir being empty at the end of the drawdown season.

The NYC rule (Clark, 1950) equalizes the probability of spills at the end of the refill season for all reservoirs. This is equivalent to minimize physical spill and the water supply shortfall (Sand, 1984).

The Space Rule's objective is to leave more space in reservoirs where greater inflows are expected (Bower et al. 1966). This rule is a special case of the NYC rule when the distribution forms of inflows into each reservoir are the same (Sand, 1984).

The LP NYC rule (Lund and Guzman, 1999) represents the incorporation of the New York City rule into a Linear Programming model. The advantage of this approach is the possibility of incorporating other constraints to the model and the direct application of the concept in the management of the system. All of these rules can be modified to consider hydropower spills or differing water quality values between reservoirs.

The present paper establishes a new formulation for the LP-NYC rule and develops a new rule for water quantity and quality considerations with multiple water qualities in each reservoir. First an improved formulation of the LP-NYC rule is developed for minimizing physical spill, energy spill, or water quality spill. Second a new model is proposed to consider multiple water qualities in each reservoir and downstream water quality. Finally the paper presents a comparison of management results of each model.

Linear Programming Rules for Quantity

The original LP-NYC rule proposed by Lund and Guzman (1999) is a linear programming problem to be solved for each time-step of the refill season. The model resolves the releases of water in a parallel reservoir system with a demand downstream all reservoirs minimizing the expected value of total spill. Figure 1 represents the topology of the problem. The LP problem has to be solved for each time step. The objective function minimizes the weigh probability of spill from the current step to the end of the refill season.

A more complete and correct formulation of the NYC-LP rule is:

(1) $$MINZ = \sum_{j=1}^{m} \sum_{i=1}^{n} (h_i * (L_{ij} + \alpha * X_i))$$

Subject to:

(2) $L_{ij} - E_{ij} = S_{fi} + CQ_{ij} - K_i \quad \forall$ i, and j

(3) $S_{fi} = S_{oi} + Q_i - R_i - X_i \; \forall$ i

(4) $\sum_{i=1}^{n} R_i = D$

(5) $S_{fi} \le K_i \; \forall$ i

$R_i \ge 0$; $S_{fi} \ge 0$; $E_{ij} \ge 0$; $L_{ij} \ge 0$; $X_i \ge 0$; $\forall$ i, and j

Where:

m = Number of equally probable refill seasons

n = Number of reservoirs

h_i = Unit value of water in reservoir i

S_{fi} = End-of-period storage for the current period for reservoir i

S_{oi} = Beginning of current period storage for reservoir i

K_i = Storage capacity of reservoir iD = Demand for the current period

V = Total volume of water in storage at the end of the current period

CQ_{ij} = Expected cumulative inflow to reservoir i from the end of the current period to the end of the refill cycle

L_{ij} = Spill from reservoir i under hydrologic year j

E_{ij} = Empty storage capacity in reservoir I under hydrologic year j

X_i = Spill of the reservoir i in the current period

α = Behavior coefficient

The weight of the spill represents the value of water in each reservoir. This coefficient depends on water quality or energy storage of the reservoir. For the water quality case this value represent the marginal value of the water minus its treatment cost for each reservoir (Lund & Guzman 1999).

Spills in the current period (X_i) have been considered. Otherwise the objective function minimizes the probability of spill (L_{ij}) trying to cancel the final capacity of reservoirs in current period (S_{fi}). The behavior coefficient α is necessary because if not in some cases where L_{ij} is greater than zero for all the years the model can reduce the value of the variable S_{fi} in order to minimizes the total summation. The value of α depends on the characteristics of the system and on the h_i coefficients established. The parameter has to be calibrated to avoid the situation where one reservoir is spilling while the other is releasing all the water to satisfy the demand.

Equation (1) represents the estimation of the probability of spill for each reservoir and for each year. The difference between spill and empty storage is calculated as the final storage for this time step plus the cumulative inflows from the final step to the end of the refill season minus the capacity of this reservoir.

Equation (4) represents the aggregate supply of the downstream demand. Equation (3), represents the continuity balance in the current period.

Linear Programming Rules for Quality

Due to stratification of the reservoirs, water quality variables have different values for the different stratification pools. The LP model has been adapted to consider water quality both within and between reservoirs. The reservoirs have been fragmented in different pools where the water quality variables have the same range of values. Moreover the model considers different water quality variables for the inflows. Finally there is a target of quality for the downstream demand. The model assumes that releases can be made from the different pools of the reservoirs and the stratification is constant over the refill season. Figure 2 shows a diagram of the problem.

The formulation of the model is as follows:

(6) $$MINZ = \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{l=1}^{r}(h_{il} * (L_{ijl} + \alpha * X_{il}))$$

Subject to:

(7) $$L_{ijl} - E_{ijl} = \sum_{w=1}^{l}(S_{fwi} + CQ_{ijw}) - K_i - \sum_{w=1}^{l-1} L_{ijw} \quad \forall \text{ i, j, and l}$$

(8) $$S_{fil} = S_{oil} + Q_{il} - R_{il} - X_{il} \quad \forall \text{ i, and l}$$

(9) $$\sum_{l=1}^{r} S_{fil} \le K_i \quad \forall \text{ i}$$

(10) $$\sum_{i=1}^{n}\sum_{l=1}^{r} R_{il} = D$$

(11) $$\sum_{i=1}^{n}\sum_{l=1}^{r}((R_{il} + X_{il}) * T_{il}) = T_t * \sum_{i=1}^{n}\sum_{l=1}^{r}(R_{il} + X_{il})$$

$$R_{il} \ge 0\,; S_{fil} \ge 0\,; E_{ijl} \ge 0\,; L_{ijl} \ge 0\,; X_{il} \ge 0 \quad \forall \text{ i, j, and l}$$

Where:

r = Number of pools in the reservoir (index: l and w)

T_l =Water Quality variable of the pool l of the reservoir i

T_t = Water Quality Target of the demand

Index w also indicates pools.

The objective function has the same terms but with a new sub index that represents the pool. The aim of the LP model has changed because in this case it is considering the probability of the spills of each pool. Moreover the weigh is applied to the different spills and not only to the different reservoirs. This allows improving the management of the system for water quality because it better water quality pools and be more highly valued both within and between reservoirs. The probability of the spill from each pool is considered in equation (7). At the time of estimating the spills or the probability of the spills it has to be considered that the spill of one pool depend on the spills of lower pools.

The final storage and the releases for each period have been considered for each pool. Finally, equation (11) incorporates a requirement of blended water quality demand downstream (such as a downstream instream temperatures) blended water quality from the demand. This model can be applied to any water quality variable that stratificates in reservoirs. No more extensive model of water quality has been incorporated because it is assumed that the water quality variables are non-diffusive and conservative during the refill season in each pool.

Example application

Both models have been applied to the same case, two parallel reservoirs in Northern California: Shasta and Whiskeytown reservoirs. A simplification for this case is that Whiskeytown has no reservoirs upstream. The example covers one refill season with monthly time steps. The software used to solve the models was GAMS.

Quantity Example

Input Data

The series of monthly inflows for both reservoirs are available for October 1921 to September 1993. Although the maximum capacity for both reservoirs depends on the month of the year representative values have been chosen for this simulation; capacity values are 4000 and 220 Kaf for Shasta and Whiskeytown respectively. The initial storages for the first month of the refill season are 2496 and 200 Kaf for Shasta and Whiskeytown respectively. For the other months the initial storage is equal to the final storage obtained by the model in the previous month. For the forecast inflows an average value of the historic inflows has been used. However this value can be substituted by any better value from hydrology forecast models. Finally the value of downstream demand is set as 30% of combined expected inflows. The weight coefficients h_i in this case represent the value of the water in each reservoir. Chosen coefficients are 0.45 for Shasta reservoir and 0.55 for Whiskeytown reservoir. These coefficients have been chosen to establish a comparison with the water quality case. The coefficient α used is set at 2.

Results

For this case the refill season covers October until April. For each month the linear programming defined by equations (1) to (5) is resolved. Table 1 shows the results for each refill month for releases, final storage in each month and the spill in each month. Figure 3 depicts the final storage for both reservoirs in each month and Figure 4 shows the spills in each month for each reservoir.

In table 1 it can be seen that most of the releases come from Shasta. This is because as figure 4 shows the spills in Shasta are very high. As it can be seen in the same figure the spills star for both reservoirs in February. In December and January Whiskeytown is full while Shasta has storage capacity. This is the cause that in these months the releases comes from both reservoirs. Because Shasta is full at the end of January, in the next months the releases are only from Shasta. Figure 4 depicts the difference of the spills between both reservoirs. February spill from Shasta is greater than all spills from Whiskeytown for the entire refill season. The system ends the refill season with both reservoirs full.

Quality Example

Input Data

The LP Rule for Quality is applied to the same example. Temperature is the chosen water quality variable. Many of the physical-chemical characteristics of the water depend on temperature. Maintaining water temperature standards during summer months is important to the biological integrity of warm plain rivers that serve as habitat for fish and birds (Craswshaw, 1977; Kapra, 1981; Gu and Li, 2002). Some modifications have to be done in order to adapt the problem to the quality case:

- Two pools of different water temperatures are considered for each reservoir. For Shasta reservoir, Pool 1 is 13 ºC and Pool 2 has a temperature of 22 ºC. Pool 1 is the lower pool in the reservoir. For Whiskeytown the temperatures are 8 and 17.5 ºC for pools 1 and 2 respectively.

- Initial storages for each water temperature pool for Shasta are 498 and 1998 for Pool 1 and Pool 2 respectively. For Whiskeytown the values are 140 and 60.

- Due to the unavailable series of inflows for different temperatures the initial inflows have been disaggregated to two new series with different temperature. In the process of disaggregating some available data of temperature inflows and randomness were considered.

- The Weight coefficients, h_{ij}, are 0.35 and 0.1 for Pool 1 and Pool 2 of Shasta and 0.4 and 0.15 for Pool 1 and Pool 2 of Whiskeytown. The weight of Pool 1 is greater because the water temperature is lower. In this case cold water is considered better for downstream salmon habitat.

- The target temperature downstream is 15 ^{0}C. High temperatures (more than 25ºC) are dangerous for some fish species as salmon and their reproductive activities during summers.

Results

With these new data the linear programming for Quality has been solved for the same refill season. Table 2 represents a summary of the results. Figures 5 and 6 depict the final storage and spills for each month respectively. Figure 6 shows the effect of the downstream temperature requirement in Whiskeytown. The release of the coldest water is necessary to achieve the temperature goal. Because of this the releases in the first three months come from both reservoirs. In February the spill from Shasta is done from both pools due to the same reason. Finally this new constraint produces an extra release of water from Whiskeytown and Shasta in April.

Comparative of the two Rules

Management of the system under the Quality Rule must produce physical spill than the Quantity Rule because the additional constraints. Moreover, the behavior of the models differs because of the different spill weight coefficients. However, for this example the quantity and quality results are very similar. Figures 7 and 8 compare the results of final storage and cumulative spills for both alternatives. The main difference between the cases is that for the “quality rule”, final storage of Whiskeytown is approximately 99 Kaf less. Moreover for the “quality case” the spills are 144.799 Kaf greater. However this amount of spill represents only 3.5% of the total inflow in the refill season (4200 Kaf).

Conclusions

The LP NYC method rule for refill season operation of parallel reservoirs has been reformulated as a linear program for water quantity and quality. An example demonstrates the method and its usefulness. This approach provides a simple way to derive an operating rule for some water resources systems. In this type of system, consideration of a water quality requirement downstream of both reservoirs can be considered in the LP rule. However, for the example developed, this environmental requirement has a little influence on optimal management of the system. With this model the water quality aspect is introduced into the model and management of the reservoirs system depends on both water quantity and quality aspects.

Tables and Figures

KAF	Demand	Exp. Inflows Shasta	Exp. Inflows Whisk.	Releases Shasta	Releases Whisk.	Initial Storage Shasta	Initial Storage Whisk.	Final Storage Shasta	Final Storage Whisk.	Spills Shasta	Spills Whisk.
October	75	244.92	4.69	75	0	2496	200	2665.92	204.69	0	0
November	106.6	341.74	13.63	106.6	0	2665.92	204.69	2901.06	218.32	0	0
December	167	530	26.633	142.07	24.953	2901.06	218.32	3289.013	220	0	0
January	214	672.74	40.818	173.182	40.818	3289.013	220	3788.471	220	0	0
February	247.14	772.61	51.2	247.14	0	3788.471	220	4000	220	313.941	51.2
March	255.8	804.51	48.44	255.8	0	4000	220	4000	220	548.71	48.44
April	216.78	684.97	37.62	216.78	0	4000	220	4000	220	468.19	37.62

Table 1. LP rule for quantity results

KAF		Demand	Exp. Inflows Shasta	Exp. Inflows Whisk.	Releases Shasta	Releases Whisk.	Initial Storage Shasta	Initial Storage Whisk.	Final Storage Shasta	Final Storage Whisk.	Spills Shasta	Spills Whisk.
October	Pool 1	75	73.476	3.283	0	37.5	498	140	571.476	105.783	0	0
	Pool 2		171.44	1.407	37.5	0	1998	60	2131.94	61.405	0	0
November	Pool 1	106.6	68.34	10.22	0	53.3	571.476	105.783	639.816	62.703	0	0
	Pool 2		273.4	3.41	53.3	0	2131.94	61.405	2352.04	64.815	0	0
December	Pool 1	167	63.6	23.97	0	83.5	639.816	62.703	703.416	3.173	0	0
	Pool 2		466.4	2.663	83.5	0	2352.04	64.815	2734.94	67.478	0	0
January	Pool 1	214	214.35	24.49	151.323	9.721	703.416	3.173	766.443	17.492	0	0
	Pool 2		458.29	16.328	52.956	0	2734.94	67.478	3140.274	83.806	0	0
February	Pool 1	247.14	215.89	33.28	247.14	0	766.443	17.492	453.968	51.222	281.225	0
	Pool 2		556.72	17.92	0	0	3140.274	83.806	3564.032	101.726	150.962	0
March	Pool 1	255.88	321.804	38.752	255.88	0	453.968	51.222	150.042	89.974	369.85	0
	Pool 2		482.706	9.688	0	0	3564.032	101.726	3849.958	111.414	178.78	0
April	Pool 1	216.78	325.24	30.691	97.887	118.893	150.042	89.974	0	1.772	377.395	0
	Pool 2		359.73	6.929	0	0	3849.958	111.414	4000	118.343	254.688	0

Table 2. LP rule for quality results

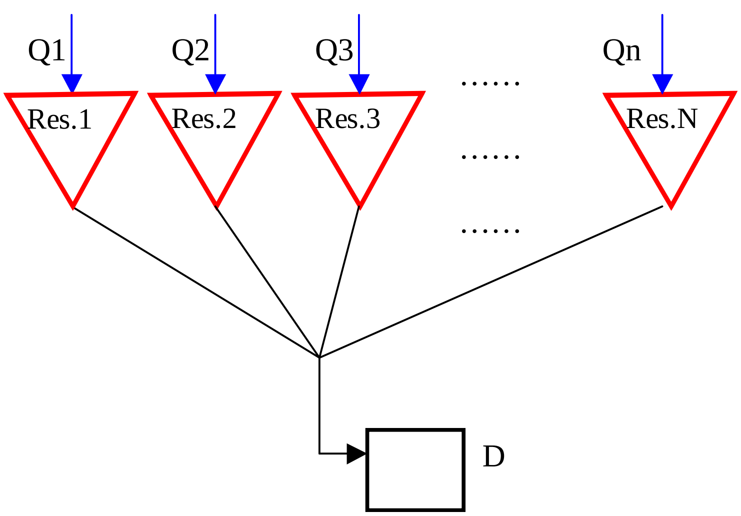

Figure 1. Schematic of reservoirs in parallel

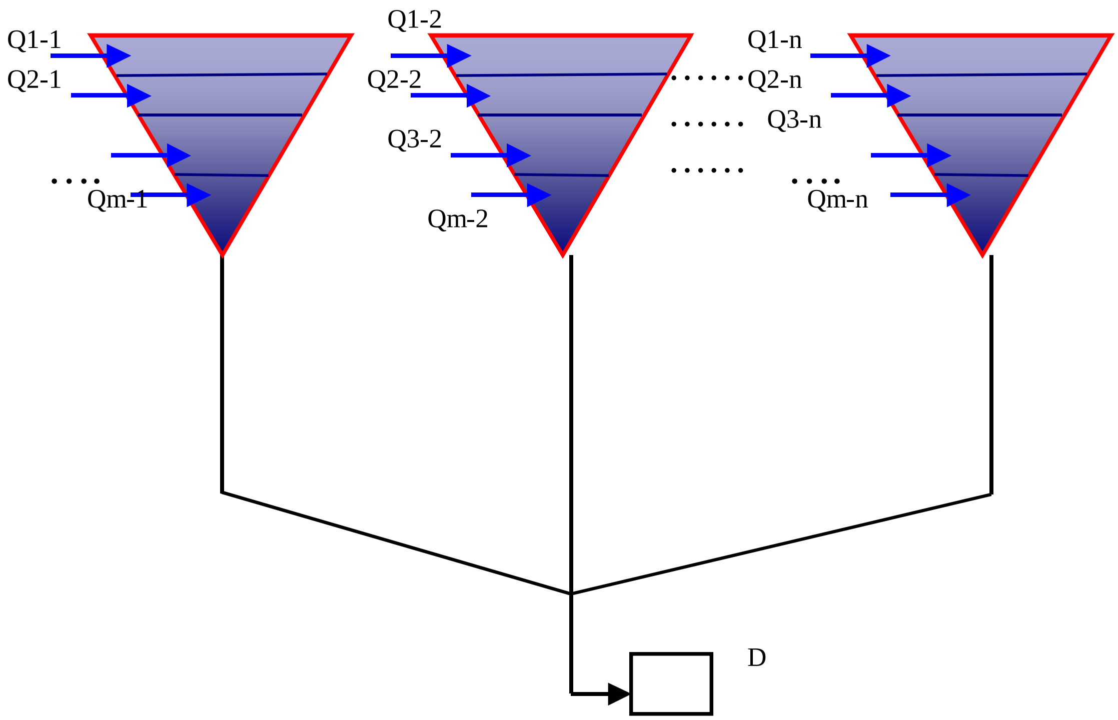

Figure 2. Schematic representation with quality

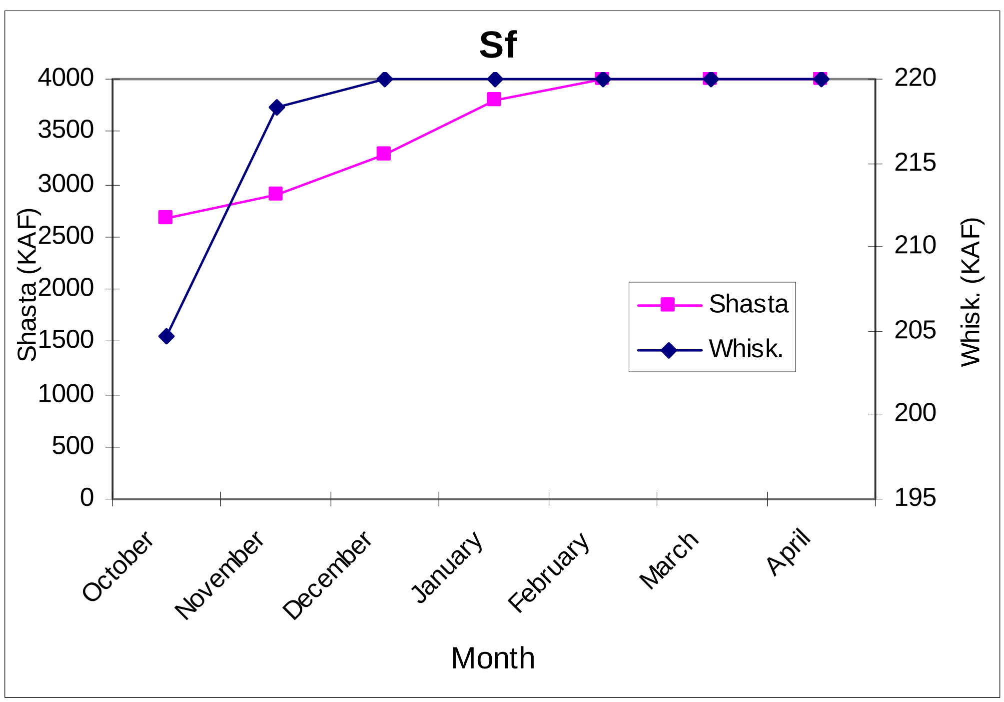

Figure 3. Monthly final storage for the LP rule for quantity

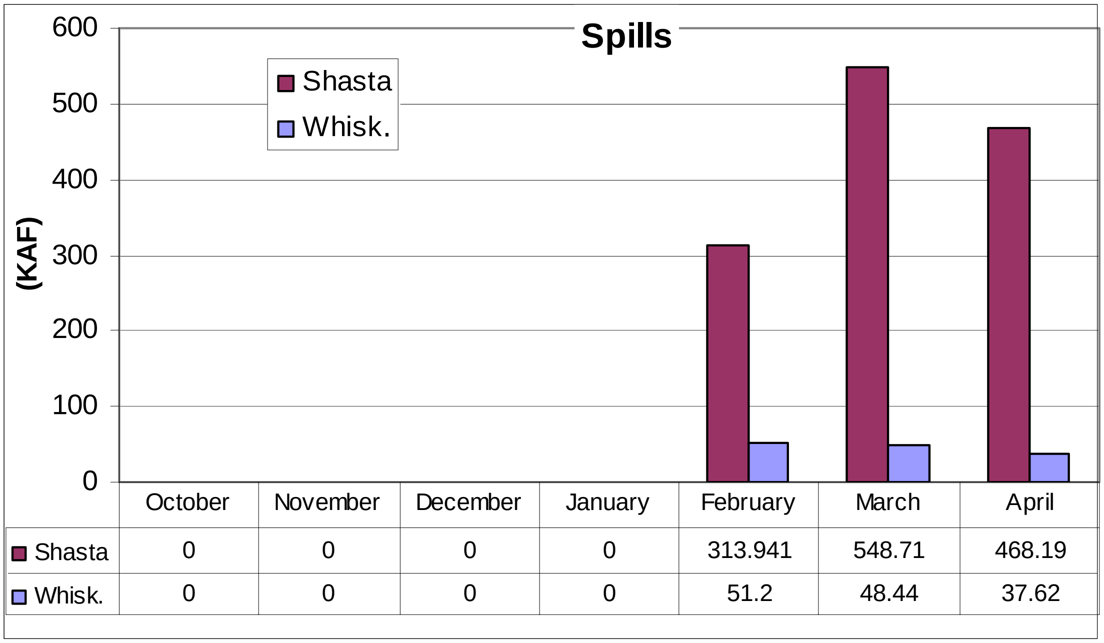

Figure 4. Monthly spill for the LP rule for quantity

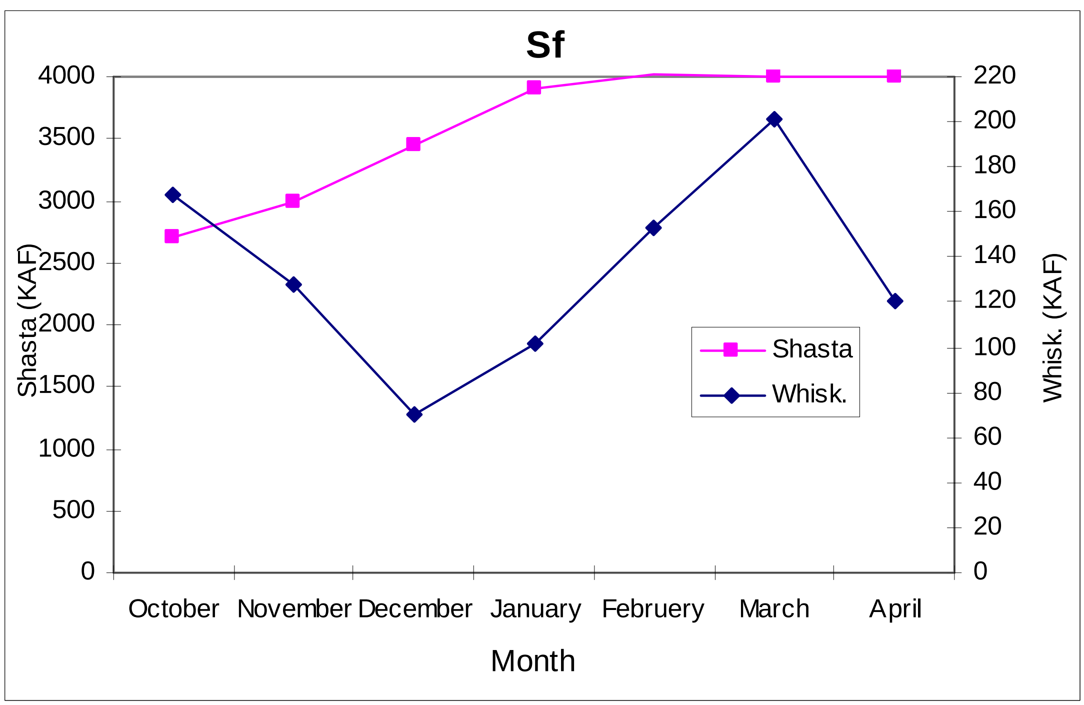

Figure 5. Monthly final storage for the LP rule for quality

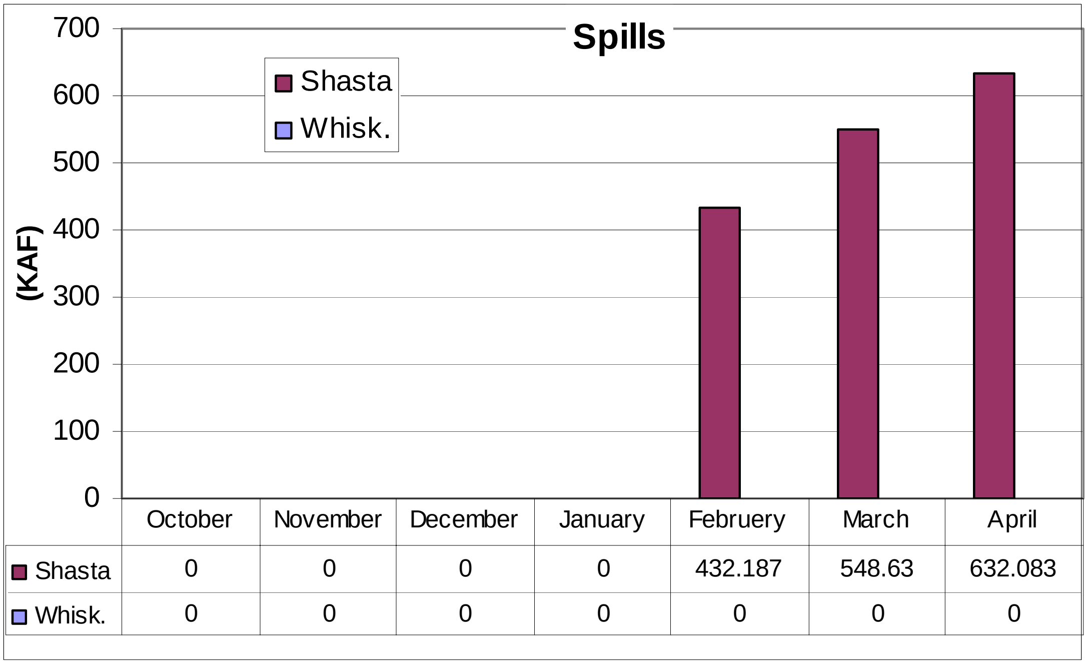

Figure 6. Monthly spill for the LP rule for quality

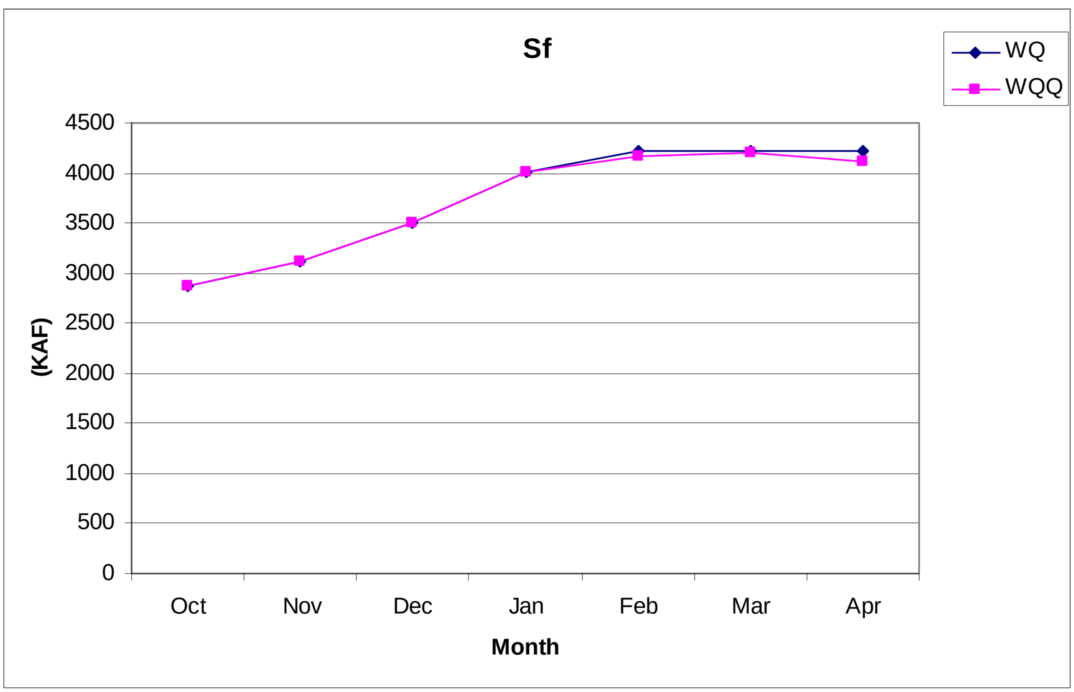

Figure 7. Comparison of the total final storage between water quantity and water quality rules

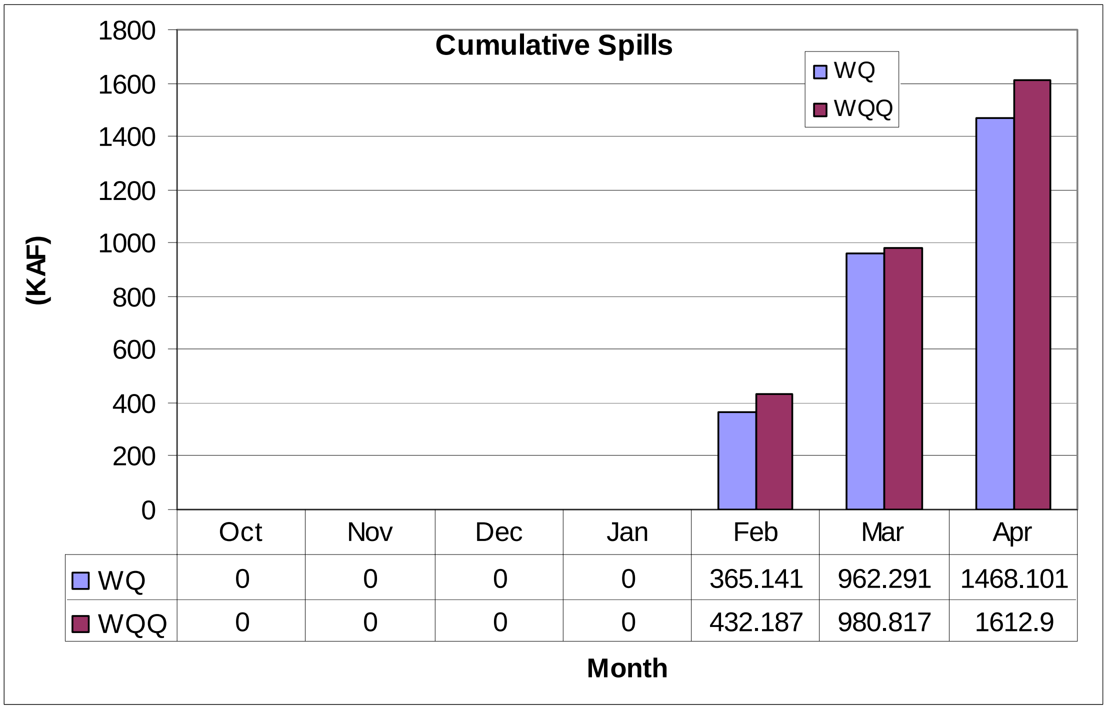

Figure 8. Comparison of the cumulative spills between water quantity and water quality rules

References

Arnold, U. and Orlob, G. T. (1989). “Decision support for estuarine water quality management.” J. Water Resour. Plng. and Mgmt., ASCE, 115(6), 775-792.

Bower, B. T., Hufschmidt, M. M., and Reedy, W. W. (1966). “Operating procedures: Their role in the design of water–resource systems by simulation analyses”. Design of water-resource system. A. Maass etal., eds., Harvard University Press, Cambridge, Mass., 443-458.

Chapra, S. C. (1997). “Surface water-quality modeling”. McGraw-Hill, New York.

Clark, E.J. (1950). “New York control curves” J. AWWA, 42(9), 823-827.

Clark, E.J. (1956) “Impounding reservoirs” J. AWWA, 48(4), 349-354. Engineering manual: Engineering and design, Hydropower. (1985). EM 1110-1701, U.S. Army Corps of Engineers, Washington, D.C.

Costa, J. R., and Loucks, D. P. (1987). “Water quality management in the Ave River: From research to practice.” System Analysis in Water Quality Mgmt., Proc., IAWPRC Symp.

de Azevedo, L.G. T. (1994). “Integration of water quantity and quality in multi-sector river basin planning.” PhD thesis, Dept. of Civ. Engrg., Colorado State University, Fort Collins, Colo.

de Azevedo, L. G. T., Gates, T. K., Fontane, D. G., Labadie, J. W., and Porto, R. L. (2000). “Integration of water quantity and quality in strategic river basin planning.” J. Water Resour. Plng. And Mgmt., ASCE, 126(2), 85-97

Dai, T. and Labadie, J. W. (2001) “River basin network model for integrated water quantity/quality management.” J. Water Resour. Plng. and Mgmt., ASCE,, 27(5). 295-305.

Gu, R. R., and Li, Y. (2002). “River Temperature sensitivity to hydraulic and meteorological parameters”. Journal of Environmental Management 66, 43-56.

Hayes, D., Labadie, J., Sanders, T., and Brown, J. (1998). “Enhancing water quality in hydropower system operations.” Water Resour. Res., 34(3), 471-483.

Johnson, S.A., Stedinger, J.R. and Staschus, K. (1991). “Heuristic operating policies for reservoir system simulation.” Water Resour. Res., 27(6), 673-685.

Labadie, J. (1997) “Reservoir system optimization models”. Water Resoruces Update, University Council on Water Resources, 108(Summer), 83-110.

Loftis, B., Labadie, J. W., and Fontane, D.G. (1985). “Optimal operation of a system of lakes for quality and quantity.” Computer applications in water resources, H.C. Torno ed., ASCE, New York, 693-702.

Lund, J.R., and Guzman, J. (1996). “Developing seasonal and long-term reservoir system operation plans using HEC-PRM.” Tech. Rep. No. RD-40, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif.

Lund, J. R., and Guzman, J. (1999). “Derived operating rules for reservoirs in series or in parallel.” J. Water Resour. Plng. and Mgmt., ASCE,. May/June.143-153.

Mehrez, C., Percia, C., and Oron, G. (1992). “Optimal operation of a multisource and multiquality regional water system.” Water Resour. Res., 28(5), 1199-1206.

Orlob, G., and Simonovic, S. (1982). “Reservoir operation for water quality control.” Experience in operation of hydrosystems, Water Resources Publications, Highlands Ranch, Colo., 263-285

Sand, G. M. (1984). “An analytical investigation of operating policies for water-supply reservoirs in parallel.” PhD dissertation, Cornell University, Ithaca, N.Y.

Tu, M-Y., Hsu, N-S., Yeh, W-G. (2003). “Optimization of Reservoir Management and Operation with Hedging Rules”. J. Water Resour. Plng. and Mgmt., ASCE, 129(2), 86-97

Willey, R.G., Smith, D.J., and Duke Jr, J. H. (1996). “Modeling water-resource systems for water-quality management”. J. Water Resour. Plng. and Mgmt., ASCE, May/June, 171-179

Wu, R.S. (1998). “Derivation of balancing curves for multiple reservoir operation.” MS thesis, Dept. of Civ. and Envir. Engrg., Cornell University, Ithaca, N.Y.