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Refill and Drawdown Rules for Parallel Reservoirs: Quantity and Quality

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Abstract

This paper presents two operating rules for the refill and drawdown seasons of reservoirs in parallel for water supply, considering water quality. For the refill season a Linear Programming form of the New York City Rule is developed. Another Linear Programming form based on equalizing the probability of emptying each reservoir is developed for the drawdown season. Both formulations are extended to consider stratified water quality in the reservoirs and a water quality requirement for a downstream demand. The refill rule is applied to Shasta and Whiskeytown reservoirs in California (USA). The drawdown rule is applied to Alarcón and Contreras reservoirs in the Júcar Basin (Spain). The results of these applications show the effect of a water quality consideration in water supply operation.

Keywords: Integrated management. Operations Research. Water quality and management. Reservoir Optimization

Introduction

Historically, water quantity and water quality concerns have been separated, with most attention given to the provision of required water quantities (de Azevedo at al. 2000).. Considering both aspects in a common strategy is commonly advocated (Loucks 1981, Arnold and Orlob 1989, Strzepek and Chapra 1990). Many approaches have tried to consider both aspects for specific problems for lake management (Loftis et al. 1985), water supply operation (Mehrez et al. 1992), and hydropower operations (Hayes et al 1998).

Several water management Decision Support Systems (DSS) also 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 (Azevedo et al 2000; Wu et al. 1996), the same DSS is considered with classical water quality models in a trial and error linkage. However, in this approach water quality remains separated from the primary water operation process.

This paper establishes and illustrates application of an improved formulation of the LP-NYC rule and develops new rules for water quantity and quality considerations with multiple water qualities in each reservoir. First an improved formulation of the LP-NYC refill rule for parallel reservoirs is developed for minimizing physical spill, energy spill, or water quality spill. Second a new refill rule is proposed to consider multiple water qualities in each reservoir with simple stratification and a downstream water quality constraint, with illustrative application to the Shasta-Wiskeytown system in California (USA). Then drawdown season rules are developed, applying the LP-NYC rule isea to Wu's (1988) drawdown rule, with illustrative application to the Alarcón and Contreras reservoirs in the Júcar Basin (Spain). Given the practical complexity of reservoir operations and physical processes, these results should be seen as having primarily theoretical and conceptual value, although the numerical linear programming formulation should facilitate a more flexible and complex representation of reservoir operations objectives and reservoir processes.

Refill Season Rules

Despite the development and growing use of optimization models (Labadie 2004), most reservoir planning and operation studies are based on simulation modeling and thus require intelligent specification of operating rules. Lund and Guzman (1996, 1999) reviewed derived single-purpose operating rules for reservoirs in series and in parallel for different purposes, with derived rules supported by conceptual or mathematical deduction for explicit operating objectives and constraints. 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 (NYC) (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 minimizing physical spill and 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 distributional 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 program. Advantages of this approach is the possibility of incorporating other constraints into the model and the direct application of the concept in system management. All of these rules can be modified to consider hydropower spills or differing aggregate water quality values between reservoirs.

Linear Programming Refill 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 of all reservoirs, minimizing the expected value of total spill. Figure 1 represents the schematic of the problem. The LP problem is solved for each time step. The objective function minimizes the value of spilled water from the current step to the end of the refill season over a set of m equally-likely refill season inflows. 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) $$L_{ij} - E_{ij} = S_{fi} + CQ_{ij} - K_i \quad \forall \text{ i and j}$$

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

(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 i

d = Demand for 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

Q_i = forecast inflow to reservoir i for the current period

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 = dimensionless coefficient (>1)

R_i = relase from reservoir i.

The weight of the spill (h_i) 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 represents 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. The dimensionless coefficient α is necessary because if L_{ij} is greater than zero for all the years, the model can reduce the value of the variable S_{fi} to minimize the total summation. The value of α depends on the characteristics of the system and on the h_i coefficients established, but should always exceed 1 to discourage spills in the immediate period. 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) is the value of spill for all reservoirs over all hydrologic years, (m* average spill from all reservoirs). 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 2). Equation (3) represents the continuity balance in the current period. Equation (4) represents the aggregate supply of the downstream demand. Equation (5) limits end-of-period storages in the current period to not exceed reservoir storage capacities.

Linear Programming Refill Rules for Quality

Due to stratification of the reservoirs, water quality characteristics and values differ for each stratification pool. The LP rule has been adapted to consider water quality both within and between reservoirs. The reservoirs have been fragmented into different pools within which water quality value is the same. The model also considers different water qualities for the inflows. Finally there is a quality target for the downstream demand. The model assumes reservoir outlet structures can release from the different pools and that stratification is constant over the refill season. Figure 2 shows a diagram of the problem. The formulation of the model is as follows:

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

Subject to:

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

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

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

$$\sum_{i=1}^{n}\sum_{l=1}^{r} R_{il} = d \tag{10}$$

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

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

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

l, w = water quality pool indices.

The objective function has the same terms but with a new subscript index representing the pool. The LP model has changed to consider the quantities of the spills of each pool.

Moreover the weight is applied to the different spills and not only to the different reservoirs. This allows improving the management of the system for water quality both within and between reservoirs. The quantity of the spill from each pool is considered in equation (7). At a given time, spills from one pool will depend on total storage and spills from other pools.

The sum of pool storages cannot exceed reservoir capacity (Equation 9). Equation (10) sets the water demand quantity. Finally, Equation (11) incorporates a requirement of blended water quality demand downstream (such as downstream instream temperature), where blended water quality must not exceed a concentration target T_t. This model can be applied to any water quality variable that stratifies 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 rules are applied to 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. GAMS (Brooke et al., 1992) software was used to solve the models. Figures 3, 4, and 5 compare the results of the water quantity and water quality models.

Quantity Example

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, representative capacity values were chosen for this simulation, 4940 hm^3 for Shasta and 272 hm^3 for Whiskeytown. The initial storages (S_{oi}) for the first month of the refill season are 3083 and 247 hm^3 for Shasta and Whiskeytown respectively. For the other months the initial storage is the final storage obtained by the model in the previous month. For the forecast inflows (Q_i) an average value of the historic inflows has been used. However, this value could be replaced by any better hydrology forecast estimate. The value of downstream demand (d) is set as 30% of average combined 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.

For this case the refill season covers October until April. For each month the linear program defined by equations (1) to (5) is solved. Table I shows the results for each refill month, assuming average inflows (Q_i) for each current month. Table I illustrates that most releases come from Shasta. This is because the spills in Shasta are very high. The spills start for both reservoirs in February. To minimize the total expected value of spill in December and January, Whiskeytown is full while Shasta has available storage capacity. Because both reservoirs are full at the end of January, in the next months the releases and spills come from both reservoirs. February spill from Shasta exceeds all spills from Whiskeytown for the entire refill season. The system ends the refill season with both reservoirs full (for this scenario where actual monthly flows are their averages over all m years of record).

Quality Example

The LP Rule for Quality is applied to the same example, with temperature as the water quality variable. Some modifications have to be done 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 759 hm^3 and 2468 hm^3 for Pool 1 and Pool 2 respectively. For Whiskeytown the values are 173 and 74 hm^3. Due to the unavailable series of inflows for different temperatures, inflows have been disaggregated into two new series with different temperatures. In disaggregating inflows 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. Cold water is better for downstream salmon habitat. The target temperature downstream is 15 ^{0}C. High temperatures (more than 25ºC) are dangerous for salmon and their reproductive activities.

With these new data, the linear programming rule for quality has been solved for the same refill season (where actual monthly flows are set to their averages). Table II summarizes the results. Figure 4 shows the effect of the downstream temperature requirement in Whiskeytown. The release of the coldest water is needed to achieve the temperature goal. This causes releases in the first three months come from both reservoirs. In February spill from Shasta occurs from both pools for the same reason. This requires some release from Whiskeytown in April to reduce downstream temperature.

Comparison of the two Rules

Management of the system under the Quality Rule must produce more physical spill than the Quantity Rule because the additional constraints. Moreover, the behavior of the models differs because of the different spill weight coefficients. Otherwise, for this example the quantity and quality results are very similar. Figures 5 compares 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 122 hm^3 less. Moreover for the "quality case" total spill is 179 hm^3 greater. However this spill represents only 3.5% of the total inflow in the refill season (5187 hm^3).

Drawdown Season Rules

The above linear-program-based balancing rules for refill of parallel reservoirs can be adapted to drawdown season operations. General theory of drawdown among parallel reservoirs is pioneered by Wu (1988). This work extends these concepts to develop linear-programming-based drawdown rules. A slight difference from Wu's work is that our general objective here is to maximize the expected value of water retained at the end of the drawdown season, rather than equalizing the probability of emptying the parallel reservoirs.

Drawdown Rule for Weighted Water Quantity

A reasonable objective for drawdown among parallel reservoirs might be to maximize the expected value of weighted water quantity. This is done with the following linear program. In developing drawdown season rules, it is assumed that the possibility of spills can be neglected during each period in the drawdown season.

$$(12)\qquad MAXZ = \sum_{j=1}^{m}\sum_{i=1}^{n} h_i V_{ij}$$

Subject to:

$$(13)\qquad V_{ij} = S_{fi} + CQ_{ij} - e_{ij}S_{fi} - Fs_{ij}S_{fi}\ \ \forall \text{ i, and j}$$

$$(14)\qquad S_{fi} = S_{oi} + Q_i - R_i\ \forall \text{ i}$$

$$(15)\qquad \sum_{i=1}^{n} R_i Fr_i = d$$

$$(16)\qquad S_{fi} \geq 0\ \ \forall \text{ i}$$

$$R_i \geq 0;\ S_{fi} \geq 0; V_{ij} \geq 0\ \ \forall \text{ i, and j}$$

Here terms are defined as they were in the refill formulations, with the additional terms,

V_{ij} = Volume of water in reservoir i at the end of the drawdown season for hydrologic year j

e_{ij} = average cumulative proportion of storage evaporated from reservoir i for hydrologic year j over the remainder of the drawdown season.

Fs_{ij} = average cumulative proportion of seepage from reservoir i for hydrologic year i over the remainder of the drawdown season

Fr_i = Coefficient representing the loss of releases from reservoir i due to seepage from the river.

The coefficient h_i represents the value of the water in each reservoir. In hydropower systems it represents the economic value of the water due to energy production. In a water supply system the coefficient Fr_i depends on seepage from each river. This formulation assumes there is no shortage to demands, no spills, and seepage is proportional to the flow. Including seepage and evaporation coefficients for storage and releases allows the model to consider such losses in allocating drawdown season storages among parallel reservoirs.

Drawdown Season Rule for Water Quality Releases

Where reservoirs are not homogeneous pools in terms of water quality, perhaps due to stratification, and outlet structures allow water to be drawn flexibly from different stratified pools, a reasonable objective for drawdown might be to maximize the expected value of pool-weighted water quantity at the end of the drawdown season, where, h_{il} represents the value of water stored in reservoir i and pool l. This is done with the following linear program.

(17) $$MAXZ = \sum_{j=1}^{m} \sum_{i=1}^{n} \sum_{l=1}^{L} h_{il} V_{ijl}$$

Subject to:

(18) $$V_{ijl} = S_{fil} + CQ_{ijl} - e_{ijl} S_{fil} - Fs_{ijl} S_{fil} \quad \forall \text{ i, and j}$$

(19) $$S_{fli} = S_{oil} + Q_{il} - R_{il}, \forall i, l \ \forall \text{ i}$$

(20) $$\sum_{i=1}^{n} \sum_{l}^{L} R_{il} Fr_i = d$$

(21) $$\sum_{i=1}^{n} \sum_{l}^{L} \left(R_{il}. Fr_i T_{il} \right) \geq T_t \sum_{i=1}^{n} \sum_{l}^{L} \left(R_{il} Fr_i \right)$$

(22) $\sum_{l}^{L}\left(R_{il}.Fr_{i}T_{il}\right) \geq T_{ti}\sum_{l}^{L}\left(R_{il}Fr_{i}\right)\ \forall$ i

$S_{fil} \geq 0\,;\ R_{il} \geq 0\,;\ V_{ijl} \geq 0\ \ \forall$ i, j, and l

where the index l indicates a particular water quality pool. T_t represents a blended water quality concentration target downstream and T_{ti} is a different water quality target immediately downstream each reservoir. In this formulation two water quality constraints are included, just downstream each reservoir and after the confluence where waters are mixed.

This particular formulation does not allow mixing or transfers of water quality among pools. For simple mass transfers among stratified layers, a simple modification in equation (23) can be done:

(23) $V_{ijl} = S_{fil} + CQ_{ijl} + (m_{ijl}V_{ijl} - m_{ijl+1}V_{ijl+1}) - e_{ijl}S_{fil} - Fe_{ijl}S_{fil}$,

where m_{ijl} represents a constant transfer coefficient of water between pools j and l in reservoir i.

Example application of the drawdown case

In this case two parallel reservoirs, Alarcón and Contreras, in the Júcar river (Spain) have been used to apply both models. The example has been applied to one drawdown season for the two models. Again, GAMS solved the models.

Quantity Example

With a capacity of 1,112 and 463 hm^3 respectively, Alarcón and Contreras reservoirs are the main regulating reservoirs in the Jucar system in eastern Spain. The available series of inflows include data from 1941 to 2001. Initial storages are 530 and 240 hm^3 for Alarcón and Contreras in the beginning of May. The period simulated starts in May and ends in August. Downstream demand, 725 hm^3/month, is the sum of agricultural uses in the basin. The weight coefficients h_i are 0.5 for each reservoir. Evaporation and seepage coefficients have been obtained from previous research. The evaporation is similar in both reservoirs but Contreras reservoir has more seepage. Currently, near-river pumping downstream of Alarcón has caused significant seepage to the aquifer from the river.

The simulation results are shown in Table IV. At the end of June, Contreras reservoir is empty and remains empty until the end of August. Releases from Alarcón start in June due to insufficient water in Contreras. At the end of the drawdown season, Contreras is empty and Alarcón ends with 224 hm^3.

Quality Example

As in the refill model, the quality variable chosen is temperature. In this case, the temperature target varies monthly with temperature targets downstream of each reservoir and at their confluence. 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). The water quality is represented as follows. Two pools, epilimnion and hypolimnion, are considered in each reservoir. Temperatures and targets vary over the season, as described in Table III. Initial storages for each pool for Alarcón are 190 and 458 hm^3 for epilimnion and hypolimnion respectively. For Contreras the values are 89 and 208 hm^3. The weight coefficients are the same for each pool and each reservoir. The evaporation and seepage coefficients are the same as in the water quantity model.

Table V shows the results for this drawdown water quality case. For the first month, May, all releases come from the hypolimnion of Contreras. In all other months, all pools of all reservoirs are used. This use of all pools is due to temperature targets downstream of the reservoirs. In Contreras, water from the hypolimnion is used in almost all months.

Comparison of the two rules

Figures 6 and 7 compare the final storages and releases of each reservoir for each month for the water quantity and water quality simulations. Figure 8 compares cumulative total releases. Water quantity inefficiency increases when quality constraints are added, but the difference is small, less than 6 hm^3. The other difference is that while the quantity model ends the drawdown season with all the water in Alarcón, the quality model ends the season with water in both reservoirs.

Conclusions

The NYC method rule for refill season operation of parallel reservoirs has been reformulated as a linear program for water quantity and quality. For the drawdown season, a new LP rule based in Wu's rule is developed. The two examples demonstrate the methods and their potential usefulness. Both approaches provide a simple way to derive preliminary operating policies for parallel reservoirs. Water quality requirements downstream of each and all reservoirs can be considered in the LP rules. For the examples developed, the environmental requirements can significantly influence optimal management. This is particularly evident for the drawdown season rule example. Such rules integrate water quality aspects explicitly into the representation and management of the reservoirs.

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Tables and Figures

hm3		Exp. Inflows		Releases		Initial Storage		Final Storage		Month's Spills		Season Ev Spills	
	Demand	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.
October	93	302	6	68	24	3083	247	3317	228	0	0	3096	231
November	132	422	17	123	8	3317	228	3615	237	0	0	2976	222
December	206	655	33	178	28	3615	237	4092	242	0	0	2797	194
January	264	831	50	221	43	4092	242	4701	249	0	0	2573	150
February	305	954	63	305	0	4701	249	4940	272	410	41	1857	107
March	316	994	60	316	0	4940	272	4940	272	678	60	850	47
April	268	846	46	268	0	4940	272	4940	272	578	46	0	0
									TOTAL	1813			

Table I. Refill LP rule for quantity results

hm3			Exp. Inflows		Releases		Initial Storage		Final Storage		Month's Spills		Seasonal EV Spills	
		Demand	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.	Shasta	Whisk.
October	Pool 1	93	91	4	0	46	615	173	706	131	0	0	0	63
	Pool 2		212	2	46	0	2468	74	2633	76	0	0	3124	138
November	Pool 1	132	84	13	0	66	706	131	790	77	0	0	0	45
	Pool 2		338	4	66	0	2633	76	2905	80	0	0	3034	121
December	Pool 1	206	79	30	0	103	790	77	869	4	0	0	0	35
	Pool 2		576	3	103	0	2905	80	3378	83	0	0	2838	116
January	Pool 1	264	265	30	187	12	869	4	947	22	0	0	0	23
	Pool 2		566	20	65	0	3378	83	3878	104	0	0	2573	126
February	Pool 1	305	267	41	305	0	947	22	561	63	347	0	0	7
	Pool 2		688	22	0	0	3878	104	4402	126	186	0	1857	99
March	Pool 1	316	397	48	316	0	561	63	185	111	457	0	0	0
	Pool 2		596	12	0	0	4402	126	4755	138	221	0	850	46
April	Pool 1	268	402	38	121	147	185	111	0	2	466	0	0	0
	Pool 2		444	9	0	0	4755	138	4940	146	315	0	0	0
										TOTAL	1992			

Table II. Refill LP rule for quality results

Temperatures ºC					
		May	June	July	August
Alarcón	Epilimnion	15	18	22	25
	Hypolimnion	13	14.5	15	17
	Target	18	18	18	18
Contreras	Epilimnion	12	14.5	15.3	16.8
	Hypolimnion	10.5	11	12.1	12.5
	Target	12	12	14	14
	Junction Target	16.5	16.5	17.5	17.5

Table III. Temperatures in the drawdown season

hm3		Exp. Inflows		Releases		Initital Storage		Final Storage	
	Demand	**Alarcón**	**Contreras**	**Alarcón**	**Contreras**	**Alarcón**	**Contreras**	**Alarcón**	**Contreras**
May	145.00	42.30	36.05	0.00	145.00	530.00	240.00	572.30	131.05
June	217.50	32.36	30.11	62.61	161.15	572.30	131.05	542.06	0.00
July	217.50	20.64	22.74	216.40	22.74	542.06	0.00	346.30	0.00
August	145.00	16.71	19.67	139.25	19.67	346.30	0.00	223.76	0.00

Table IV. Drawdown LP rule for quantity results

hm3			Exp. Inflows		Releases		Initital Storage		Final Storage	
		Demand	**Alarcón**	**Contreras**	**Alarcón**	**Contreras**	**Alarcón**	**Contreras**	**Alarcón**	**Contreras**
May	Epilimnion	145.00	12.69	10.81	0.00	0.00	159.00	72.00	171.69	82.81
	Hypolimnion		29.61	25.23	0.00	145.00	371.00	168.00	400.61	48.23
June	Epilimnion	217.50	9.71	9.03	65.11	27.71	171.69	82.81	116.38	64.12
	Hypolimnion		22.65	21.08	68.84	69.31	400.61	48.23	354.43	0.00
July	Epilimnion	217.50	6.19	6.82	33.97	23.26	116.38	64.12	88.61	47.68
	Hypolimnion		14.45	15.92	164.17	15.92	354.43	0.00	204.71	0.00
August	Epilimnion	145.00	5.01	5.90	3.06	7.38	88.61	47.68	88.57	46.21
	Hypolimnion		11.70	13.77	134.55	13.77	204.71	0.00	81.85	0.00

Table V. Drawdown Lp rule for quality results

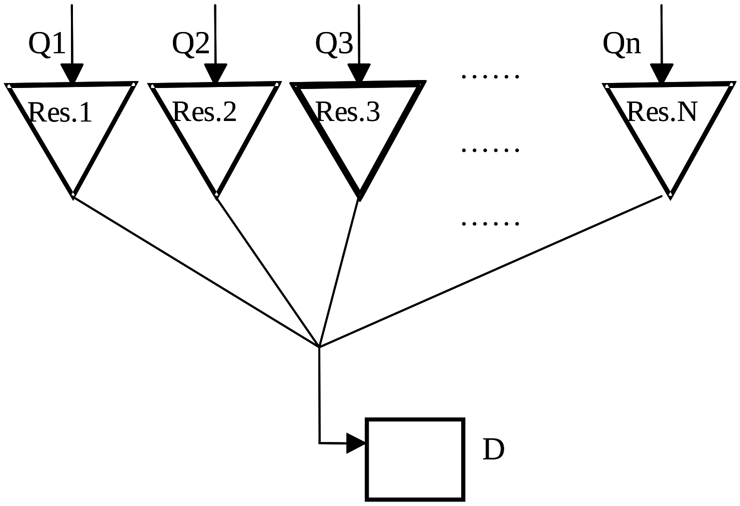

Figure 1. Schematic of reservoirs in parallel

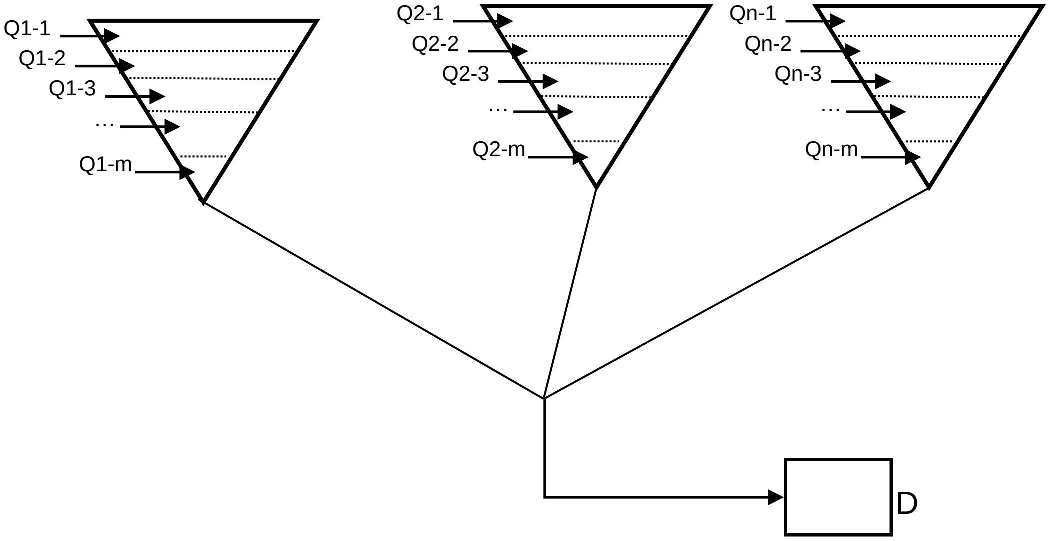

Figure 2. Schematic representation with quality

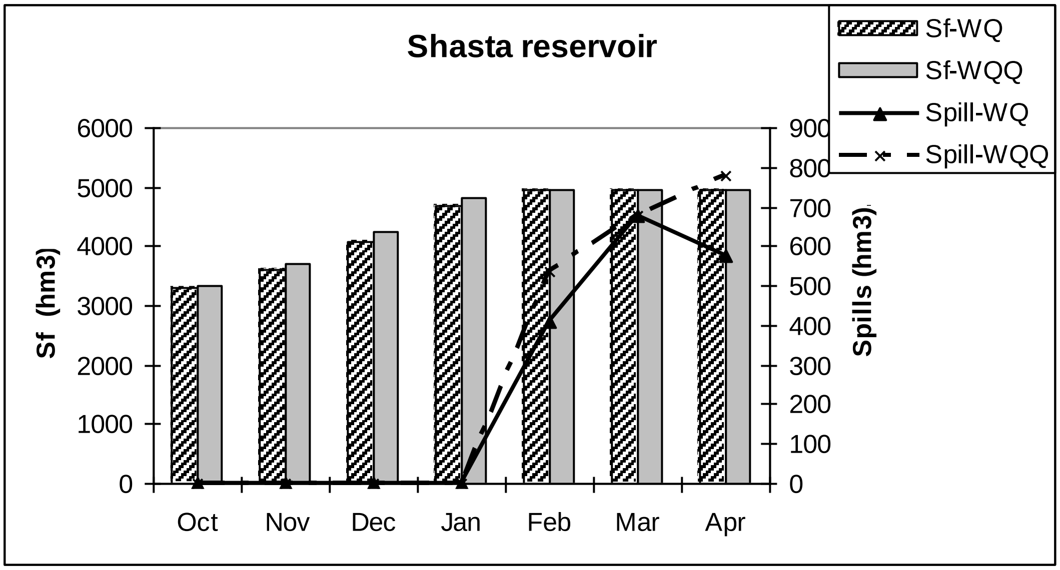

Figure 3. Results for Shasta reservoir (LP-Refill season rule).

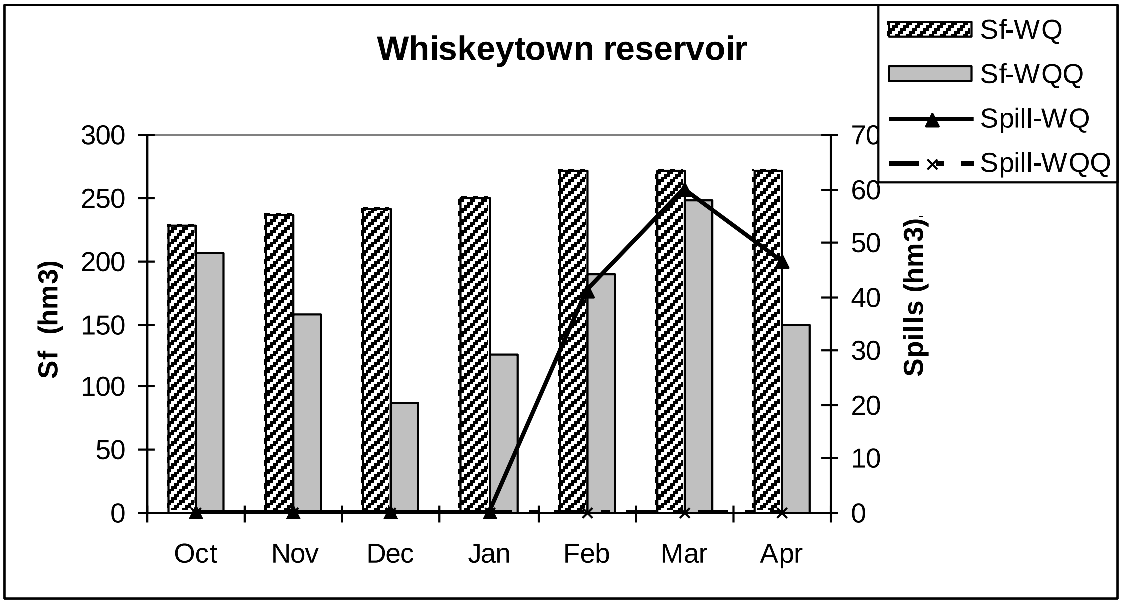

Figure 4. Results for Whiskeytown reservoir (LP-Refill season rule).

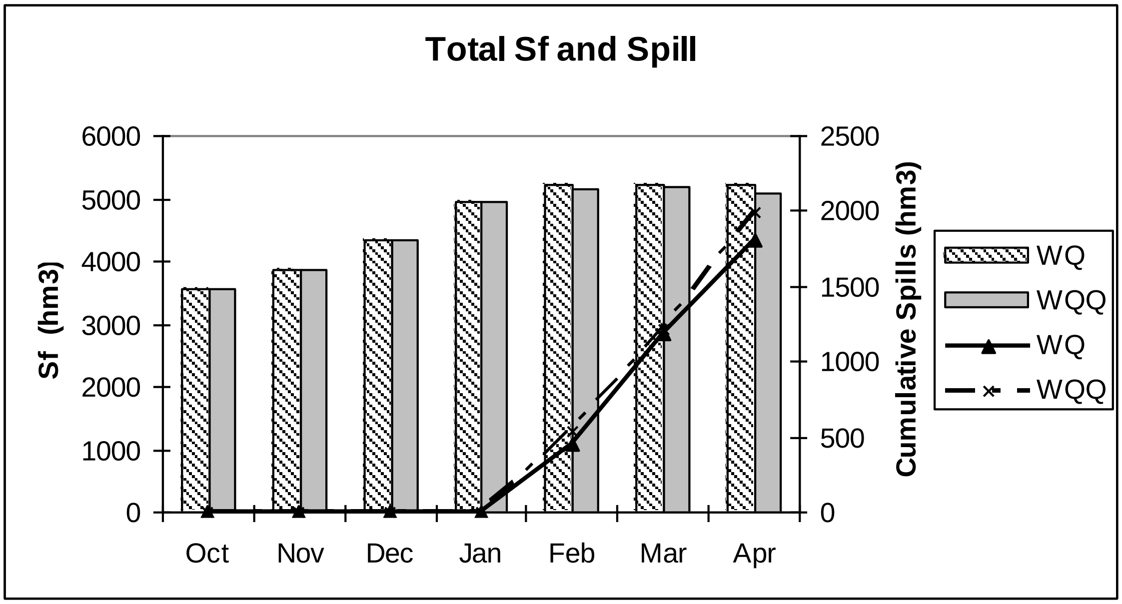

Figure 5. Global results of the LP-refill season rule.

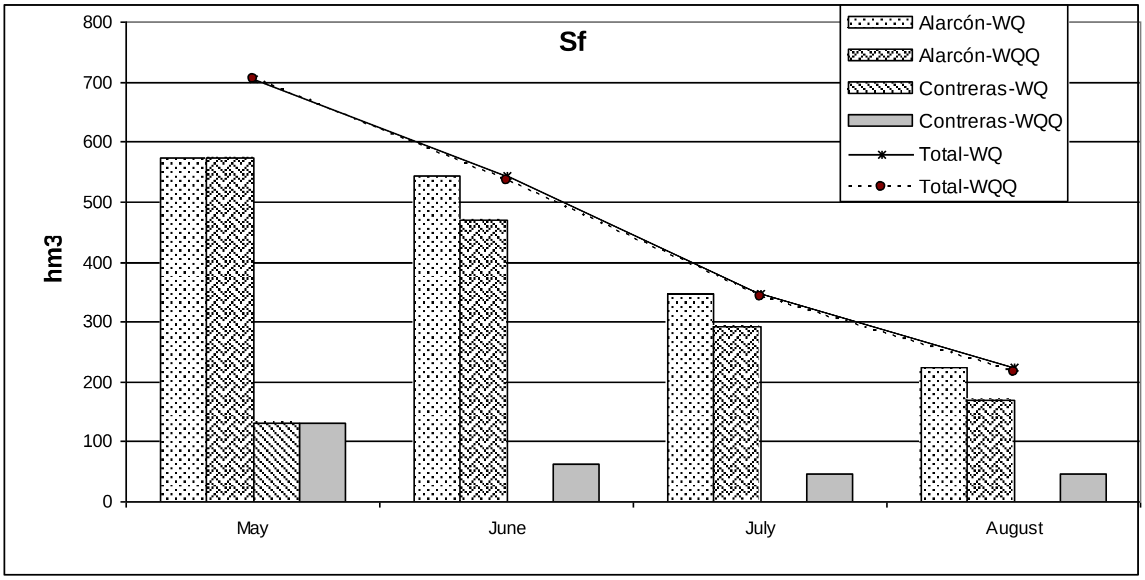

Figure 6. Monthly final storage for the drawdown LP rule

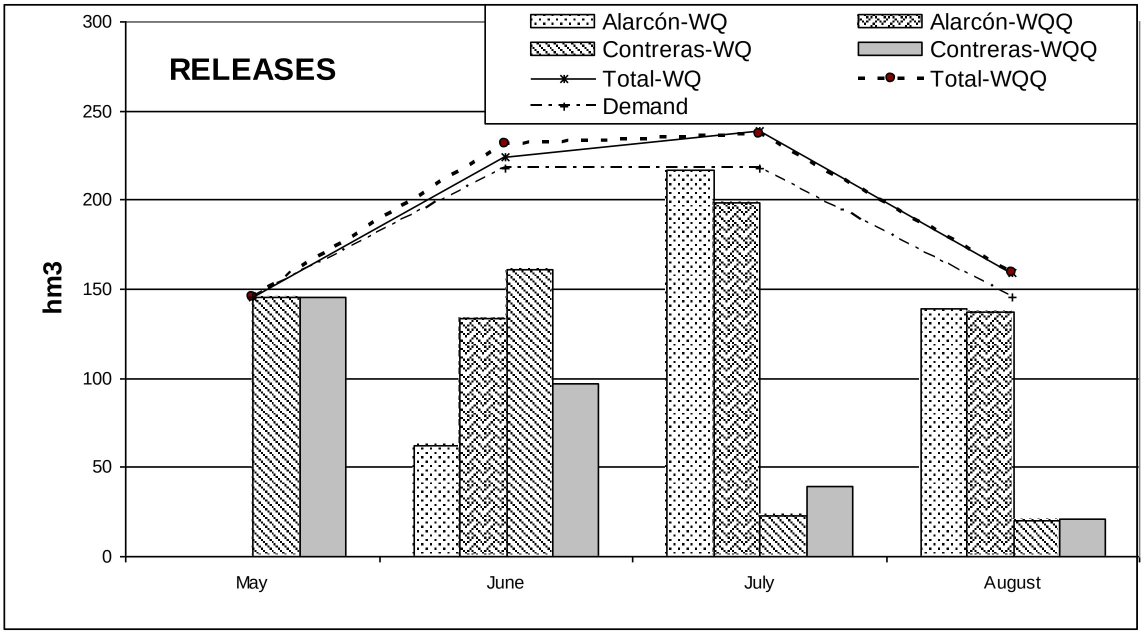

Figure 7. Monthly releases for the drawdown LP rule

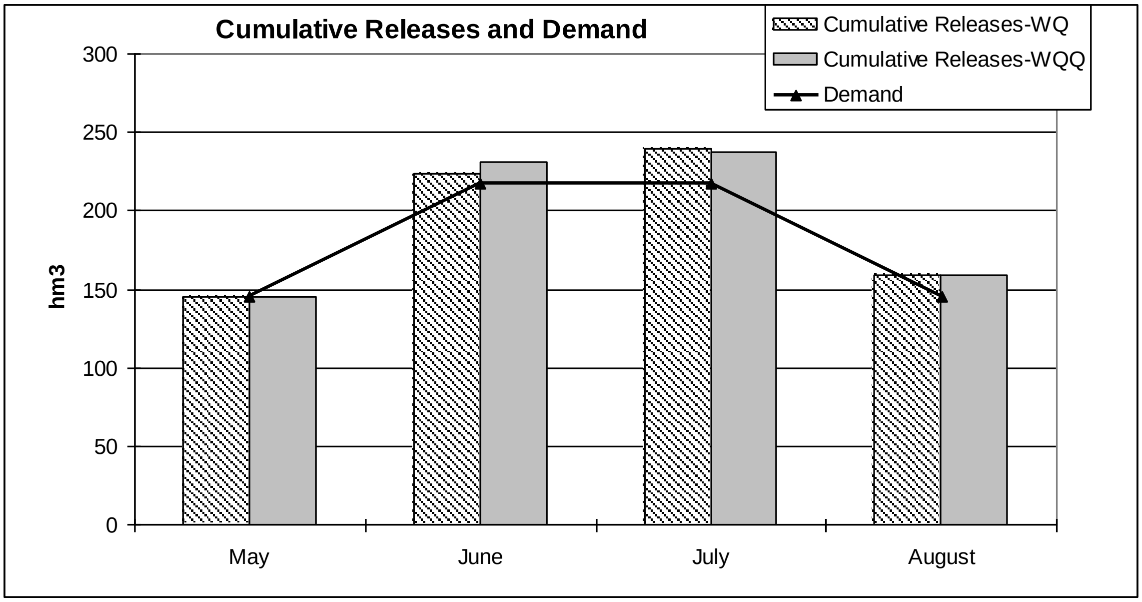

Figure 8. Cumulative releases for the drawdown LP rule