Reservoir Operation

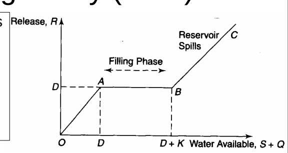
Standard Operating Policy
Optimal Policy

Reservoir Operation

- A reservoir operating policy is a sequence of release decisions in operational periods (such as months), specified as a function of the state of the system.
- The state of the system in a period is generally defined by the reservoir storage at the beginning of a period and the inflow to the reservoir during the period.
- Once the operating policy is known, the reservoir operation can be simulated in time with a given inflow sequence.
- A number of optimization algorithms have been developed for deriving reservoir operating policies. However, the most common policy implemented in practice is the so-called standard operating policy. This policy by itself is not based on or derived from any optimization algorithm.

Standard Operating Policy (SOP)

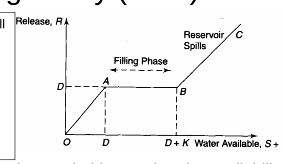
- The standard operating policy (SOP) aims to best meet the demand in each period based on the water availability in that period.
- It thus uses no foresight on what is likely to be the scenario during the future periods in a year.



- Let *D* and *R* represent, respectively, the demand and the release in a period.
- Let the capacity of the reservoir be *K*.
- The available water in any period is the sum of the storage, S, at the beginning of the period, and the inflow *Q* during the period.
- Standard operating policy for the period is represented as illustrated in Figure.
- SOP release is made as per the line *OABC* in the figure.

Standard Operating Policy (SOP)

Along *OA:* Release = water available; reservoir will be empty after release.
Along *AB:* Release = demand; excess water is stored in the reservoir (filling phase).
At A: Reservoir is empty after release.
At *B:* Reservoir is full after release.
Along *BC:* Release = demand + excess of availability over the capacity (spill)



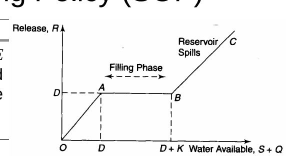
In other words, the release in any time period is equal to the availability, *S + Q,* or demand, *D,* whichever is less, as long as the availability does not exceed the sum of the demand and the capacity.

Once the availability exceeds the sum of the demand and the capacity, the release is equal to demand plus excess available over the capacity.

SOP releases need not be optimum.

Standard Operating Policy (SOP)

With evaporation loss *E* included, the standard operating policy may be expressed as



$$R_t = D_t \text{ if } S_t + Q_t - E_t \geq D_t$$
$$= S_t + Q_t - E_t, \text{ otherwise}$$
$$O_t = (S_t + Q_t - E_t - D_t) - K \text{ if positive}$$
$$= 0 \text{ otherwise}$$
$$S_{t+1} = S_t + Q_t - E_t - R_t - O_t, \text{ with } R_t \text{ and } O_t \text{ determined as above}$$

SOP – Example

Q_t, D_t and E_t are given and S_1=200

K = 350

t	Q_t	D_t	E_t
1	70.61	51.68	10
2	412.75	127.85	8
3	348.40	127.85	8
4	142.29	65.27	8
5	103.78	27.18	6
6	45.00	203.99	6
7	19.06	203.99	5
8	14.27	179.47	5
9	10.77	89.76	6
10	8.69	0.00	8
11	9.48	0.00	8
12	18.19	0.00	10

SOP – Example

Q_t, D_t and E_t are given and S_1=200

$K = 350$

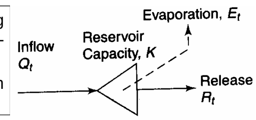
t	S_t	Q_t	D_t	E_t	R_t	S_{t+1}	O_t
1	200.00	70.61	51.68	10	51.68	208.93	0.00
2	208.93	412.75	127.85	8	127.85	350.00	135.83
3	350.00	348.40	127.85	8	127.85	350.00	212.55
4	350.00	142.29	65.27	8	65.27	350.00	69.02
5	350.00	103.78*	27.18	6	27.18	350.00	70.60
6	350.00	45.00	203.99	6	203.99	185.01	0.00
7	185.01	19.06	203.99	5	199.07	0.00	0.00
8	0.08	14.27	179.47	5	9.27	0.00	0.00
9	0.00	10.77	89.76	6	4.77	0.00	0.00
10	0.00	8.69	0.00	8	0.00	0.69	0.00
11	0.69	9.48	0.00	8	0.00	2.17	0.00
12	2.17	18.19	0.00	10	0.00	10.36	0.00

$R_t = D_t$ if $S_t + Q_t - E_t \geq D_t$
$= S_t + Q_t - E_t$, otherwise
$O_t = (S_t + Q_t - E_t - D_t) - K$ if positive
$= 0$ otherwise
$S_{t+1} = S_t + Q_t - E_t - R_t - O_t$, with R_t and O_t determined as above

Optimal Operating Policy using LP

Derivation of an optimal operating policy for a reservoir to meet a long-term objective. (classical problem)

Single reservoir operation with deterministic inflows



Objective: Maximize sum of releases

Upper limit of release is D_t.

Model aims to make the release as close to the demand as possible over the year.

To ensure that the overflows O, assume a nonzero value in the solution only when the storage at the end of the period is equal to the reservoir capacity, K, integer variables may be used.

$$\text{Max} \sum_t R_t$$

Subject to

$$S_{t+1} = S_t + Q_t - R_t - E_t - O_t \quad \forall t$$
$$R_t \leq D_t \quad \forall t$$
$$S_t \leq K \quad \forall t$$
$$R_t \geq 0 \quad \forall t$$
$$S_t \geq 0 \quad \forall t$$
$$S_{T+1} = S_1$$

LP - Example

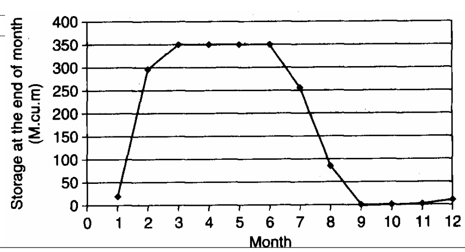
$K = 350$

t	Q_t	D_t	E_t
1	70.61	51.68	10
2	412.75	127.85	8
3	348.40	127.85	8
4	142.29	65.27	8
5	103.78*	27.18	6
6	45.00	203.99	6
7	19.06	203.99	5
8	14.27	179.47	5
9	10.77	89.76	6
10	8.69	0.00	8
11	9.48	0.00	8
12	18.19	0.00	10

LP - Solution

t	S_t	Q_t	D_t	R_t	E_t	S_{t+1}	O_t
1	10.36	70.61	51.68	51.68	10	19.29	0.00
2	19.29	412.75	127.85	127.85	8	296.19	0.00
3	296.19	348.40	127.85	127.85	8	350.00	158.74
4	350.00	142.29	65.27	65.27	8	350.00	69.02
5	350.00	103.78	27.18	27.18	6	350.00	70.60
6	350.00	45.00	203.99	39.00	6	350.00	0.00
7	350.00	19.06	203.99	108.87	5	255.19	0.00
8	255.19	14.27	179.47	179.47	5	84.99	0.00
9	84.99	10.77	89.76	89.76	6	0.00	0.00
10	0.00	8.69	0.00	0.00	8	0.69	0.00
11	0.69	9.48	0.00	0.00	8	2.17	0.00
12	2.17	18.19	0.00	0.00	10	10.36	0.00

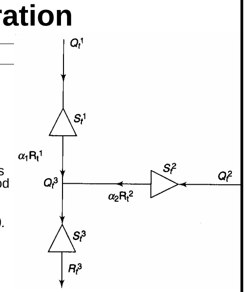
LP – Solution – Rule Curve



Re-solve the same problem with reservoir capacities 300, 400, 450 and 500 units using the same values of Q_t, D_t and E_t. Obtain the annual deficit in release for each capacity to examine whether the annual deficit can be reduced to zero by increasing the capacity.

Multi Reservoir Operation

- A multi reservoir operation problem can be formulated in a similar manner.
- Three reservoir system shown serves the purposes of water supply, flood control and hydropower generation.
- Benefits from hydropower are expressed as a function of storage alone.
- B_t^1, B_t^2 *and* B_t^3 are respectively the net benefits associated with unit release, unit available flood freeboard (= reservoir capacity - available storage), and unit storage for reservoir i in period t *(assumed to be same for 3 reservoirs).*
- A portion α_1 and α_2 of the releases made at reservoirs 1 and 2 respectively add to the natural inflow of reservoir 3.
- A minimum flood storage F^i_{min} needs to be ensured during flood season at the reservoir i.
- Maximum release that may be made at reservoir i is R^i_{max}.



Multi Reservoir Operation – LP Model

$$\max \sum_{i=1}^{3} \sum_{t=1}^{T} \left[B_t^1 R_t^i + B_t^2 (K_i - S_t^i) + B_t^3 S_t^i \right]$$

$S_{t+1}^i = S_t^i + Q_t^i - R_t^i - E_t^i - O_t^i \quad \forall t, \quad i = 1, 2$

$S_{t+1}^i = S_t^i + Q_t^i + \alpha_1 R_t^1 + \alpha_2 R_t^2 - R_t^i - E_t^i - O_t^i \quad \forall t; \quad i = 3$

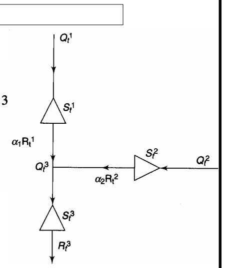
$S_t^i \le K_i \quad i = 1, 2, 3; \quad \forall t$

$K_i - S_t^i \ge F_{\min}^i \quad \forall i; \forall t \in$ Flood Season

$R_t^i \le R_{\max}^i \quad \forall i; \forall t$

$S_{T+1}^i = S_1^i \quad \forall i$

$S_t^i \ge 0; R_t^i \ge 0. \quad \forall i; \forall t$



Overflow from reservoirs 1 & 2 will also become inflows to reservoir 3

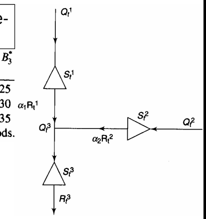
Multi Reservoir Operation – Example

Consider the data given in the table for a three-period three-reservoir system.

Reservoir	Inflow			K	Fmin			B_1^*	B_2^*	B_3^*
	t = 1	t = 2	t = 3		t = 1	t = 2	t = 3			
1	25	10	15	10	3	2	7	50	10	25
2	10	30	15	15	2	3	4	60	10	30
3	20	12	15	20	2	3	5	70	10	35

*The benefit coefficients B_1, B_2, and B_3 are assumed constant for all three periods.

$\alpha_1 = 0.2$ and $\alpha_2 = 0.3$



Example – Solution

	Reservoir 1			Reservoir 2			Reservoir 3		
	t = 1	t = 2	t = 3	t = 1	t = 2	t = 3	t = 1	t = 2	t = 3
S_t	0.0	8.0	3.0	2.0	12.0	11.0	0.0	17.0	15.0
R_t	17.0	15.0	18.0	0.0	31.0	24.0	6.4	26.3	40.8
$(K - S_t)^*$	10.0	2.0	7.0	13.0	3.0	4.0	20.0	3.0	5.0

*$(K - S_t)$ is the available flood storage in period t.

- Note that the spill from a reservoir is included in the release values shown
- Mass balance for reservoir 3 includes the contributions from the two upstream reservoirs.
- In this hypothetical example the benefit coefficients for the release are much higher than those for the flood storage. Solution will be quite sensitive to variations in these coefficients.
- It would be interesting to generate and analyze a number of solutions, varying the benefit coefficients relative to each other, for the same inflow data provided in this example.

Exercise Problem

- In a river basin there are four reservoirs. Reservoirs 1, 2 and 4 are in series. Reservoirs 3 and 4 are also in series with reservoir 3 in upstream. Reservoirs 1, 2 and 3 have power houses. Release made into the power houses subsequently reaches the immediate downstream reservoir. Each unit of power generated brings benefit of B_t in period t. The power generated at reservoir i is restricted by the plant capacity p_i. The storage elevation relationship for the reservoir i (i=1,2,3) may be assumed to be linear (known). Each unit of release made from reservoir 4 serves an irrigation area and fetches a benefit of W_t in period t. Assuming the inflows and capacities of reservoirs to be known, formulate an optimization model to maximize the benefits from the system. Identify the decision variables in the problem.
- For a 12 period problem, how many constraints and how many decision variables will result from the optimization model.

Thank You