INDIAN INSTITUTE OF SCIENCE

Water Resources Systems:
Modeling Techniques and Analysis

Lecture - 38

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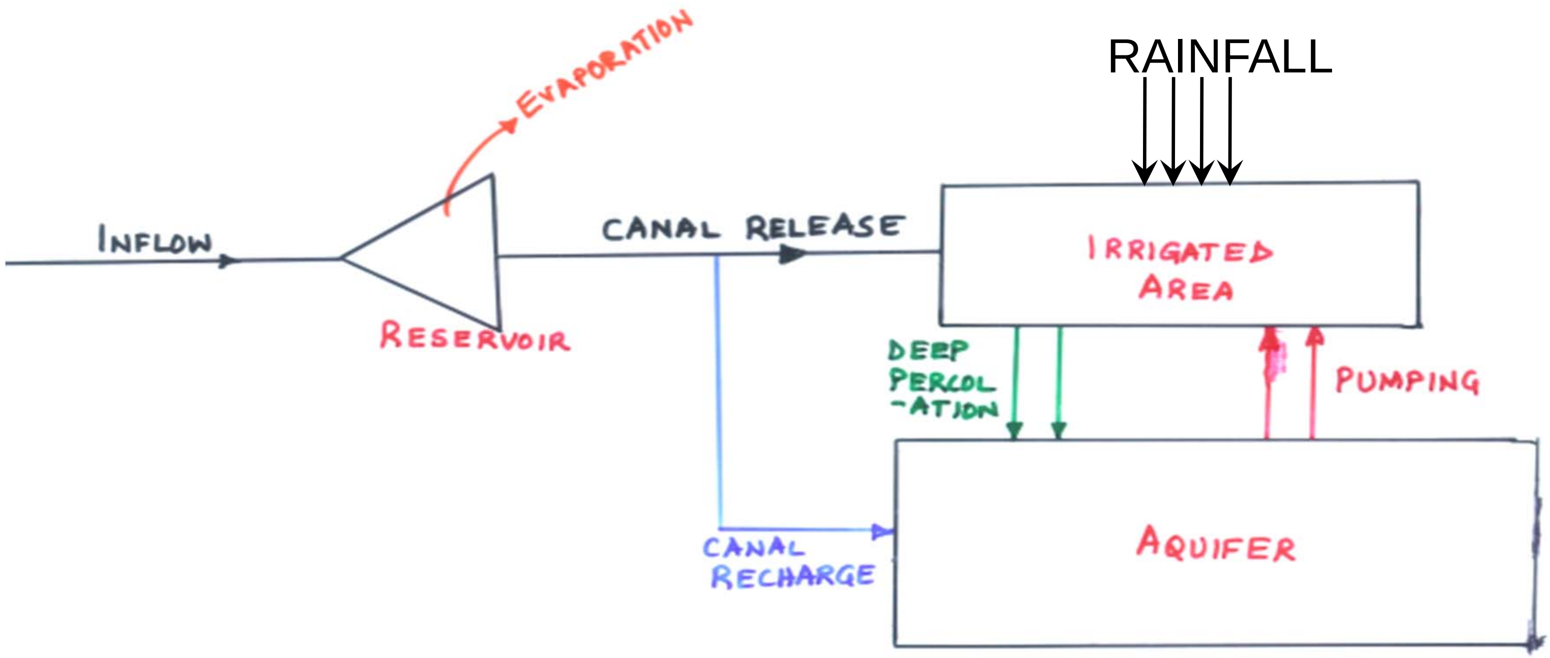
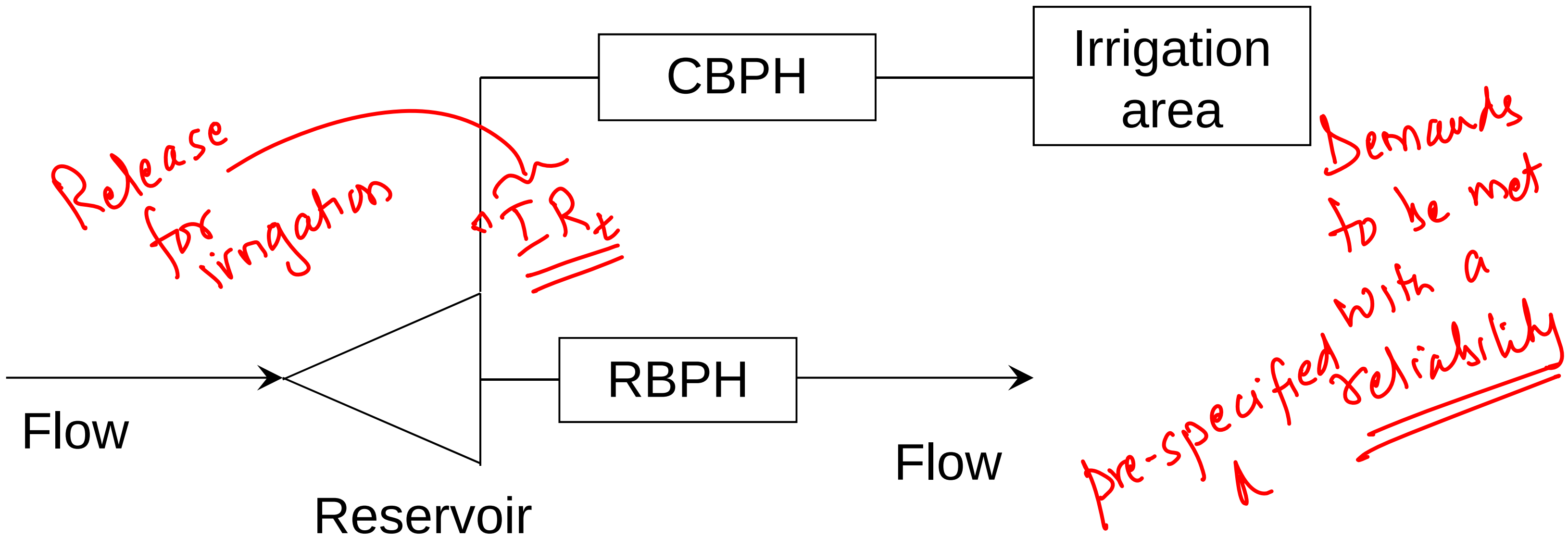
Summary of the previous lecture

Conjunctive use of surface and ground water:



HYDRO POWER OPTIMIZATION

Hydro Power Optimization



CBPH: Canal Bed Powerhouse

RBPH: Riverbed Powerhouse

Hydro Power Optimization

Reservoir operation for hydropower optimization:

- Maximize hydropower production subject to satisfying irrigation demands at a specified reliability level.
- Water drawn into irrigation canals for irrigation incidentally produces a small amount of hydropower in the powerhouses located along the canals.
- Power is produced out of the water released downstream of the reservoir in the riverbed powerhouse.
- The irrigation release into the canals is considered to be a random variable along with reservoir inflow.

Hydro Power Optimization

Only river bed power is considered for optimization

Release policy:

- The reservoir release policy is defined by a chance constraint.

$$Prob\ [IR_t \geq D_t] \geq P$$

Demand

probability of meeting demand

where IR_t is the irrigation release in period t, D_t, is the irrigation demand in period t and P is the reliability level of meeting irrigation demand.

Hydro Power Optimization

Reservoir water balance:

power release

$$S_t + I_t - IR_t - R_t - E_t = S_{t+1} \quad \forall\, t$$

evaporation

S_t is the total storage at the beginning of period t,

I_t is the random inflow into the reservoir during period t,

IR_t is the total irrigation release during period t,

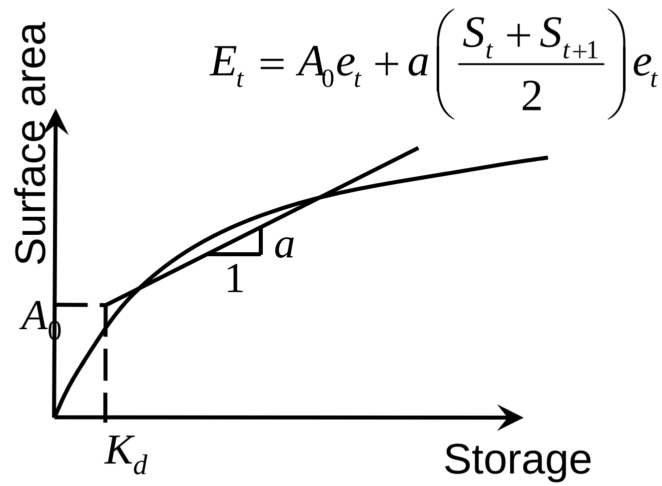
R_t is the downstream release, assumed deterministic, for bed power production during period t, and

E_t is the evaporation loss during period t

Hydro Power Optimization

E_t is approximated by a linear relationship,

$$E_t = \alpha_t + \beta_t (S_t + S_{t+1})$$



where α_t and β_t are coefficients depending on the period t.

Hydro Power Optimization

Substituting for evaporation term

$$IR_t = (1 - \beta_t)S_t - (1+\beta_t)S_{t+1} + I_t - R_t - \alpha_t$$

The chance constraint is

$$Pr[(1+\beta_t)S_{t+1} - (1 - \beta_t)S_t + R_t + \alpha_t + D_t \leq I_t] \geq P$$

Hydro Power Optimization

The deterministic equivalent is written using the linear decision rule (LDR),

deterministic

$$IR_t = S_t + I_t - R_t - E_t - b_t$$

where b_t is a deterministic parameter.

As a consequence,

Refer to Lectures 29 and 30

$$S_{t+1} = b_t$$

Effectively storage is made deterministic. E_t and R_t, both being functions of storage, are deterministic.

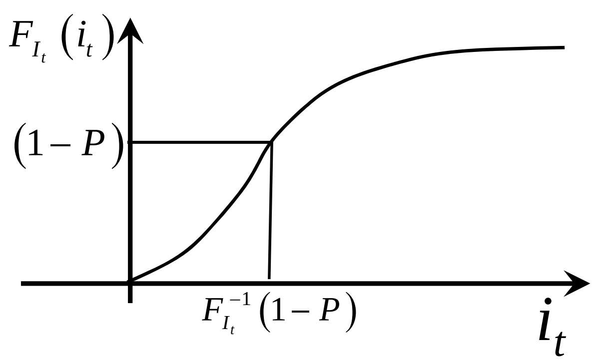
Hydro Power Optimization

Deterministic equivalent:

The deterministic equivalent of the chance constraint is

$$(1+\beta_t)b_t - (1-\beta_t)b_{t-1} + R_t + \alpha_t + D_t \le F_{I_t}^{-1}(1-P)$$

where $F_{I_t}^{-1}(1-P)$ is the reservoir inflow during period t, with probability $(1 - P)$, or exceedance probability P.



Hydro Power Optimization

Other Constraints:

Storage capacity constraints:

$$b_{t\text{-}1} \geq K_d \; ; \qquad b_{t\text{-}1} \leq K_T$$

with $b_o = b_{12}$ for a steady state solution

K_d is dead storage and K_T is total storage.

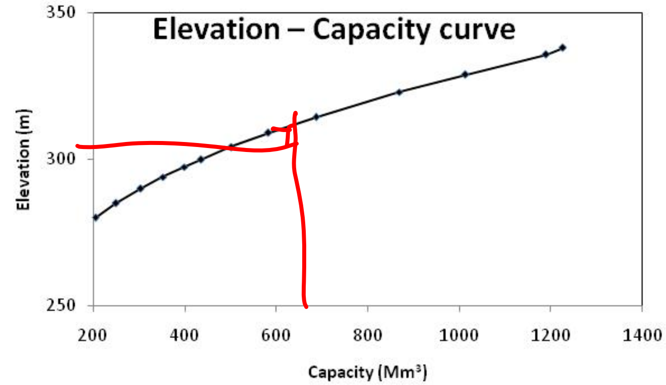
Power plant capacity:

$$EB_t \leq BC$$

EB_t is power produced in time period t

Hydro Power Optimization

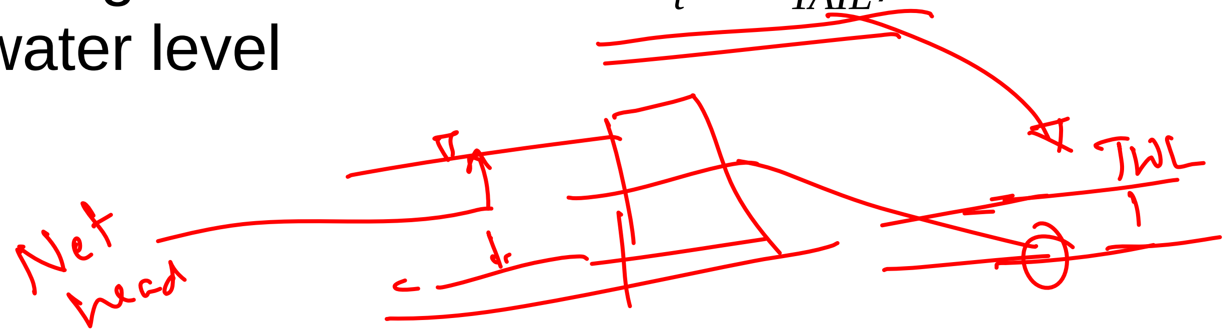
Head - Storage relationship:



$$H_t = \gamma[(b_{t\text{-}1} + b_t)/2] + \delta$$

where γ is the slope of the linear portion of the elevation-storage curve, and δ is the intercept.

The net head acting on the turbine is $H_t - B_{TAIL}$, where B_{TAIL} is the tail water level



Hydro Power Optimization

Linear approximation for power production function:

A linear approximation of the nonlinear power production term following Loucks et al. (1981) is used.

$$Q_t H_t = Q_t H_{to} + Q_{to} H_t - Q_{to} H_{to}$$

where, Q_{to} and H_{to} are the average values of Q_t and H_t, respectively.

Loucks, D.P., Stedinger, J.R., and Haith, D.A., (1981) Water Resource Systems Planning and Analysis, Prentice Hall, Inc, Englewood Cliffs, New Jersey.

Hydro Power Optimization

Known

$EB_t = c\,[R_t\,(H_t - B_{TAIL})\}$ is expressed as

$$EB_t = c\,[R_t\,(H_{to} - B_{TAIL}) + R_{to}\,(H_t - B_{TAIL}) - R_{to}\,(H_{to} - B_{TAIL})]$$

EB_t is power produced in time period t
R_{to} is the average value for the bed power release R_t, in period t, and
H_{to} is the average value for the reservoir elevation H_t in period t,
B_{TAIL} is the tail water elevation of the bed turbine, and
c is a constant to convert R_t and H_t into EB_t
(e.g., refer $P = 0.003785\;R_t\;H_t\;\eta$).

Hydro Power Optimization

The operating range of the reservoir elevation for power production is specified as,

$H_{min} \leq H_t \leq H_{max}$ for bed turbine operation, H_{min} and H_{max} being specified

Hydro Power Optimization

Objective Function:

The objective is to maximize the annual hydropower production by the bed turbine.

$$Maximize \sum_{t} EB_t$$

Lingo software

Hydro Power Optimization

Methodology

- The CCLP model is run for a specified value of P (reliability).
- Initially, the solution is obtained by assuming some reasonable values H_{to} and R_{to} for each t.
- If the values of H_t and R_t in the solution are different from these, then another run is made replacing H_{to} and R_{to} by H_t and R_t respectively.
- Thus the CCLP model is run successively each time replacing the values of R_{to} by R_t, and H_{to} by H_t, till convergence is reached.

say 0.65

Hydro Power Optimization

- The model is run for increasing values of P, till the solution becomes infeasible.
- This gives the maximum reliability possible for the given inflow data.
- The model is applied to Bhadra Reservoir in Karnataka State.

Hydro Power Optimization

Data:

- The total storage capacity of the reservoir: 2024 Mm^3,
- Dead storage capacity: 240 Mm^3.
- The installed capacity of the bed turbine: 24,000 kW.
- Inflow data of 52 years are used in the study.
- Each time a run is made for a particular value of P, the corresponding inflow sequence for the 12 months has to be used

Ref: Sreenivasan, K. R., and Vedula, S., (1996) Reservoir Operation For Hydropower Optimization: A Chance Constraint Approach, Sadhana, Vol. 21, Part 4, August, pp 503-510

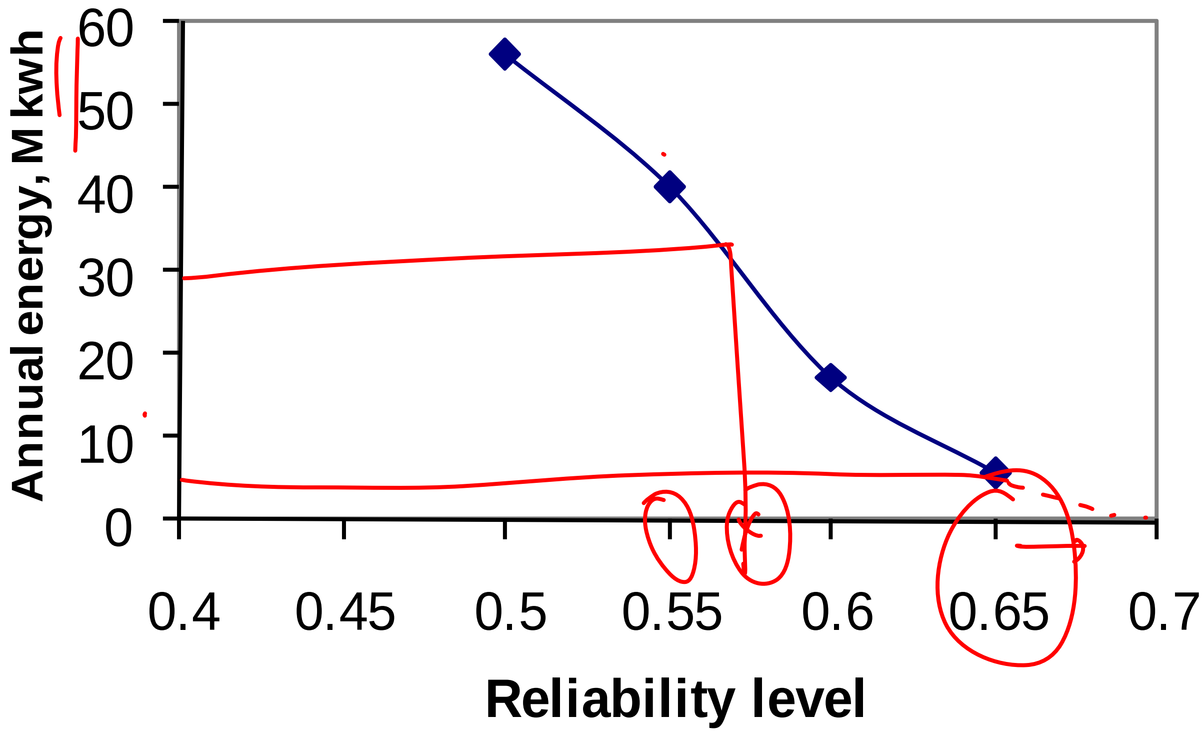
Hydro Power Optimization

Monthly inflows with P = 0.65, along with irrigation demands

Month	Inflow (Mm^3)	Irrigation demand (Mm^3)
Jun	163.40	119.90
Jul	813.20	136.80
Aug	702.97	200.60
Sep	261.73	195.80
Oct	302.81	203.20
Nov	89.31	189.70
Dec	50.52	109.40
Jan	26.93	137.30
Feb	17.10	180.10
Mar	10.64	197.39
Apr	11.70	197.90
May	11.06	178.60

Demand (Known)

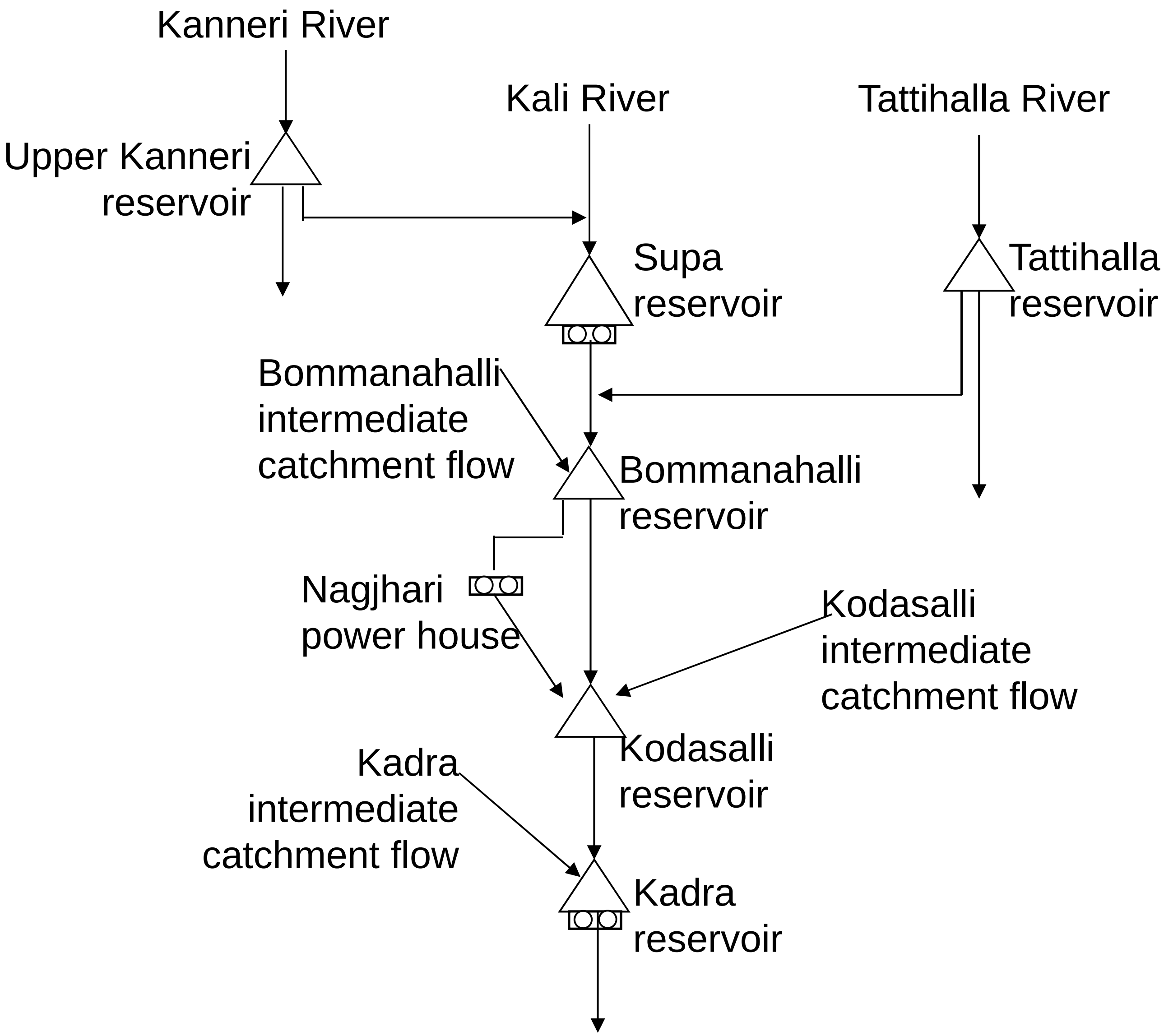
Hydro Power Optimization



Annual energy produced vs Reliability level

MULTI-RESERVOIR SIMULATION FOR HYDRO POWER GENERATION

Hydro Power Generation



Hydro Power Generation

Physical Features of Reservoirs

	Supa	Tattihalla	Bomman a-halli	Kodasal li	Kadra	Remarks
FRL (EL.) (meters)	564.00	468.30	438.38	75.50	34.50	Full Reservoir Level
MDDL(EL.) (meters)	513.50	449.58	429.24	62.50	27.00	Minimum drawn down level
Max. Water spread area (sq. km)	123.00	25.33	15.25	17.35	34.75	Water spread area with respect to maximum storage of dam
Max. Storage (M. Cum)	4178.00	264.03	96.89	286.49	388.92	Storage corresponding to FRL.
Min. Storage (M. Cum)	419.65	14.77	12.99	107.67	179.86	Min. Storage, corresponding to MDDL
Frictional Loss (meters)	1.50	----	12.00	1.50	1.00	Frictional loss
TWL (meters)	471.50	----	75.50	36.50	2.00	Tail Water Level

Hydro Power Generation

Physical Features of Power Houses

	Supa	Nagjhari	Kodasalli	Kadra
Installed Capacity (MW)	100 (2 X 50)	825 (5 X 135 + 1 X 150)	120 (3 X 40)	150 (3 X 50)
Firm Power (MW)	61.90	386.40	57.40	60.60
Secondary Power (MW)	38.10	438.60	62.60	89.40
Efficiency(%)	81.55	81.55	81.55	81.55

Hydro Power Generation

The reservoir storage continuity is considered as,

$$S_{t+1} = S_t + I_t + I_t^{Ru/s} - R_t - E_t - spill_t \quad \forall\, t$$

where

S_t is the storage at the beginning of the month t

I_t is the reservoir inflow during the month t,

$I_t^{Ru/s}$ is the contribution from release at the upstream reservoir

R_t is the power draft required in month t to generate the specified power (corresponding to the head resulting from the average of storages S_t and S_{t+1}),

E_t is the evaporation loss in month t, corresponding to the water spread area at the average storage $(S_t + S_{t+1})/2$, and

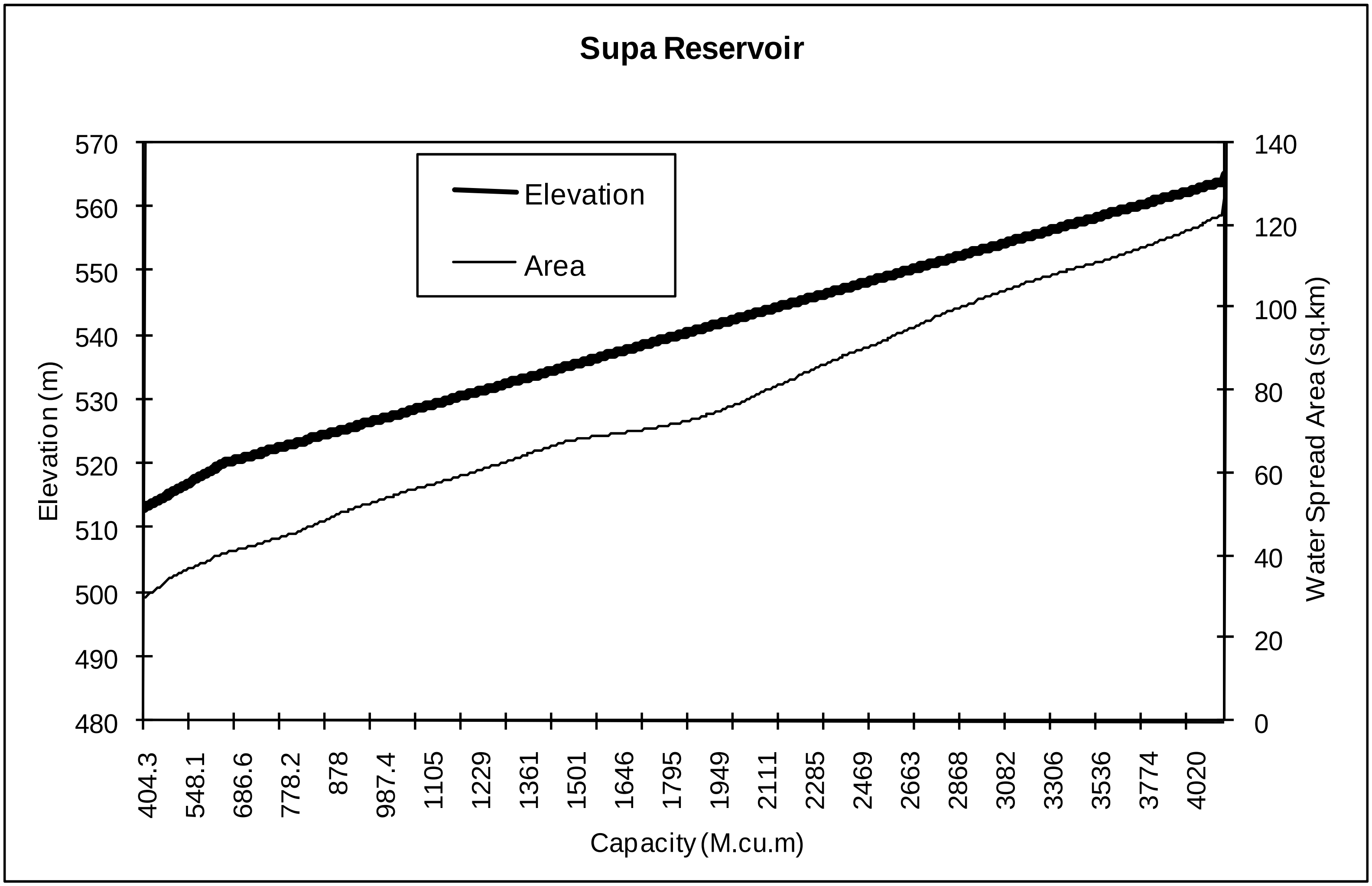
$spill_t$ is the spill during period t.

Hydro Power Generation

Month	Evaporation Rate (cm)
Jan	10.16
Feb	10.16
Mar	17.78
Apr	15.24
May	15.24
Jun	7.62
Jul	7.62
Aug	7.62
Sep	7.62
Oct	7.62
Nov	7.62
Dec	10.16

Hydro Power Generation

Capacity - Elevation - Area Curves



Hydro Power Generation

The power draft required to generate a known power P (MW) during a month works out to,

$$R = P / (0.0030864\, h)$$

where
R is the power draft during the month (M.cu.m), and h is the net head available for power generation (m).

Refer to Lecture 26

Hydro Power Generation

In simulation, the power draft R_t is determined as the lower value of the quantity and the water available in the month t.

$$R_t = \frac{P}{0.0030864\ h_t} \quad \text{if } S_t + I_t - E_t \geq P / (0.0030864\ h_t)$$

$$= S_t + I_t - E_t \qquad \text{otherwise}$$

The net head h_t, power draft R_t, evaporation loss, E_t and end-of-the-period storage, S_{t+1}, are all determined simultaneously by an iterative procedure. The reliability of power is computed based on the concept of a failure year

Hydro Power Generation

- The multi reservoir simulation starts at Supa dam.
- Bommanahalli inflows include release, overflow from Supa dam, intermediate catchment flow of Bommanahalli and Tattihalla inflows.
- Kodasalli inflows include release, overflow from Bommanahalli pickup dam and Kodasalli intermediate catchment flow.
- Kadra inflows include release, overflow from Kodasalli dam and Kadra intermediate catchment flow.

Hydro Power Generation

- The firm power, P is set to 61.90, 386.40, 57.40 and 60.60 MW for Supa dam PH, Nagjhari PH, Kodasalli PH and Kadra PH resp.
- The maximum storage, S_{max} is set to 4178.00, 264.03, 96.89, 286.49 and 388.92 M.cu.m for Supa, Thatihalla, Bommanahalli, Kodasalli and Kadra reservoirs resp.
- The effect of the initial storage used for simulation will quickly die down as simulation progresses,.

Hydro Power Generation

Supa Reservoir Operation Working Tables

1984-85

Supa Reservoir

Month	Initial Storage	Inflow	Head	Release	Evap	Overflow	Final Storage	Power
	M.cu.m	M.cu.m	m	M.cu.m	M.cu.m	M.cu.m	M.cu.m	MW
Jan	2298.82	0.00	71.33	281.18	8.26	0.00	2009.39	61.90
Feb	2009.39	0.00	67.46	297.31	7.42	0.00	1704.66	61.90
Mar	1704.66	0.00	62.96	318.54	12.23	0.00	1373.90	61.90
Apr	1373.90	0.00	57.64	347.95	9.13	0.00	1016.82	61.90
May	1016.82	0.00	50.60	396.34	7.15	0.00	613.33	61.90
Jun	613.33	214.64	43.34	405.55	2.78	0.00	419.65	54.25
Jul	419.65	1268.02	51.48	389.62	3.74	0.00	1294.32	61.90
Aug	1294.32	676.20	61.91	323.92	5.17	0.00	1641.43	61.90
Sep	1641.43	221.44	63.73	314.69	5.29	0.00	1542.89	61.90
Oct	1542.89	182.36	61.94	323.77	5.17	0.00	1396.30	61.90
Nov	1396.30	0.00	58.07	345.36	4.62	0.00	1046.32	61.90
Dec	1046.32	0.00	51.30	390.95	4.94	0.00	650.43	61.90

Hydro Power Generation

1998-99

Supa Reservoir

Month	Initial Storage	Inflow	Head	Release	Evap	Overflow	Final Storage	Power
	M.cu.m	M.cu.m	m	M.cu.m	M.cu.m	M.cu.m	M.cu.m	MW
Jan	1401.24	0.00	58.14	344.92	6.17	0.00	1050.14	61.90
Feb	1050.14	0.00	51.38	390.31	4.95	0.00	654.88	61.90
Mar	654.88	0.00	43.91	228.62	6.61	0.00	419.65	30.98
Apr	419.65	0.00	40.50	0.00	4.75	0.00	419.65	0.00
May	419.65	0.00	40.50	0.00	4.75	0.00	419.65	0.00
Jun	419.65	116.47	40.50	114.09	2.38	0.00	419.65	14.26
Jul	419.65	782.06	45.23	443.38	2.95	0.00	755.38	61.90
Aug	755.38	569.57	51.18	391.90	3.68	0.00	929.37	61.90
Sep	929.37	315.12	52.19	384.25	3.87	0.00	856.37	61.90
Oct	856.37	153.61	48.60	412.65	3.30	0.00	594.03	61.90
Nov	594.03	0.00	43.08	171.64	2.74	0.00	419.65	22.82
Dec	419.65	0.00	40.50	0.00	3.17	0.00	419.65	0.00

Hydro Power Generation

- The reliability of power generation is computed based on the concept of a failure year.
- In the computation of annual reliability, a year is reckoned as a failure year if in one or more months in that year, the power generated is less than the specified firm power, P.
- The annual reliability is computed by dividing the number of non-failure years by the total number of years in simulation.

Hydro Power Generation

Annual reliability: Supa PH