Reservoir Analysis

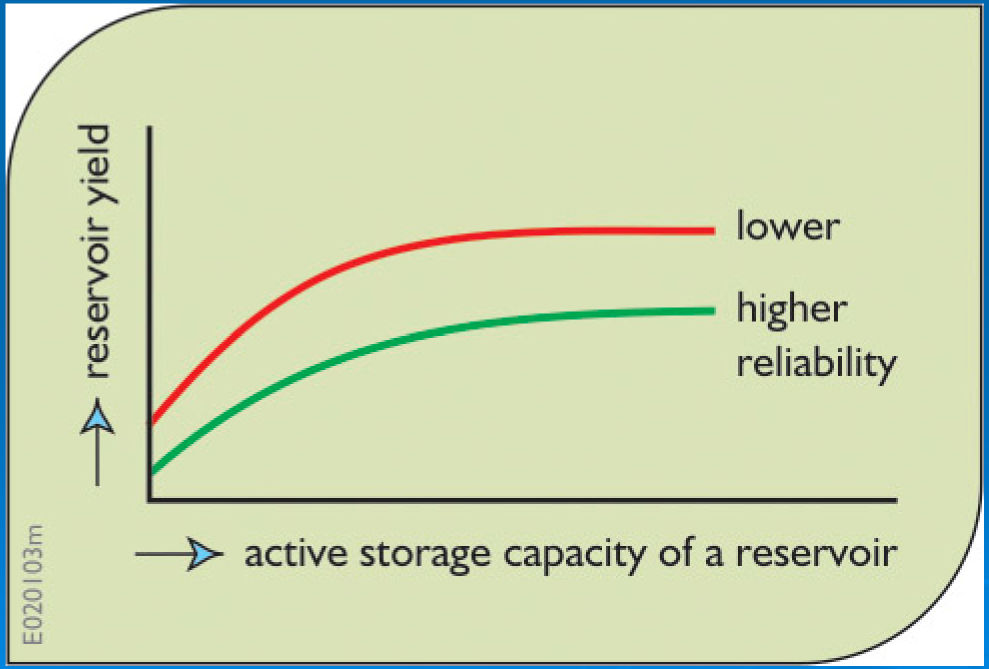
CVEN 5393

Reference: Mays and Tung 7.1, 7.2.1, 7.3, 7.4

Reservoir Yield: Controlled Release from a reservoir (or system of reservoirs).

Often expressed as a ratio of % of mean annual flow. E.g., 70% yield means the reservoir can provide a regulated release of 70% of the mean annual flow.

The Yield depends on the active **storage capacity** of the reservoir



Reliability of Yield: probability that a reservoir will be able to meet the demand in any particular time interval (usually a year)

Reliability = Ns/N

Ns is number of intervals in which demand was met; N is the total number of intervals

Firm Yield: can be met 100% of time

Mass Balance Equation of Reservoirs

$$\mathbf{S_{t-1} + Q_t - R_t - L_t = S_t}$$

Where

S_{t-1} is active storage at end of previous time interval
S_t is active storage at end of current time interval
Q_t is inflows at current time interval
R_t is release at current time interval
L_t is loss (evap/seepage) at current time interval

Reservoirs have a fixed storage capacity, K, so

S_t <= K for each interval

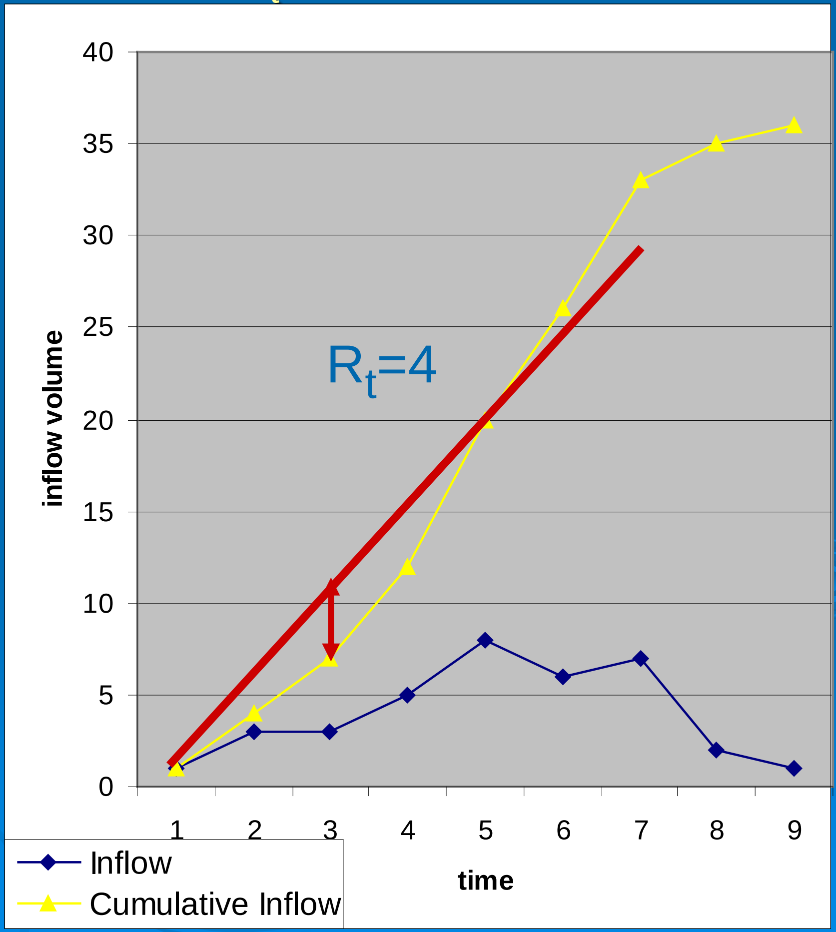
Determine Size of Reservoir for a specified Yield Mass Diagram Analysis (Rippl) Method

Find the maximum positive cumulative difference between a sequence of pre-specified (desired) reservoir releases R_t and known inflows Q_t.

Record of historical inflows is used, typically

Example: Nine period-of-record flows:

[1, 3, 3, 5, 8, 6, 7, 2, 1]



1. Plot cumulatives
2. Add demand line
3. Find max deficit

Mass Diagram Analysis (Rippl) Method

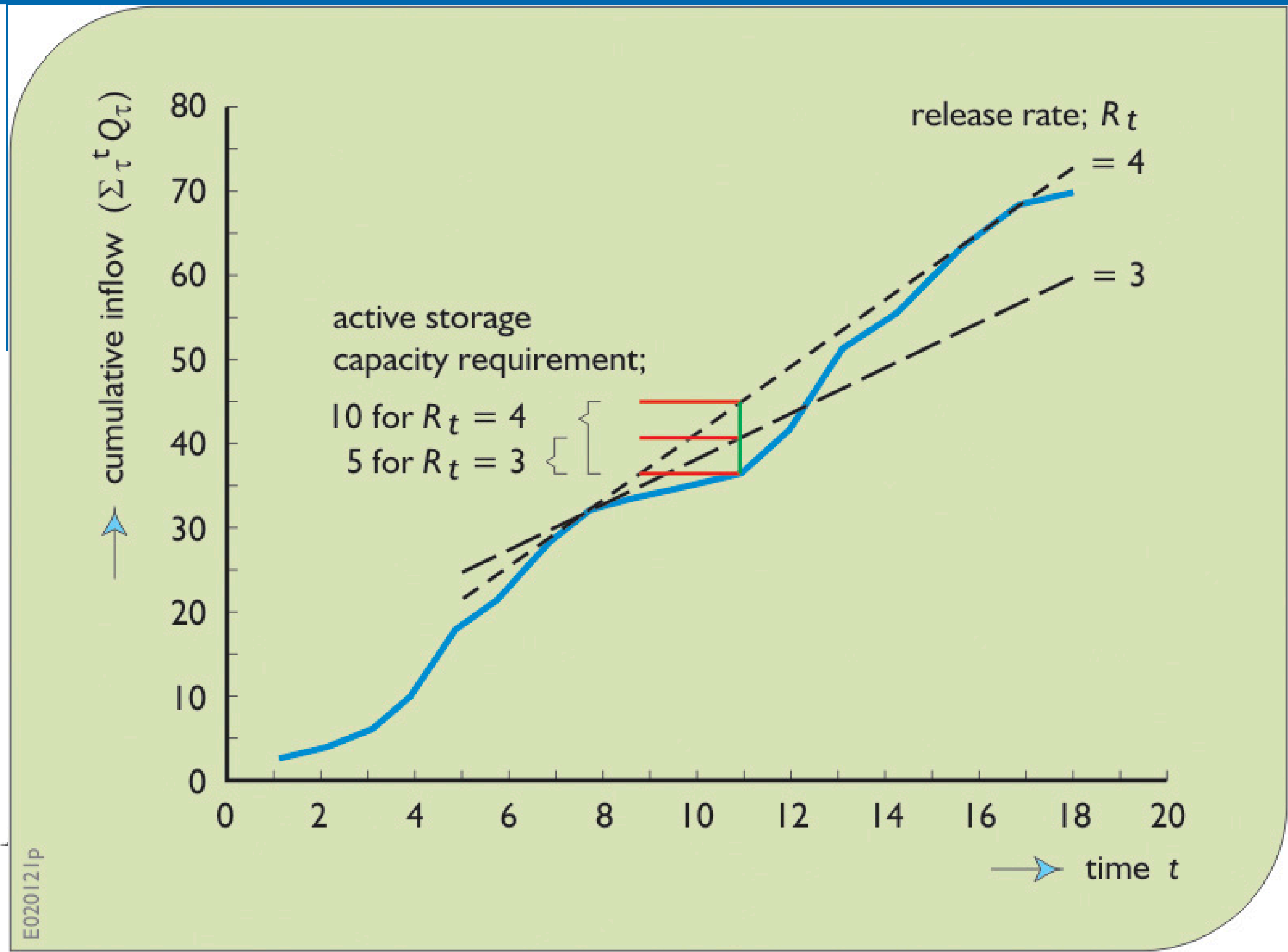
Repeat the hydrologic sequence in case critical period is at end

Start demand line at full reservoir

Calculate Active Storage K_a as max accumulated deficit over 2 successive periods of record

$$K_a = \text{maximum}\left[\sum_{t=i}^{j}(R_t - Q_t)\right]$$

where $1 \le i \le j \le 2T$.



Mass Diagram Analysis (Rippl) Method

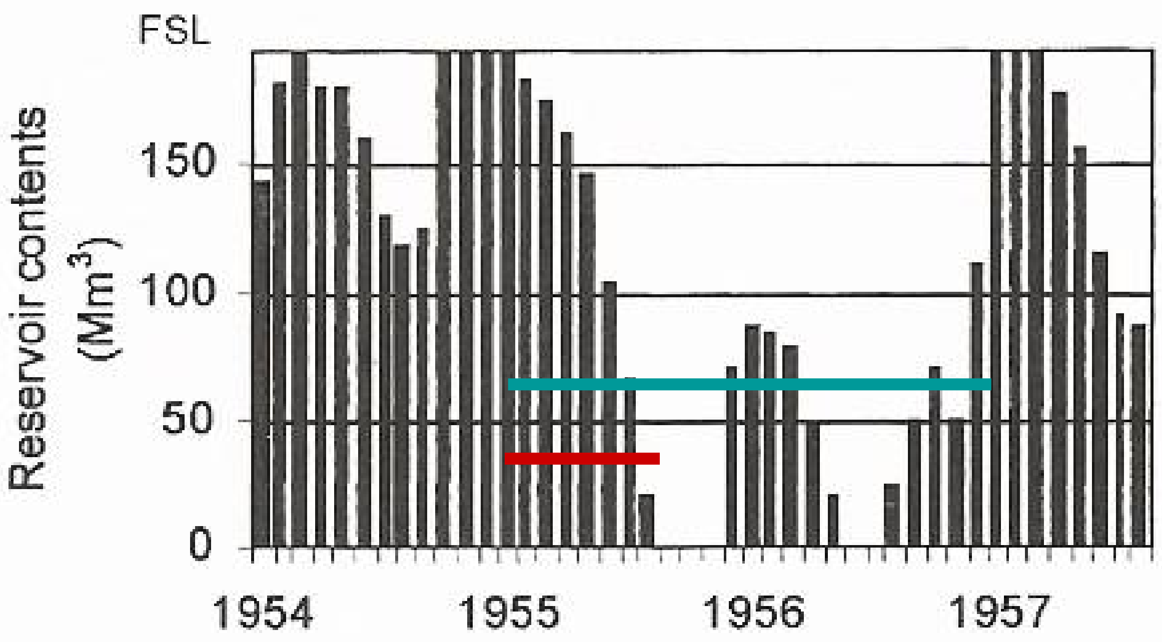
The maximum capacity is determined by the Critical Period

Critical Drawdown Period:

Longest period from full reservoir condition to emptiness

Critical Period:

Longest period from full condition, through emptiness and to a full condition again



Problems with Mass Diagram Method

- Reservoir release needs to be constant (this is not accurate for monthly interval as demands are often seasonal)
- Assumes that future hydrology is like the past
- Cannot compute storage size for a given reliability
- Evaporation and other losses that depend on level in reservoir cannot be factored into analysis
- Another approach uses deficit analysis and addresses some of these issues

Sequent Peak Analysis

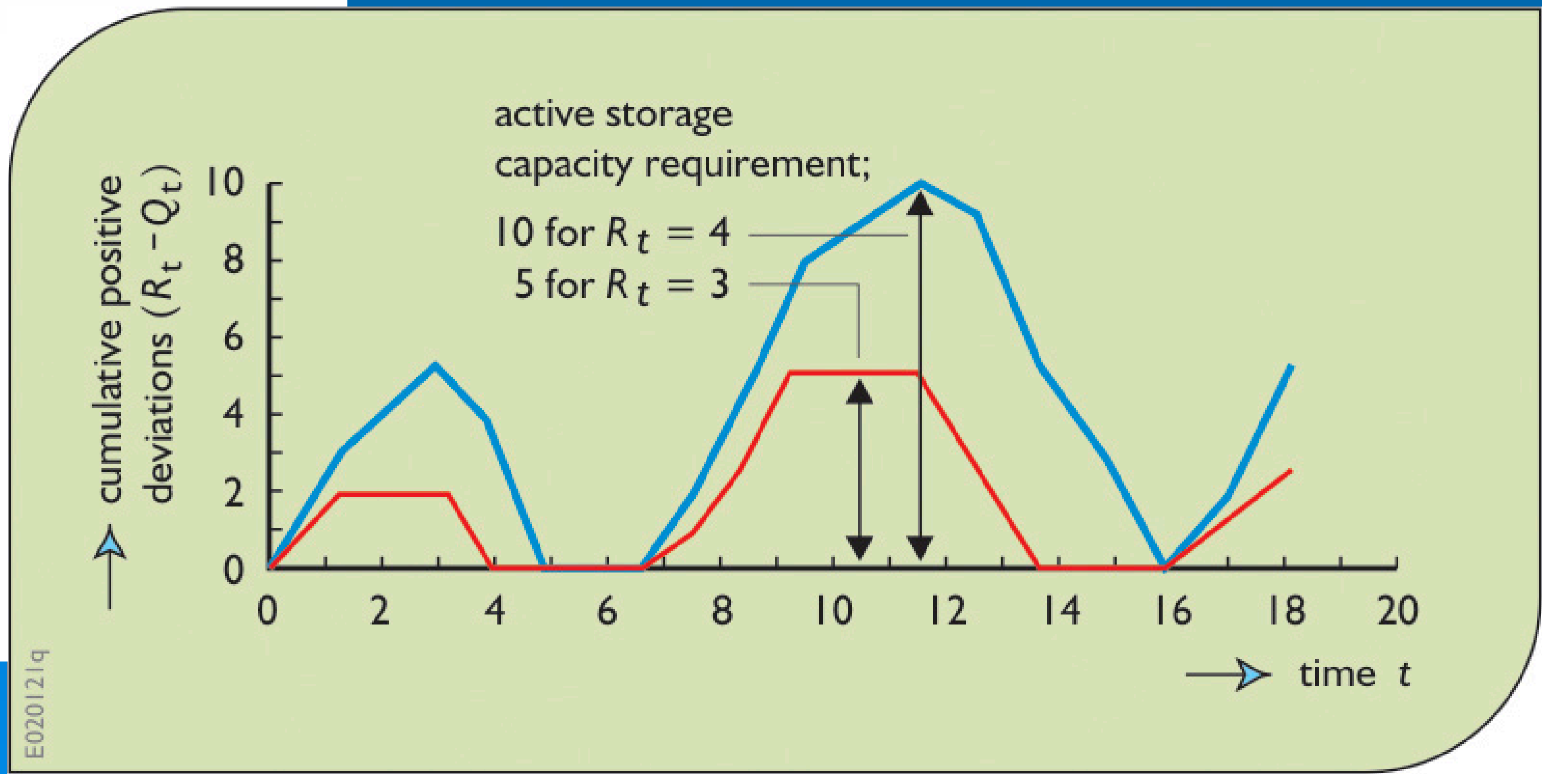
Let K_t be the maximum total storage requirements needed; Set $K_0 = 0$

Example: Nine period-of-record flows: [1, 3, 3, 5, 8, 6, 7, 2, 1]

$$K_t = R_t - Q_t + K_{t-1} \quad \text{if positive,}$$
$$= 0 \text{ otherwise}$$

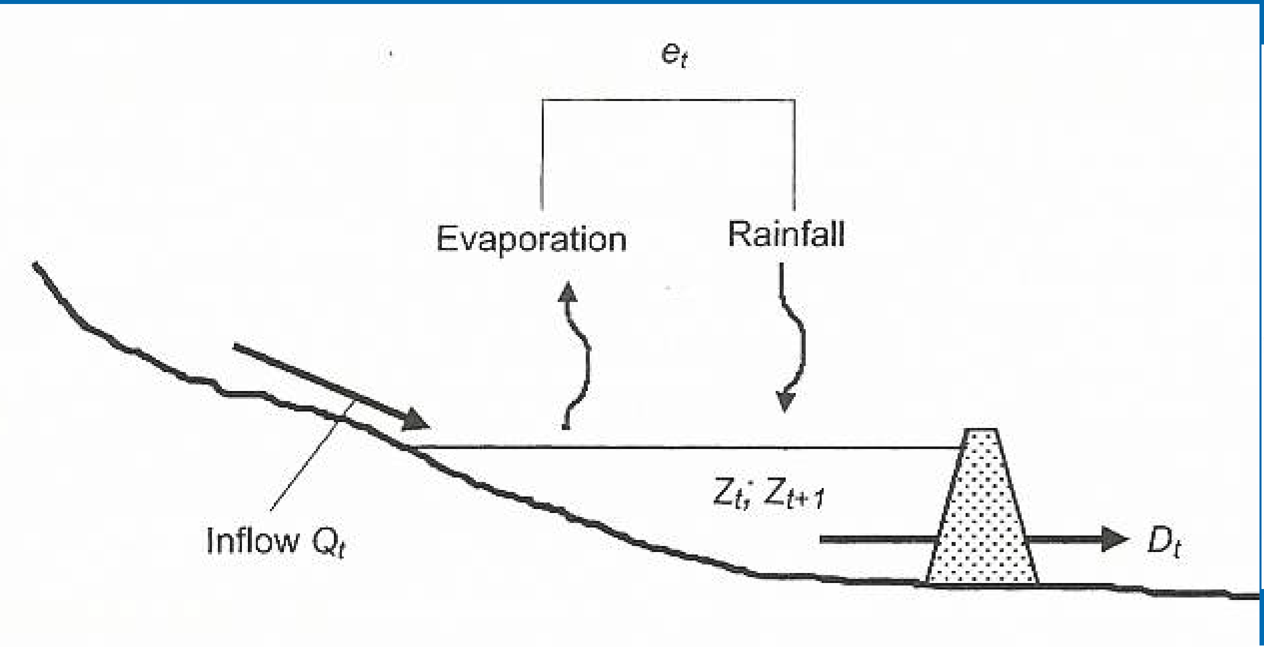
Apply the equation consecutively for up to 2x the total length of the record.

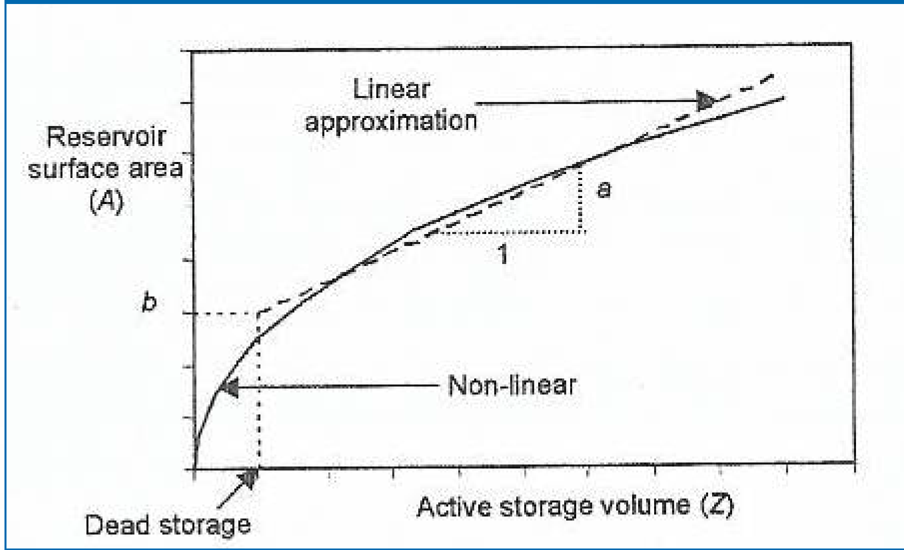
The maximum of all K_t is the required storage capacity for the specified releases R_t and inflows Q_t



Accounting for Losses

Evaporation and Rainfall (net losses) depend on Surface Area





Surface area depends on storage non linearly: $A_t = cZ_t^d$

But can be approximated linearly:

$$A_t = aZ_t + b \qquad (3.54)$$

where a, b, c and d are coefficients which can be obtained by least squares, A_t is the surface area at the beginning of period t and Z_t is the storage at the beginning of t.

Accounting for losses

- Losses can alter the critical period and change the storage capacity
- Net evap (equations) can be included in storage based simulations directly
- Approximate Evap can be included in SPA iteratively

Active storage (vol. units)	Evaporation (vol. units)
0 - 2	0.1
3 - 5	0.2

Reliability

Reliability (time-based) - Ns/N

Resiliance – Speed of recovery

Vulnerability – severity of failure (volumetric reliability)

(Tradeoffs on these 3 lead to very tricky design; several authors have developed indices that attempt to combine these (Loucks, 1997; Zongxue, 1998)

Reliability and Vulnerability can be integrated into SPA:

- Determine number of failure periods permitted (from reliability)
- Determine reduced maximum capacity permitted (from vulnerability)

Behavior Analysis – storage based simulation (detailed simulations of processes)

Case 1: Estimate System Performance

Active capacity of reservoir is known.
Series of demands is given (could be stochastic).
Starting condition is known or assumed.
Historical or synthetic inflows are used
(could be many traces) (index sequential or monte carlo)

Case 2: Find size of reservoir under consideration

Series of demands is known (could be stochastic)
series of inflows is given (historical or generated stochastic)
Performance criterion is specified
Estimate reservoir capacity; do simulations; adjust until get performance desired

Case 3: Estimate Yield of an existing reservoir

Specify performance criteria (reliability, vulnerability, maybe resiliance)
Use historic or stochastic hydrology
Estimate demand (yield) and iterate until meet performance criteria
Need to know and model detailed operating procedures

Additional important topics

- Optimization techniques

  simple ones can give identical results to SPA

  more complex methods can include cost functions

- Multiple reservoir systems

  single-reservoir techniques can be extended to multi-reservoir systems

  determine size at each site

  specify operating policies for releases and demands (heuristic policies have been developed)

  typical objective is to keep reservoirs balanced

Flood Control and Operating Criteria

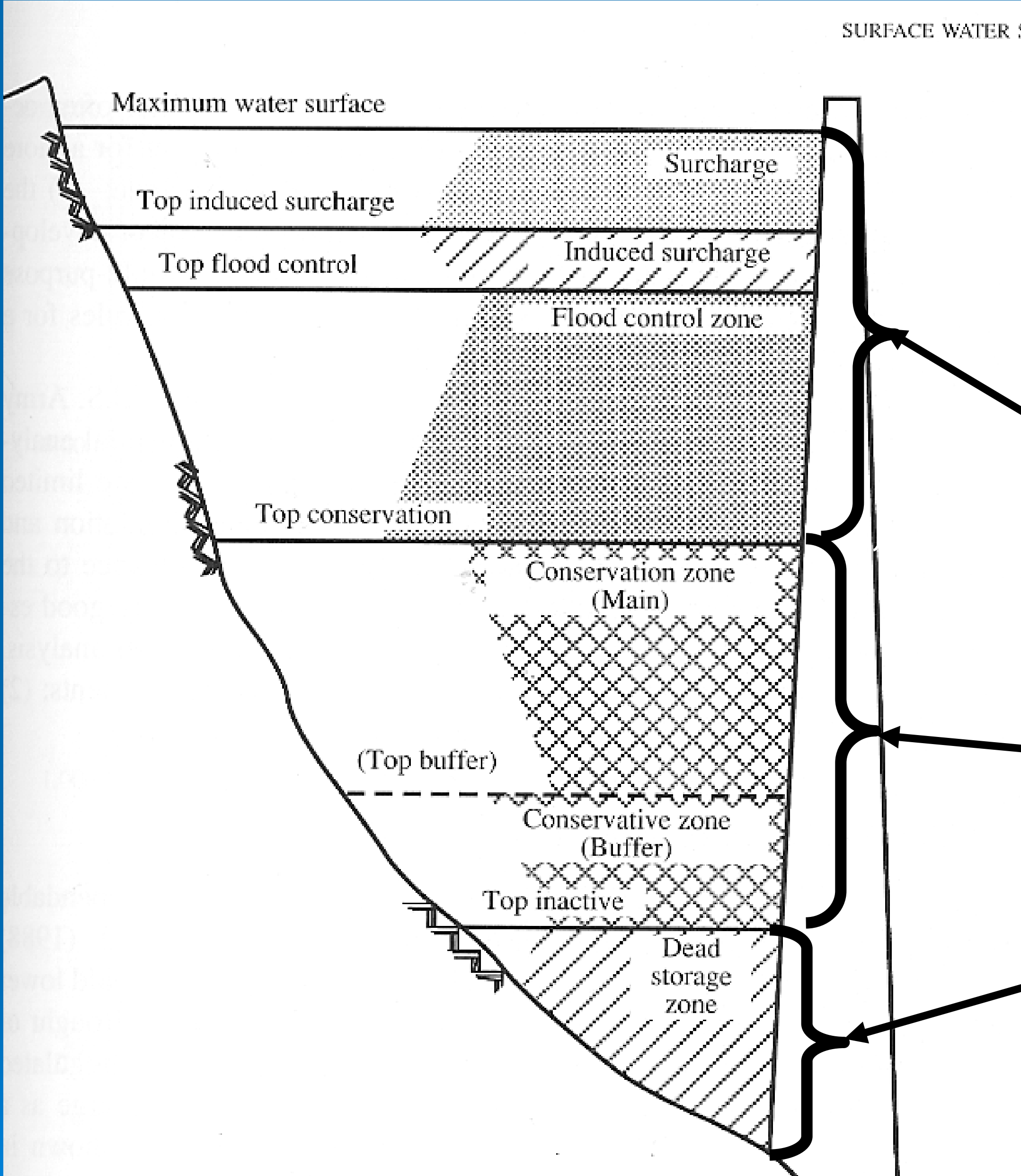
Reference: Loucks and van Beek Appendix D Section 4

Purpose of a Reservoir

To smooth out the variability of surface water flow through control and regulation and make water available when and where it is needed. The dis-benefits of evaporation and seepage are offset by the benefits of water supply, hydropower, recreation and flood control.

Two Main Operational Purposes:

1. **Conservation** – includes
   water supply (M&I and irrigation),
   low-flow augmentation for water quality and ecological habitat,
   recreation,
   navigation,
   hydropower
2. **Flood Control** – retention of water during flood events for the purpose of reducing downstream flooding.



From Mays and Tung Hydrosystems Engineering and Management, 1992. p. 271

Reservoirs have 3 primary storage zones

Flood Control Storage

reserved for storing excessive flood volume to reduce potential downstream flood damage.

Active Storage

for conservation purposes

Dead Storage

for sediment collection, hydropower head.

Design of Dead Storage Capacity

Considers estimates of sediment load

Design of Active Storage Capacity

Screening methods for yield as discussed above

Multi-objective reservoirs designed with consideration of

- Reliability of hydrology (chance-constrained optimization models; transition probability matrix; DP)
- Hydropower firm energy commitments; B/C of power
- Buffer zone design for low flow augmentation in drought
- Trade-off among objectives based on economic or other criteria

Multi-objective Tradeoff Analysis

An Example: A reservoir has 2 purposes – recreation (boating) and irrigation. These objectives conflict because boating requires high reservoir levels in the summer, whereas irrigation requires water to be released for downstream use. If X is total units of water delivered and Y is visitor-days in the season, the possible solution is:

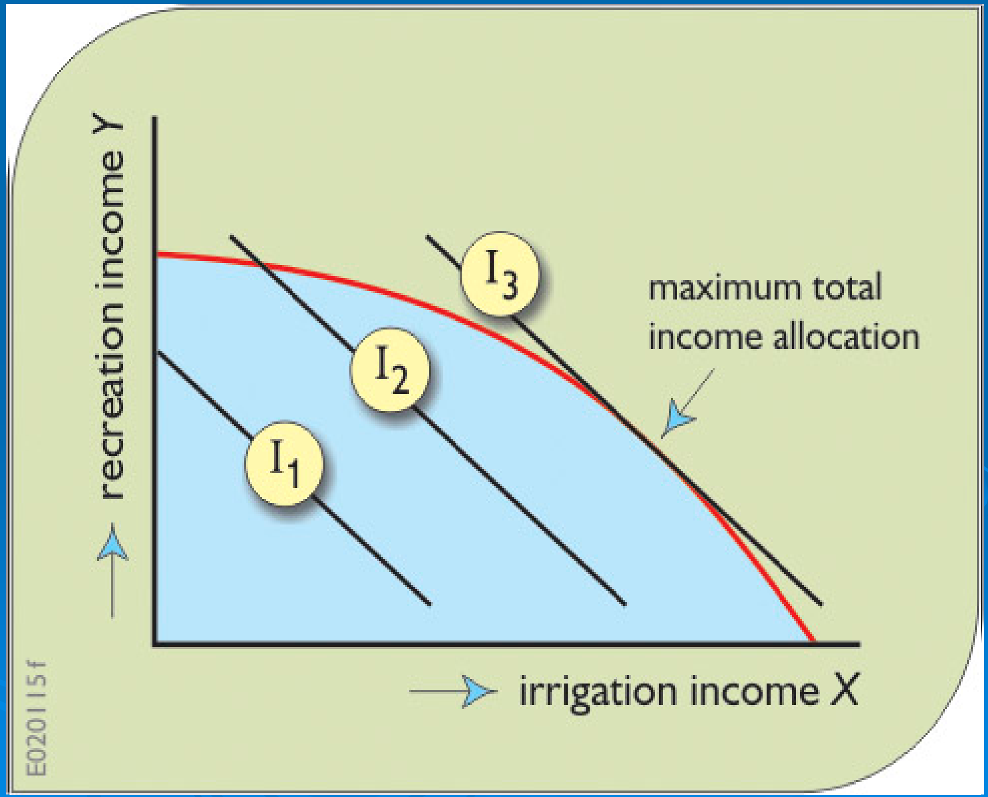
Best solution is on boundary where any improvement in one objective will result in harm to the other.

Use unit cost or value to find solution:

Income = Px X + Py Y
where Px is unit price of water
and Py is unit price of visitor-day

Find X ,Y values for constant I
where $I_1 < I_2 < I_3$

I_3 will provide the highest income and will be feasible for a single X,Y solution



Multi-objective Tradeoff Analysis

In reality, it is not easy to find a solution for multi-objective tradeoff problems because

- There may not be quantifiable and commensurate values for objectives (environmental, social objectives; also legally mandated objectives).
- The market values may not reflect social values

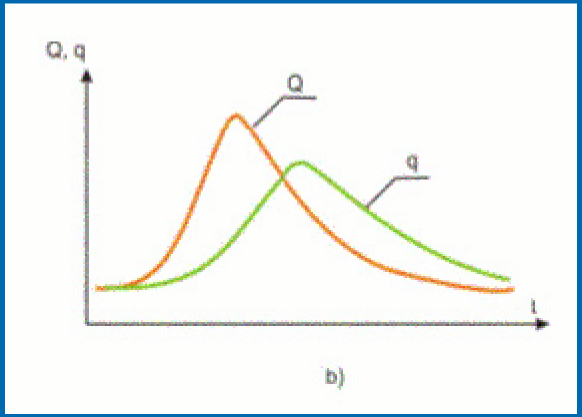
The results of rigorous benefit–cost analyses seldom dictate which of competing water resources projects and plans should be implemented. This is in part because of the multi-objective nature of the decisions. One must consider environmental impacts, income redistribution effects and a host of other local, regional and national goals, many of which may be non-quantifiable.

Other important considerations are the financial, technical and political feasibilities of alternative plans. Particularly important when a plan is undertaken by government agencies is the relative political and legal clout of those who support the plan and those who oppose it. Still, a plan's economic efficiency is an important measure of its value to society and often serves as an indicator of whether it should be considered at all.

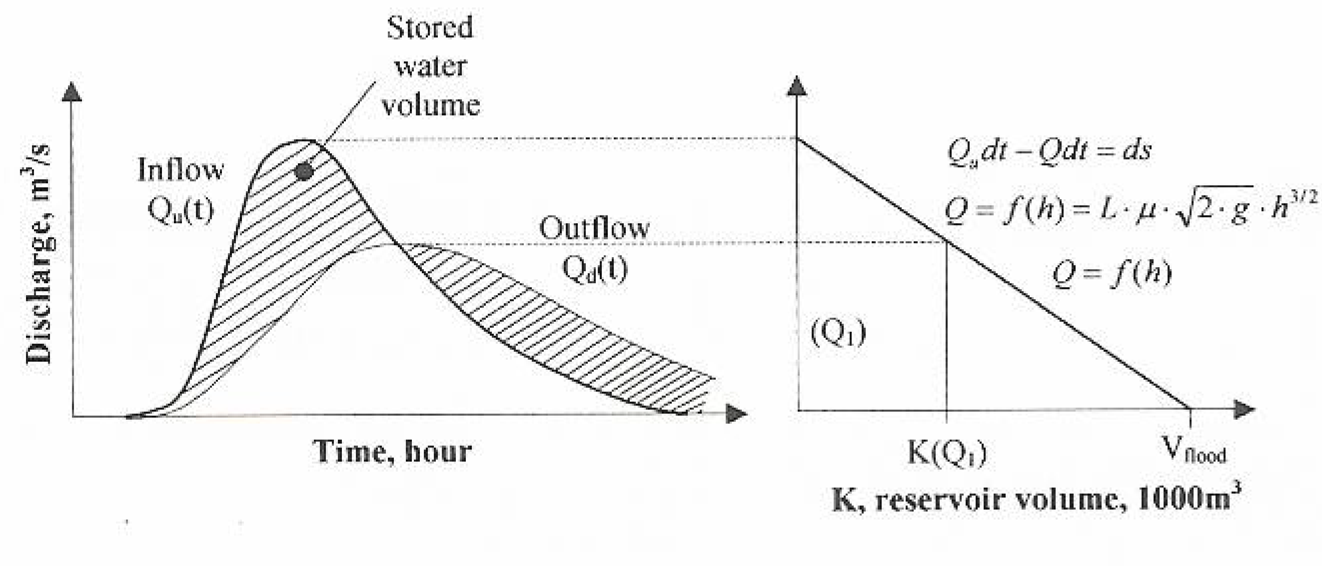
Loucks and van Beek, 2005

Sizing of Flood Pool

A flood wave passing through a reservoir is delayed and attenuated in order to lessen damage downstream.

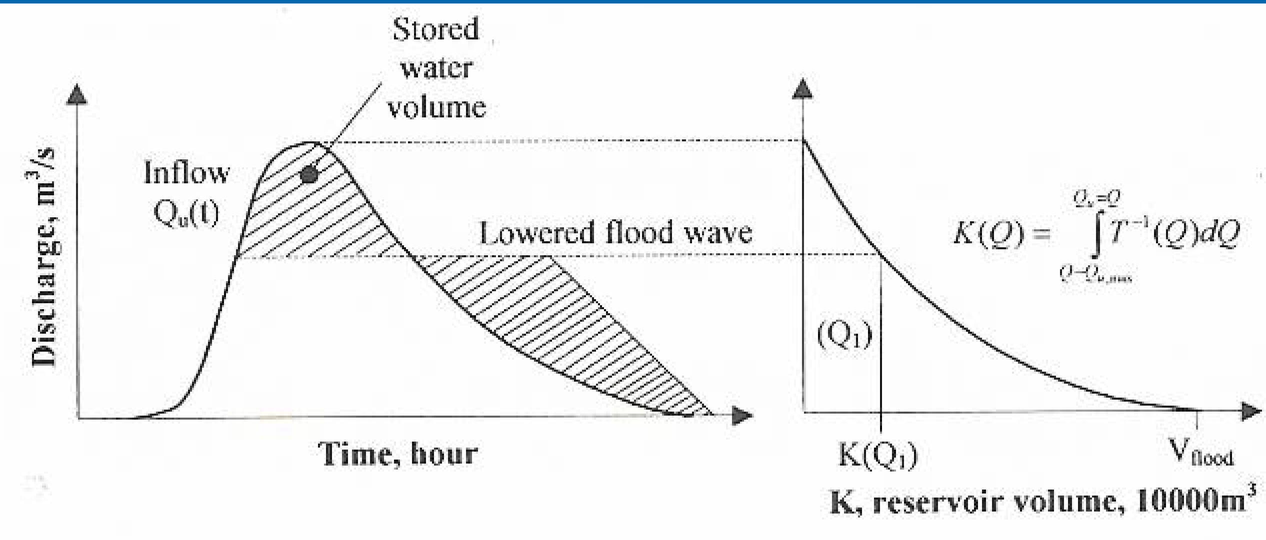


Translation of INFLOW hydrograph to OUTFLOW hydrograph depends on the geometric and hydraulic features of the pool and reservoir operation.



2. *Opened sluice*

A flood pool with an uncontrolled spillway stores water as it is released according to the weir flow equation. The hydrograph is delayed and attenuated. The outflow hydrograph depends on the area of the reservoir and the length of the spillway.



1. Regulated sluice

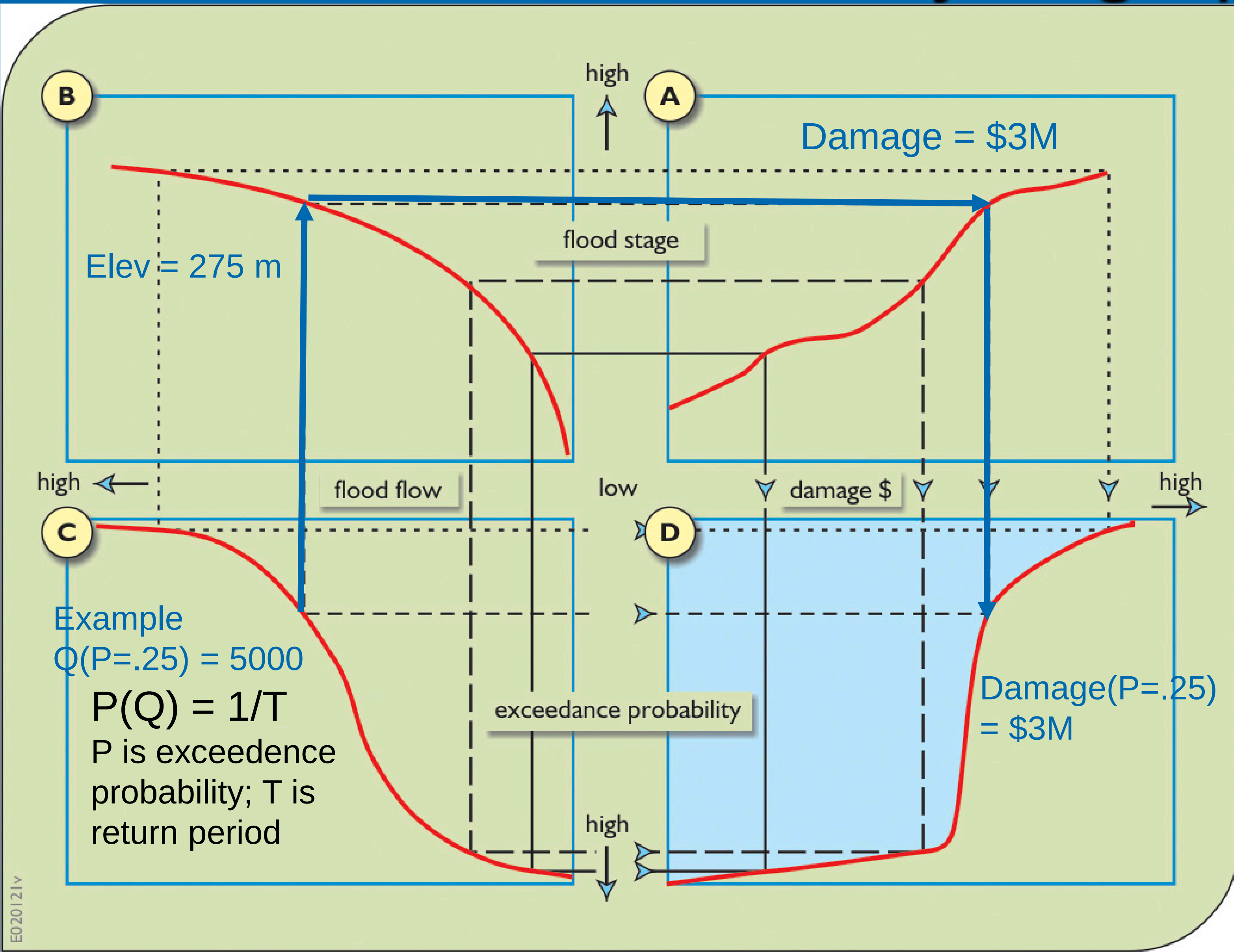
A gated structure can more efficiently control the release. Less storage space is needed for the same outflow peak Q. However, the gates add significant cost to the project.

Flood Pool Sizing

To size the pool, need to know

1. Upstream hydrograph –
   based on analysis of record
2. Downstream hydrograph –
   based on flood damage analysis

Flood Pool Sizing – determination of downstream hydrograph



Calculation of the expected annual flood damage *without the reservoir* is shown in quadrant (D) derived from:

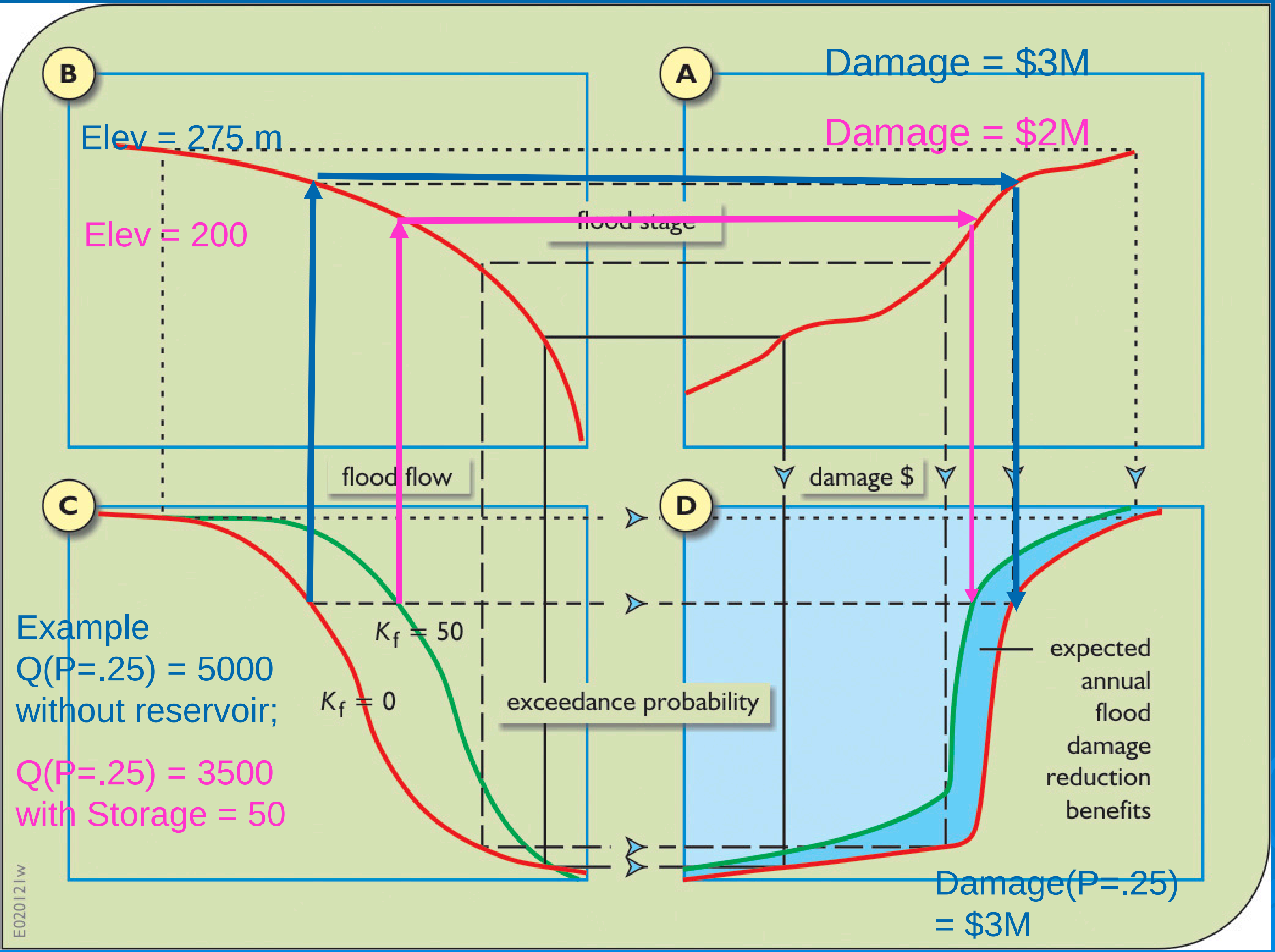
A - the expected stage-damage function,

B - the expected stage-flow relation, and

C - the expected probability of exceeding an annual peak flow.

(Loucks and van Beek, 2005)

Flood Pool Sizing – determination of downstream hydrograph



Calculation of the expected annual flood damage reduction *with the reservoir* is shown in quadrant (D) derived from the new values in:

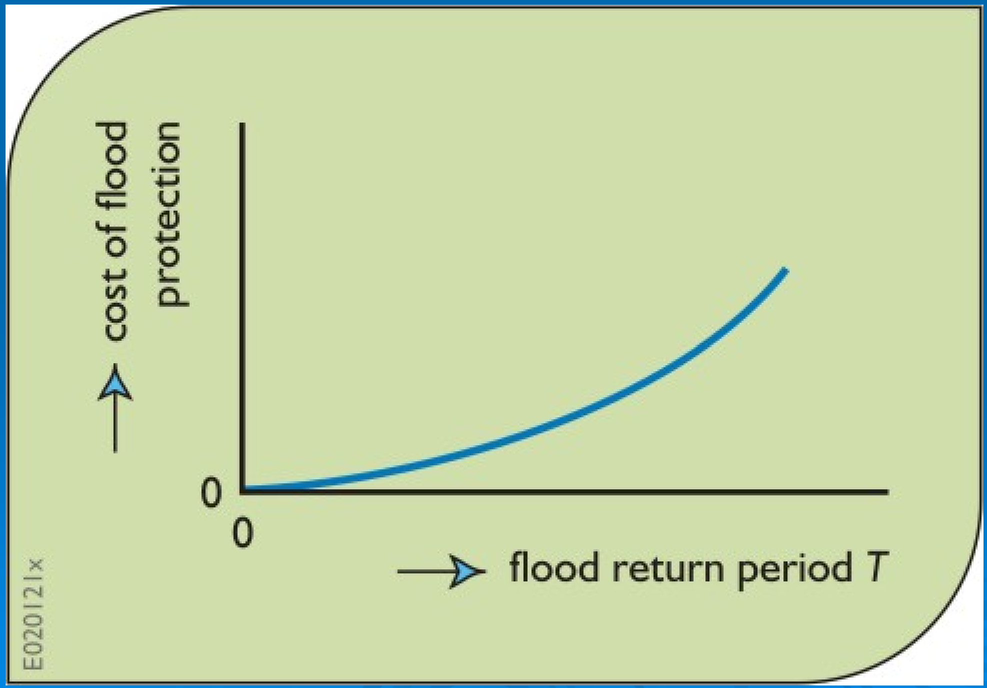
A - the expected stage-damage function,

B - the expected stage-flow relation, and

C - the expected probability of exceeding an annual peak flow.

(Loucks and van Beek, 2005)

Design Decisions are based on cost of protecting downstream. Cost of protection is based on storage (height of dam and area of reservoir) and operational capabilities (gates)



What are storage/operations requirements for meeting Q(P) downstream?

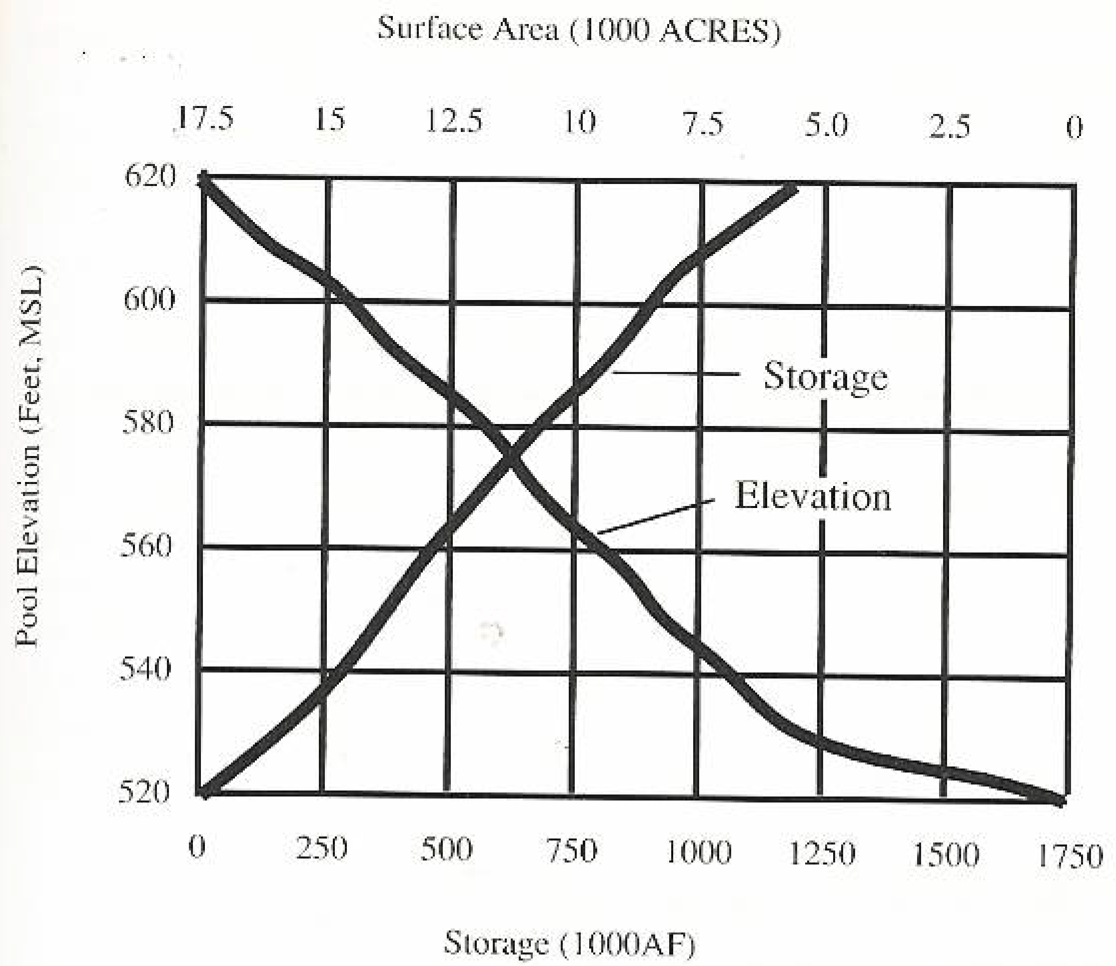
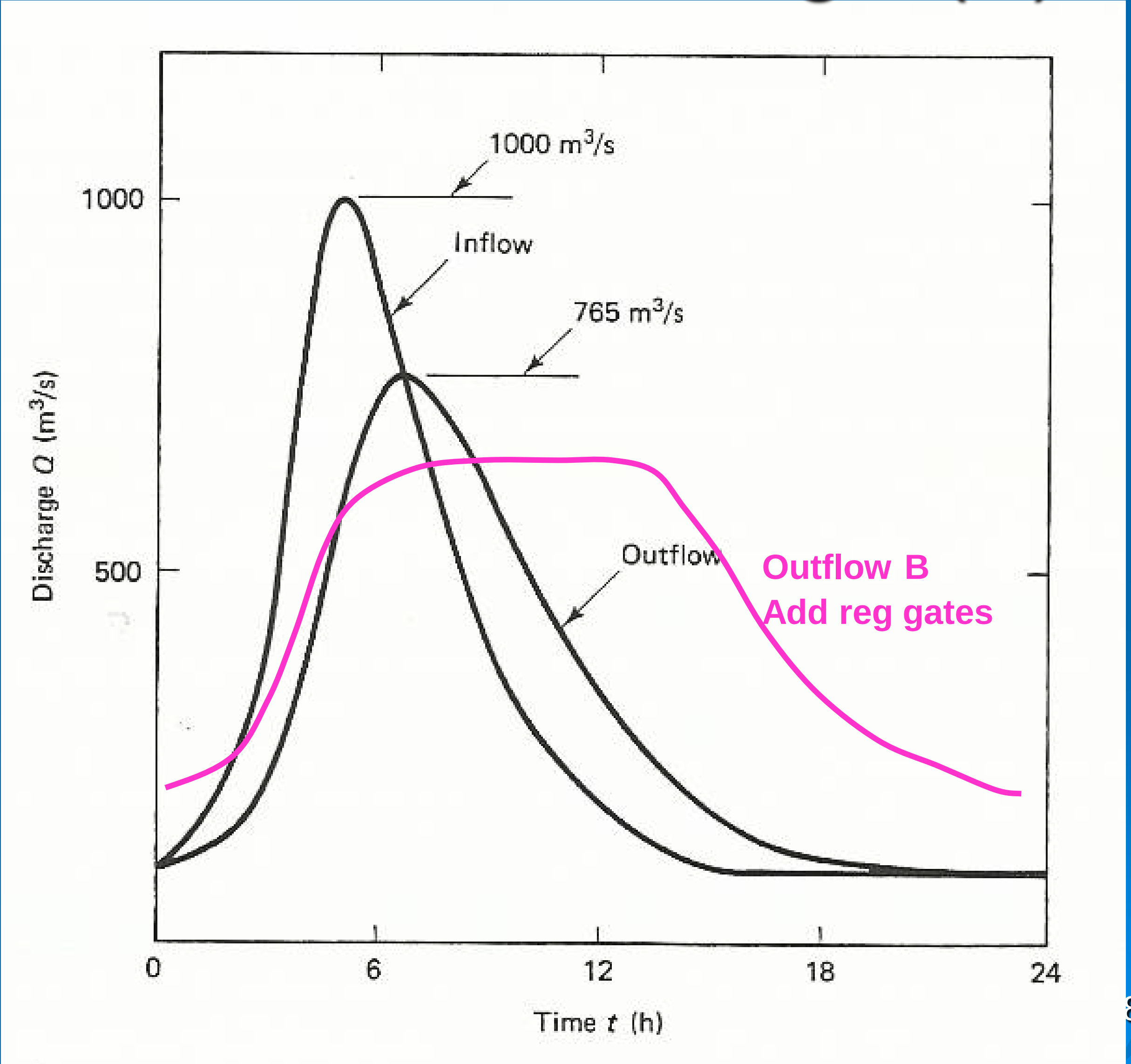


FIGURE 7.2.3 Mays and Tung, 1992 p.281

First: Develop the Elevation-Area-Storage relationships based on topography of the reservoir site

What are storage/operations requirements for meeting Q(P) downstream?



Use storage routing to simulate the outflow hydrograph, given Q(P), using different outlet capabilities:

- Uncontrolled spillway length
- Regulated outflow (gates)

What range of Q(P) upstream need to be considered?

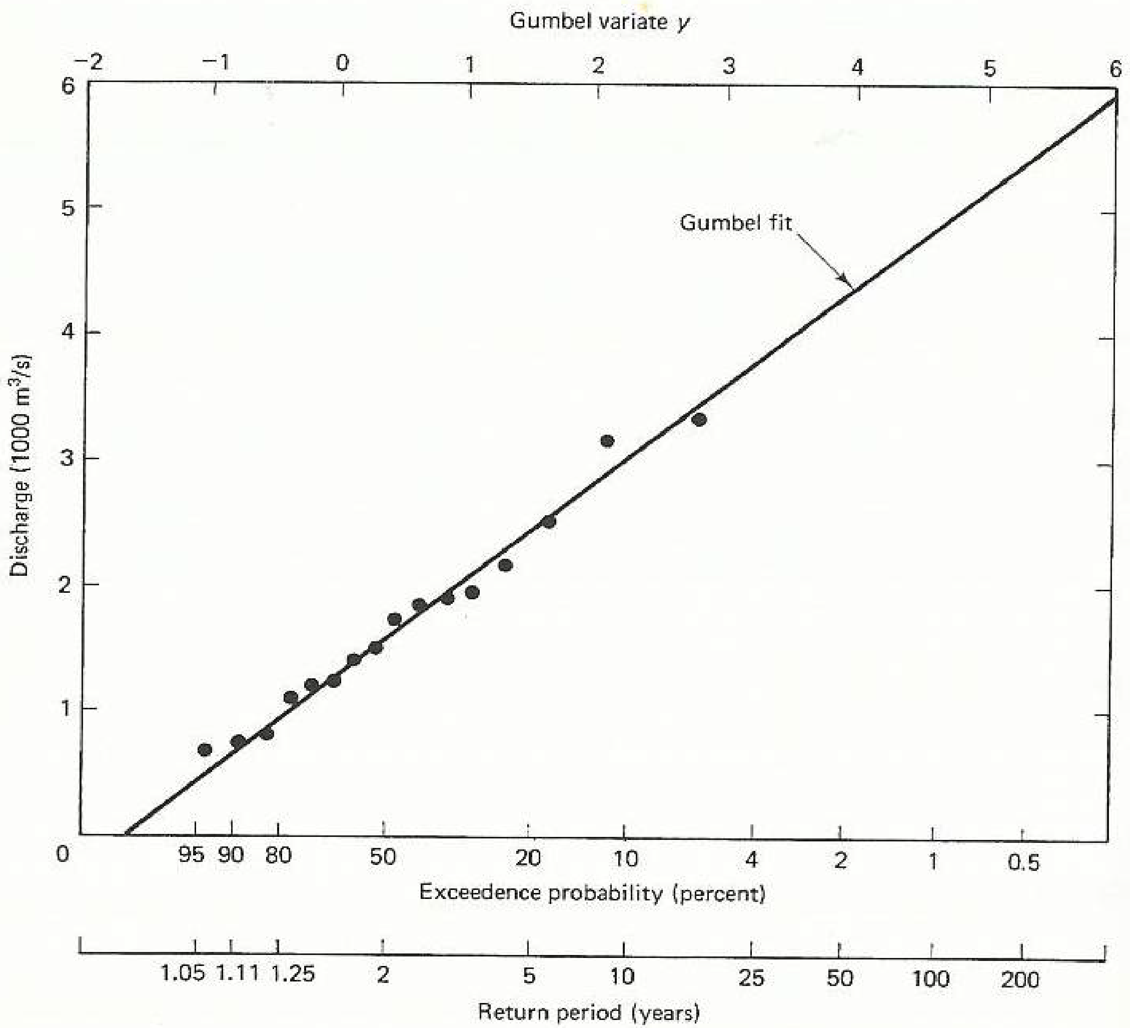


Figure 6-6 Flood-frequency analysis by Gumbel method: Example 6-6.

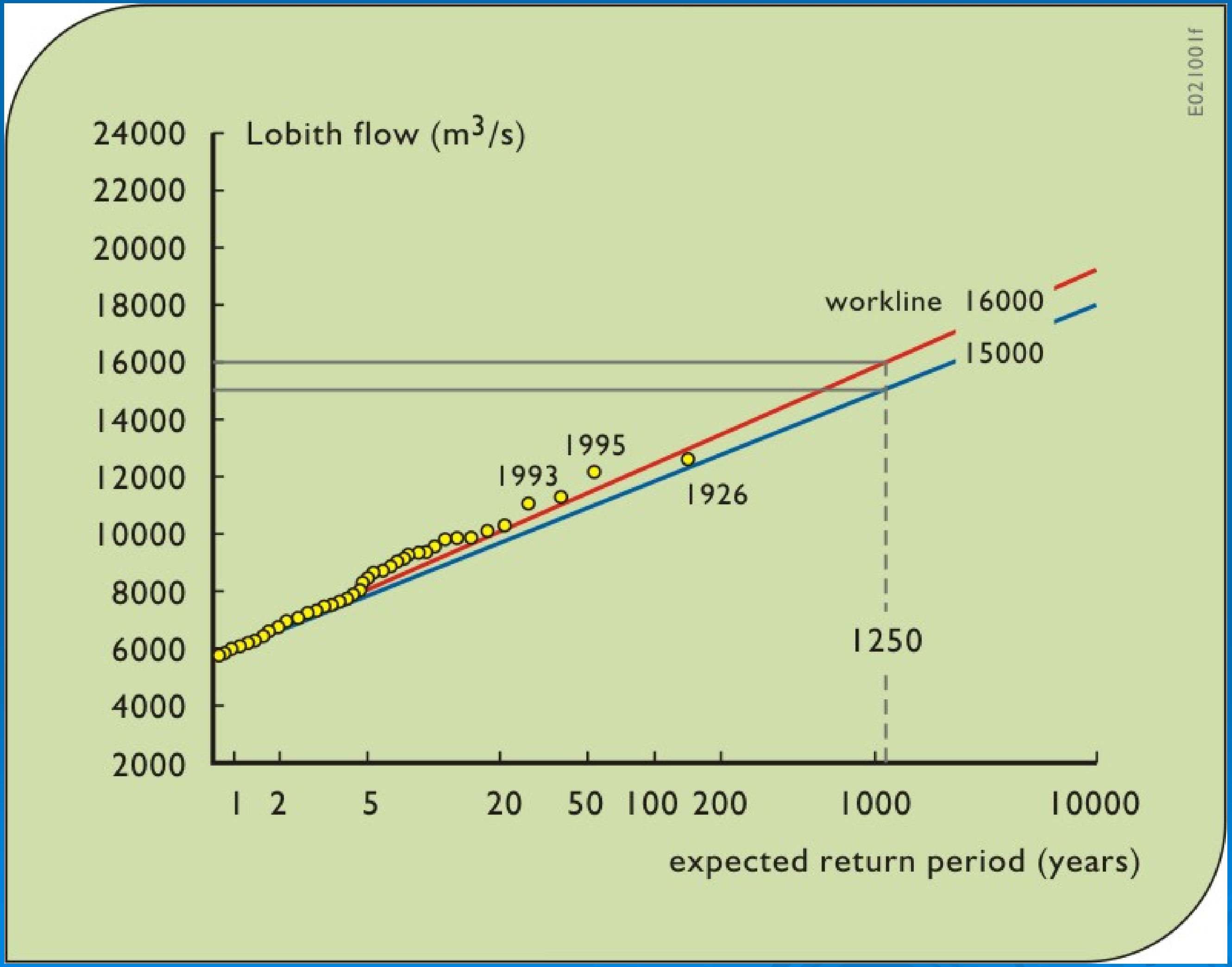
Standard methods of fitting historical data to flood frequency curves provide a means of getting Q(P) for a range of return flows that have been obseved.

What about very large flows (T = 1000 or greater)?

What range of Q(P) upstream need to be considered?

As the return period increases, the value becomes more uncertain.

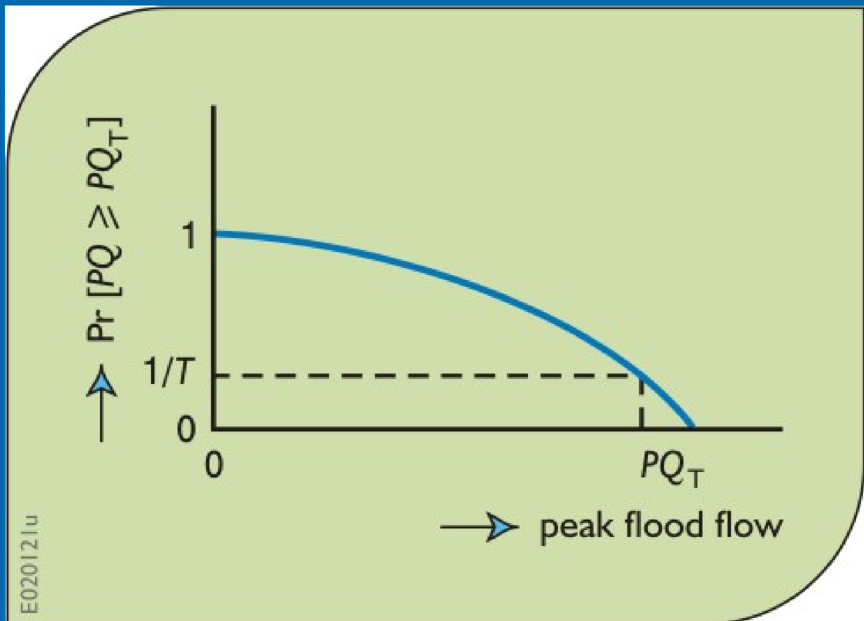
What range of Q(P) upstream need to be considered?

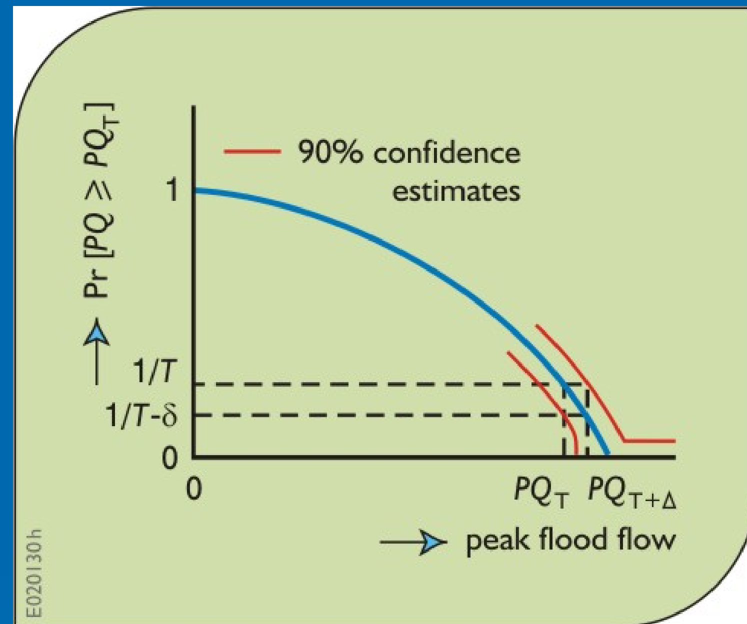


This revision of the T=1250 flow was based on two new values in the period of record.

What range of Q(P) upstream need to be considered?

Probability of annual peak flood flows being exceeded.





Portion of peak flow probability of exceedance function showing contours containing 90% of the uncertainty associated with this distribution. To be 90% certain of protection from a peak flow of PQ_T, protection is needed from the higher peak flow, $PQ_{T+\Delta}$ expected once every T+Δ years, i.e. with an annual probability of 1/(T+δ) or (1/T) -δ of being equaled or exceeded.

Why are low exceedance values so difficult to determine?

- Hydrologic record is not long enough
- Many factors determine Q: rainfall volume, intensity, spatial pattern of precip, rain on snow, antecedent moisture conditions, temperature, changing runoff characteristics,
- Low-probability combinations of conditions are numerous

Probable Maximum Flood

PMF is variously defined as T=1000, T=10,000

It can be derived statistically or by physical process modeling using an estimate of the Probable Maximum Precipiation (PMP)

Dam design policies require that the dam can pass the PMF, i.e., that the *dam does not fail*.

Example: Canyon Lake Dam, SD June 9, 1972

Forecast *"partly cloudy, scattered t-storms, some possibly reaching severe proportions"*

That evening,10 in. fell in a small, steep watershed that averages 14 in. annually; 6 in fell in 2 hours.

Rapid creek delivered 31,000cfs into Canyon Lake, a 40 ac-ft reservoir behind a 20-ft high earthen dam. The previous record flow in 20 years was 2600cfs

The dam washed out, destroyed over half of Rapid City (pop 43,000). 237 fatalities, 5000 homeless. Pactola, 15 miles u.s. of Canyon Lake was unaffected.

The small spillway (background) on Canyon Lake dam became clogged with debris, and the dam was over-topped. Rapid Creek flows through the dam in a large cut where the dam failed.

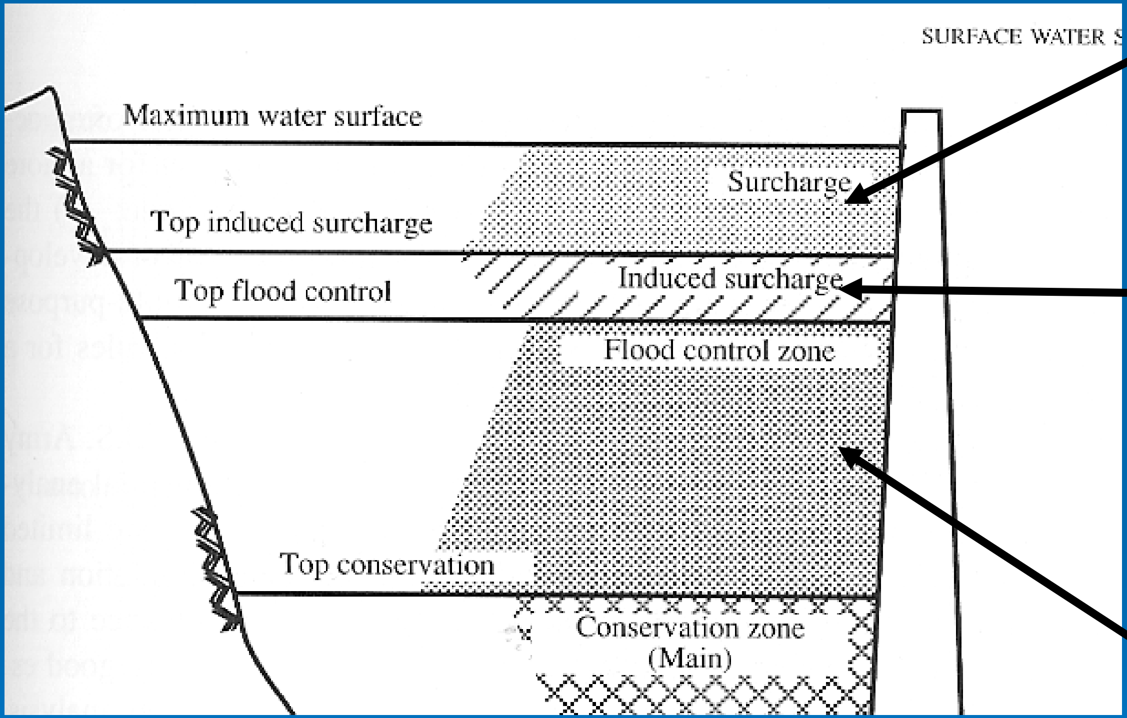
Erosion on the downstream face of Canyon Lake dam ultimately lead to its failure.

Close-up view of destroyed houses. The concrete silo houses a U.S. Geological Survey gage which had recorded a maximum of 2600 cubic feet per second in its 20 year history. On June 9, 1972, the discharge at this point was 31,200 cubic feet per second.

Flood-swept cars, pointing upstream (except for the Volkswagon bug), would stack on top of one another

People were moving into these new houses in western Rapid City the night of the flood.

Flood Release Policies



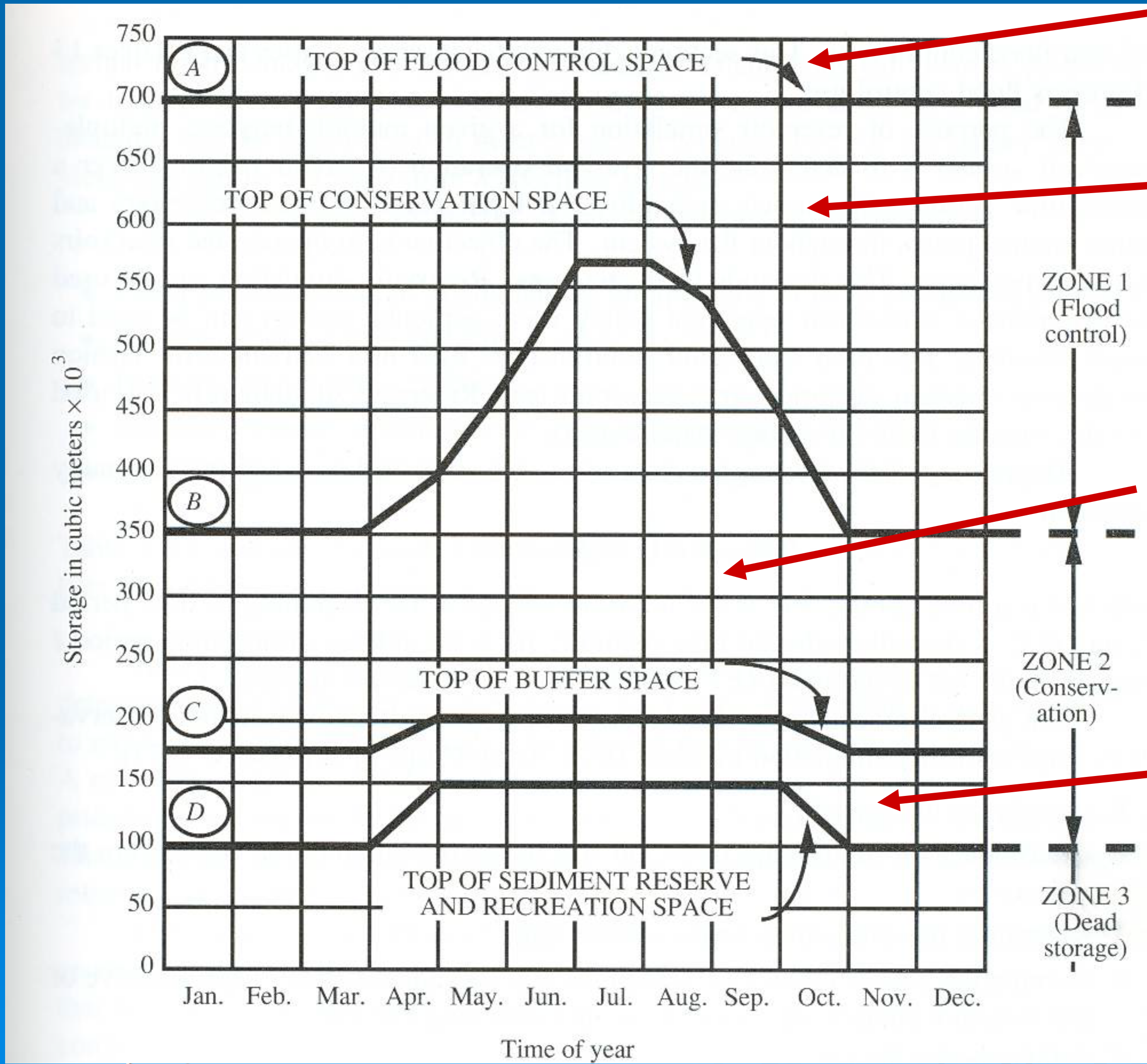
- In the Surcharge pool, all water is released as quickly as possible, without regard to d.s. damage.
- In the Induced Surcharge pool, release as quickly as possible without regard to d.s. damage, but regulation has the opportunity to flatten the peak.
- In the Flood Pool, regulated discharges evacuate the flood pool as quickly as possible, but constrained by d.s. maximum allowable channel flows and rate of change constraints.

Operating Policies (Rules)

Rules to achieve demands, flood control policies, low flow requirements and other objectives by specifying:

- Rule curves (reservoir storage over time)
- Release rules – how to release water when the storage is in specified pools.
- The rules are developed to vary seasonally and to account for uncertainties in inflow and demands.

Rule Curves



Release as quickly as possible, without regard to d.s. damage.

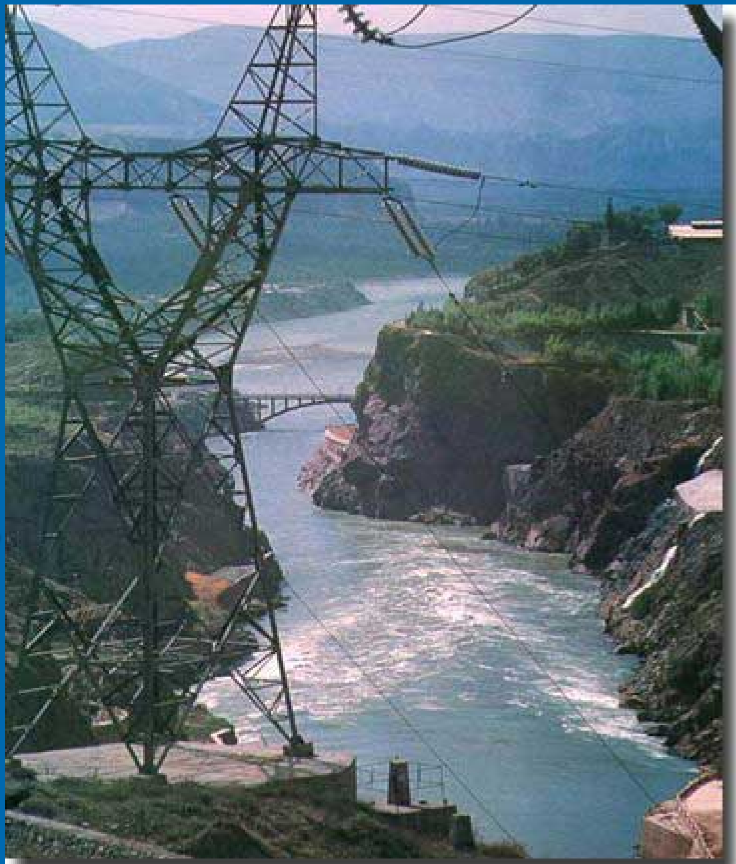
Release down to bottom of flood pool as quickly as possible, but constrained by d.s. maximum allowable channel flows and rate of change constraints.

Meet demands and other objectives, but conserve water as possbile to keep level as close as possible to top of conservation pool.

No water for other objectives, but release as needed and as possible for d.s. low flow augmentation

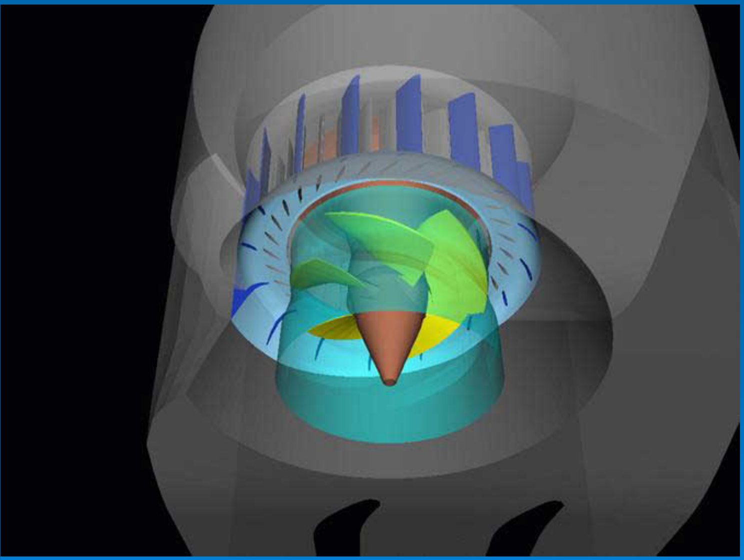
Design of Outlet works must accommodate the operating policies, release requirements and storage requirements



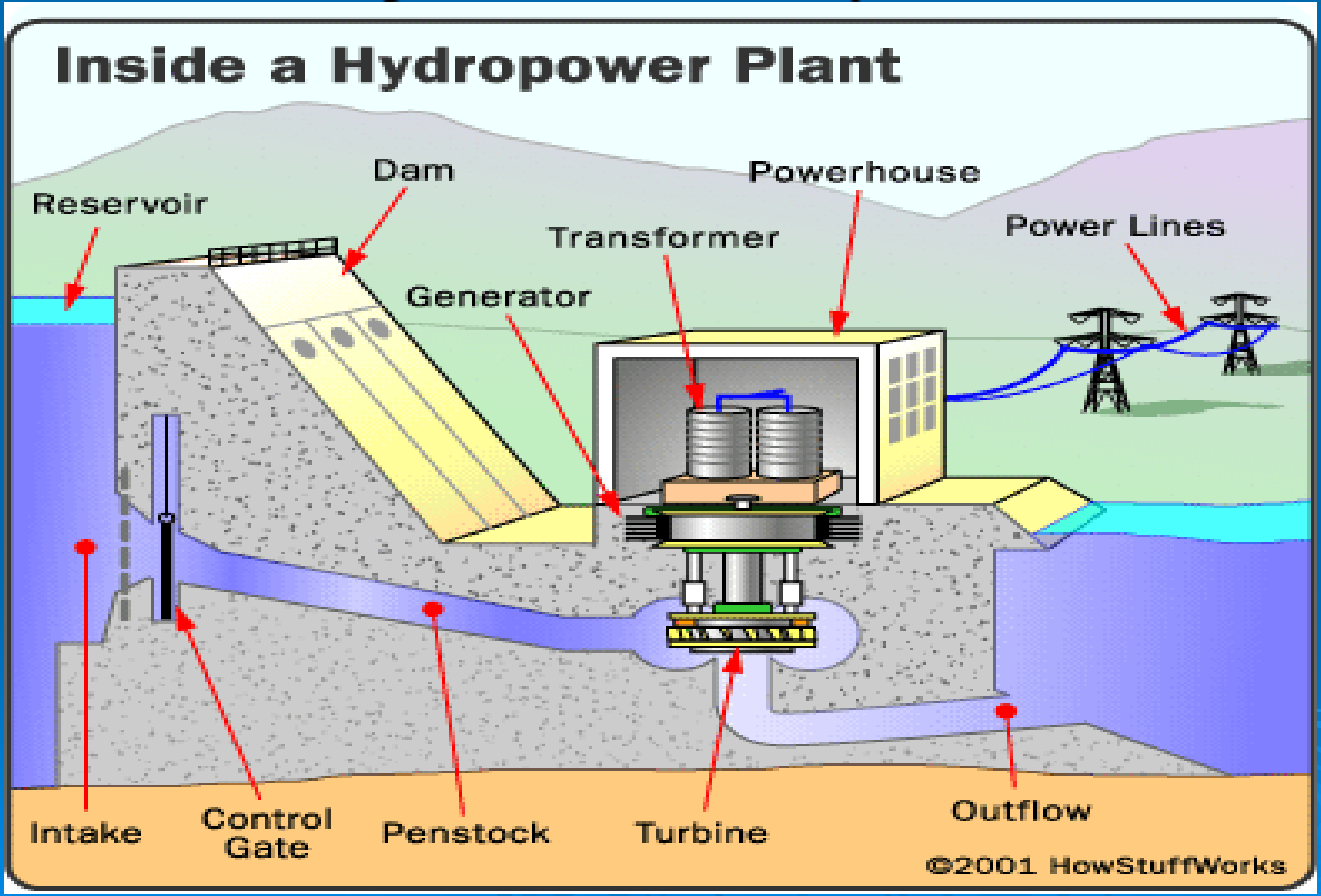


Hydropower

Reference:
Mays and Tung 7.3




Typical layout of a "concentrated fall" hydroelectric plant



Types of Hydropower Plants

- **Run-of-river**
  no usable storage; power is function of flow. There may be a small amount of storage (called **Pondage**) available with daily fluctuations to allow peaking power production. Requires adequate flow year around. Can be utilized on navigation projects, diversion dams for irrigation, and canals and pipelines for delivery to irrigation projects or water supply.
- **Storage**
  multi-purpose; have seasonal regulation capability
- **Re-regulating (after-bay)**
  receives fluctuating Q from u.s. large hydro peaking plant and releases d.s. in smooth pattern
- **Pumped Storage** (offstream or instream "pump-back")
  convert low value off-peak energy to high value on-peak energy by pumping at night/weekends and generating at peak hours.

Estimating Energy Potential

The power (in terms of electrical output) that can be produced by a hydro plant during a specified time interval can be computed using the power equation: Power = ρqgh (head x flow x gravity)

$$kW = \frac{QHe}{11.81}$$

Where: *Q* is the turbine discharge in CFS (flow available during the timestep)

H is the net head in FT

e is the plant efficiency

Gross head is the difference between the u.s. and d.s. water surface elevations.

Net head is the actual head available for power generation, accounting for head losses due to intake structures, penstocks and outlet works.

For planning purposes, the head losses and plant efficiency can be combined. An overall efficiency of .6 to .7 is typically used. Hence $kW = 0.06\ QH_g$ (for overall $e_p = .7$) can be used.

To convert the power output to energy, this equation must be integrated over time, where both Q and H vary with time.

$$KWH = 0.06\int Q(t)H(t)dt$$

Note that Tailwater varies with Q and headwater is a function of storage.

Hydropower Terms

Avg annual energy: estimate of avg amount of energy that could be generated by a hydro project in a year, based on a long period of historical streamflows.

Firm (primary) energy: energy that can be produced on an assured basis. This is the energy that can be produced through the critical period in the historical streamflow record.

Secondary energy: generated in excess of firm output; interruptible but available > 50% of time.

(Installed) Capacity: maximum power that plant can deliver at any given time.

Dependable (firm) capacity: capacity that can be met with high reliability

Hydraulic capacity: max flow that plant can use for power generation. (varies with head and is maximum at “rated” head).

Plant factor (or capacity factor): ratio of average energy (over some period) to installed capacity.

For example:

$$\text{annual plant factor} = \frac{\text{average annual energy}}{(8760\ \text{h})(\text{installed capacity})}$$

Example of Daily Plant Factor (Load Factor)

$$\text{Plant Factor} = \frac{(1{,}200\ \text{MWh})}{(24\ \text{hrs})(100\ \text{MW})} = 50\%$$

energy = 1,200 MWh

time = 24 hours

capacity = 100 Megawatts

55

Ten of the largest hydroelectric producers as at 2009.[34][36]

Country	Annual hydroelectric production (TWh)	Installed capacity (GW)	Capacity factor	% of total capacity
Venezuela	85.96	14.622	0.67	69.20
United States	250.6	79.511	0.42	5.74
Sweden	65.5	16.209	0.46	44.34
Russia	167.0	45.000	0.42	17.64
Norway	140.5	27.528	0.49	98.25
Japan	69.2	27.229	0.37	7.21
India	115.6	33.600	0.43	15.80
China	652.05	196.79	0.37	22.25
Canada	369.5	88.974	0.59	61.12
Brazil	363.8	69.080	0.56	85.56

Estimating Firm Energy

Three Basic approaches for determining energy potential of a proposed hydropower site:

1. Flow-duration curve method – uses flow-duration curve of historic streamflows to develop a power-duration curve. Energy varies only with Q. Good for run-of-river projects
2. Sequential streamflow routing (linear reservoir routing) – manual method for modeling storage, outflow and power generation. This is required for storage projects.
3. Simulation – automates the modeling process.

Flow Duration Method

Typically firm energy is considered as the energy that can be delivered 90-97% of time. Hence, it is based on flow that is equalled or exceeded 90-97% of time.

EXAMPLE (Mays and Tung, Hydrosystems Engineering and Management, p.283-5)

A run-of-river hydro plant is proposed at the Little Weiser River near Indian River, ID. The head available at the site is 30ft and the plant efficiency is about 0.70. Determine the firm energy that can be expected.

For 1 cfs of flow passing through the proposed plant, Power is $kW = 0.06\ QH_g$ = 1.778kW/cfs

Using a monthly timestep (appropriate for firm energy planning studies) and using AF/mo units:

1 AF/mo will produce 21.502 kWH

Flow Duration Method – Example cont'd (Mays and Tung)

The monthly flow duration data is given by the figure.

The firm yield of the basin is 283 AF. Hence the firm energy is

283 x 21.502 = 6085 KWH

The secondary energy is energy that can be provided at least 50% of the time. The 50% exceedance value is 2800 AF/MO. Hence the energy that can be delivered at least 50% of the time is

2800 x 21.502 = 60,206 KWH

The secondary energy is the energy in addition to the firm energy that can be delivered at least half the time.

Secondary energy = 60,206 – 6,085 = 54,121 KWH

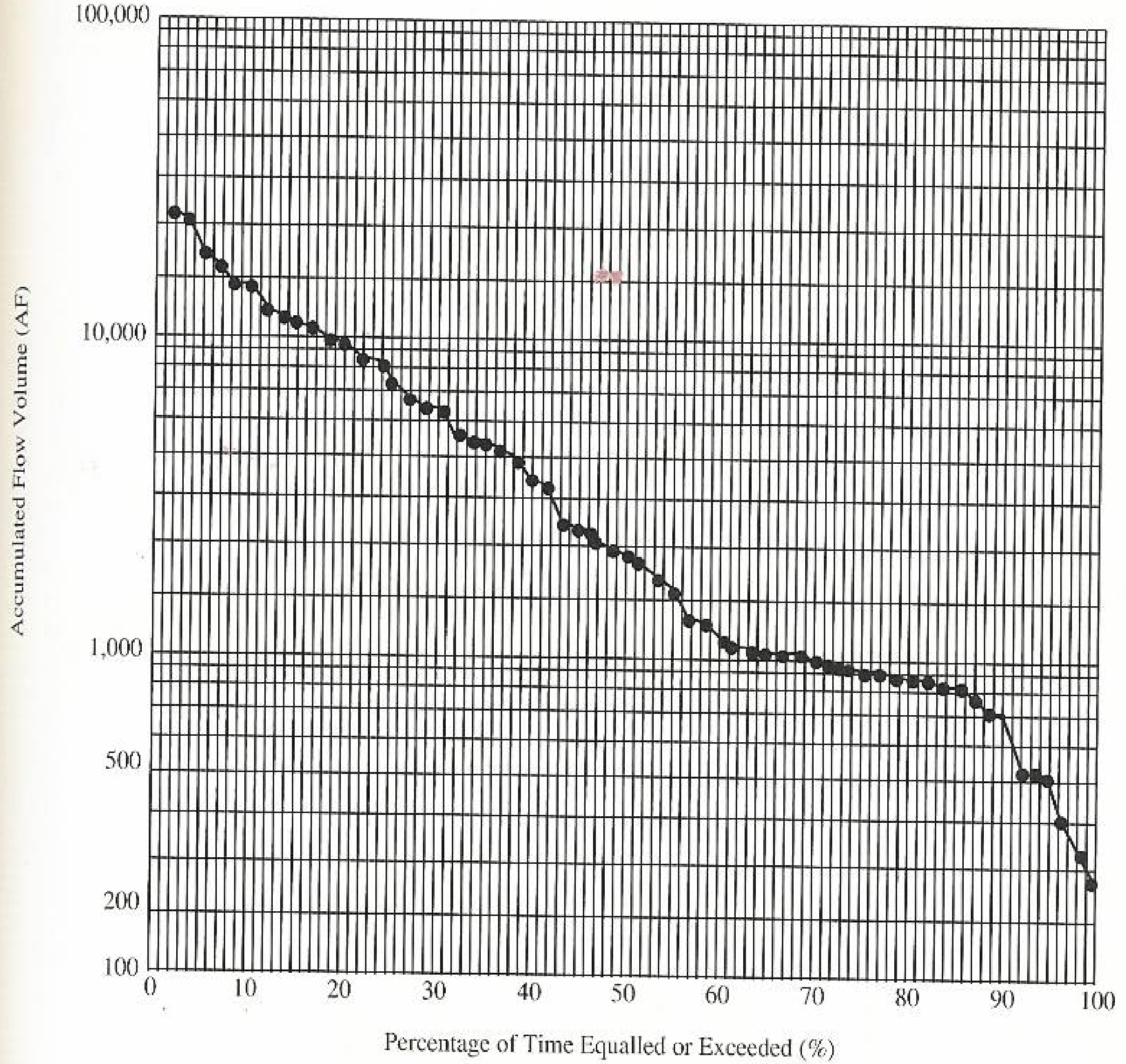


FIGURE 7.2.1
Flow-duration curve for the Little Weiser River near Indian Valley, Idaho (1966–1970).

Estimate Firm Energy

Sequential Routing Method: Like linear reservoir routing, i.e., it is “simulation” in a sequential spreadsheet-like fashion. This can be complex if you have to model the operations over a range of reservoir storages.

But firm energy is based on critical period.

Possible assumptions:

- Consider a critical drawdown period (reservoir full to minimum to full again)
- Project demands and releases
- Assume constant TW elevation H=f(storage)
  - otherwise H = f(storage, Q)

Note that by considering critical period, you don’t have to consider flood flows.

S(t) = S(t-1) + Inflow – Outflow – Losses

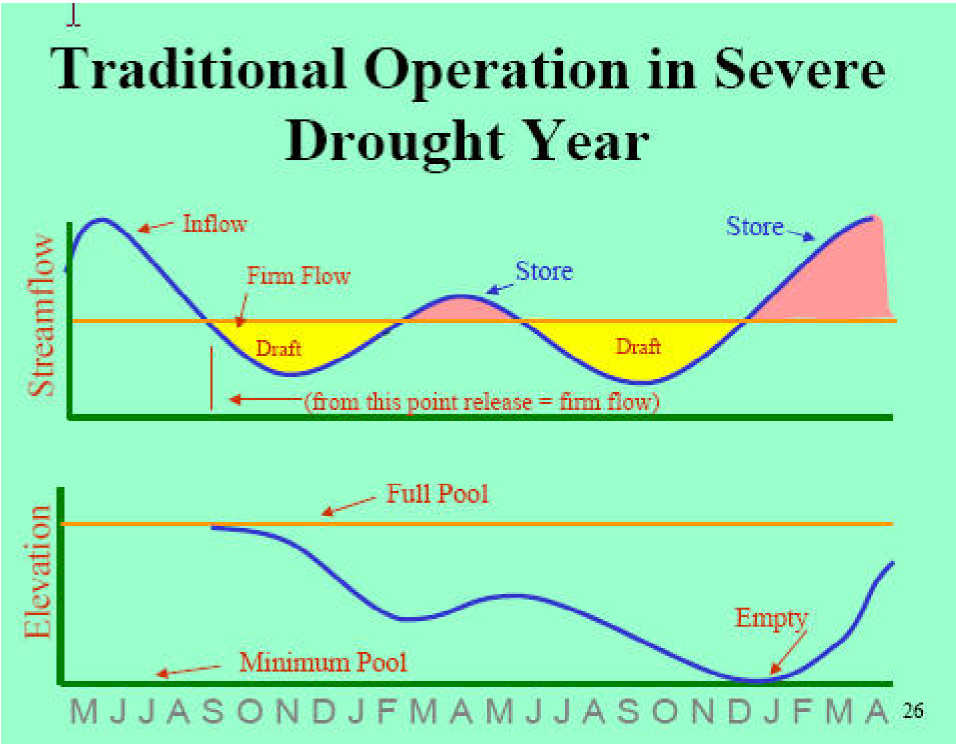
Outflow = Firm Flow (design firm draft or yield)

Energy(t) = eff/11.81 * Outflow * H(Storage) * dt

Firm Energy = minumum Energy from this computation

Can calculate firm energy for various storage

Capacities and reliabilities.



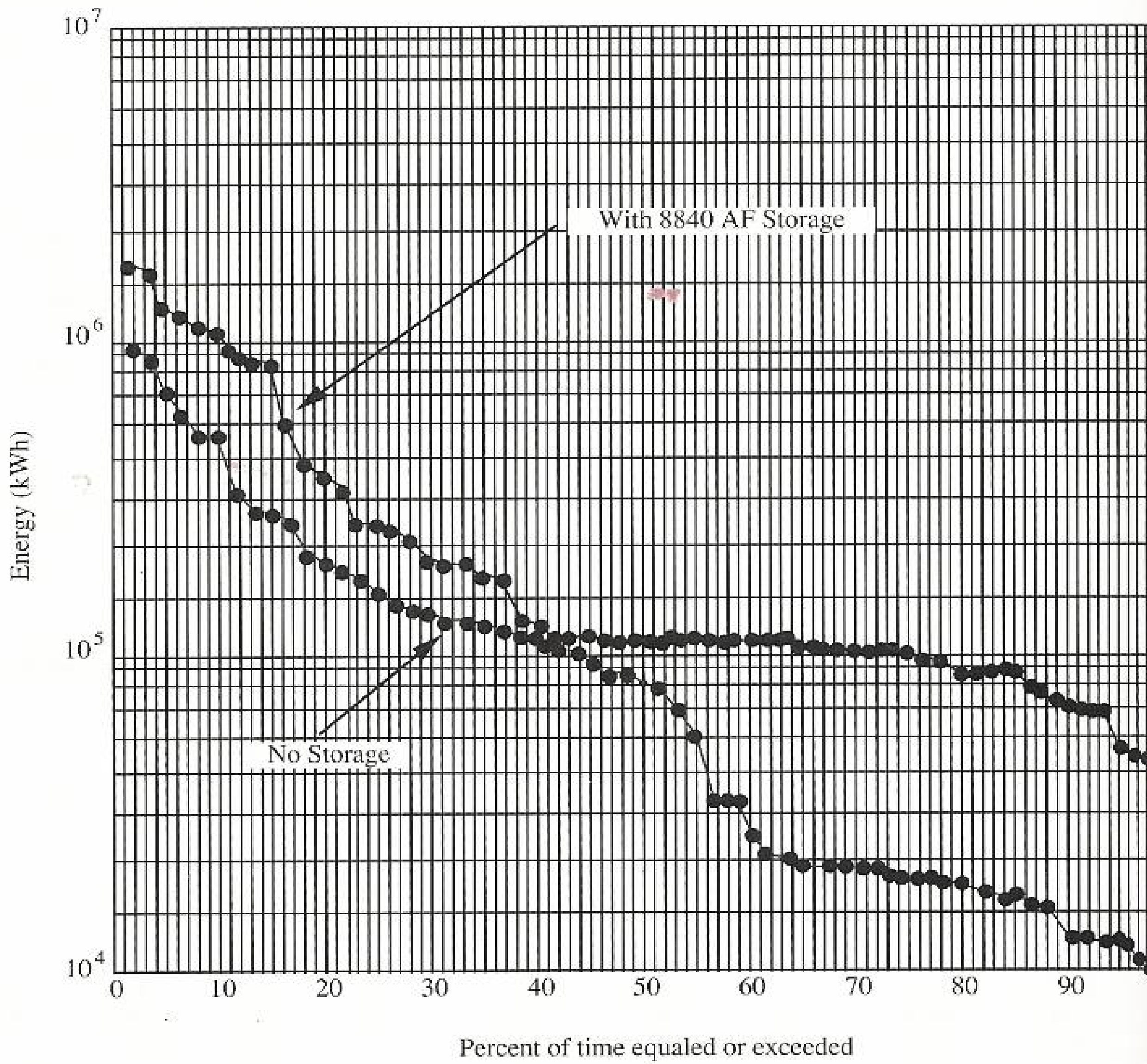


FIGURE 7.3.1
Energy-duration curves for Little Weiser River.

Test #1 February 11 ~ 1 hour

- Class lectures/presentations
- Assigned readings from Loucks, Mays and Tung
- Homework assignments

- Test will be partly multiple choice
- Some numerical problems (have a calculator)
- Closed book

Review/help session – Friday?