MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Civil and Environmental Engineering

1.731 Water Resource Systems

Lecture 17, River Basin Planning – Screening Models
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River Basin Planning

River basin planning is concerned with construction and operation of water resource facilities such as:

- Reservoirs
- Canals and aqueducts
- Irrigation projects
- Hydroelectric plants
- Navigation facilities (e.g. locks)

There are several basic planning tasks associated with large river basin projects:

- Determination of project **location** and **size**
- **Scheduling** and **sequencing** of projects
- **Real-time operation** of projects subject to variable (uncertain) inputs
- Evaluation of project **reliability** and **resilience** when inputs are variable (uncertain)
- **Allocation** of project costs and benefits and associated **financing** issues

Focus here on **screening and simulation** aspects of planning.

→ Identify configuration, operating policies, and likely benefits of the river basin plan

Screening Analyses

Begin with a map and schematic diagram identifying promising sites for facilities.

Facilities considered:

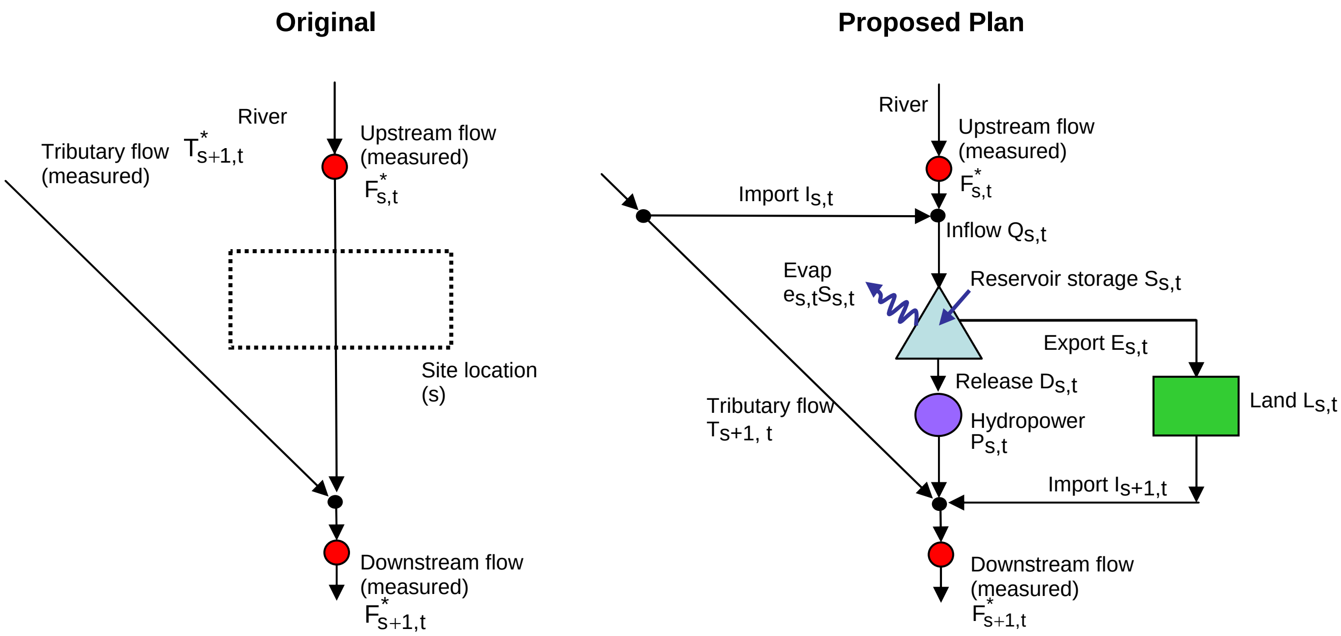
1. Reservoirs
2. Hydropower
3. Irrigation areas
4. Exports and irrigation diversions
5. Imports and irrigation returns

Organize the plan by:

s = site (location of reservoir, river diversion, or low-head hydropower facility)
f = facility (reservoir, hydropower, export, import, irrigation)
t = time (e.g. season or year)

Relationships between sites and between proposed facilities at a given site are represented in a network schematic.

Simple example (one site):



Primary decision variables considered (defined for each site and/or time, in compatible units)

- Facilities sizes/capacities $C_s^{res}, C_s^{hydro}, C_s^{land}, C_s^{imp}, C_s^{exp}$ [various units]
- Reservoir storage $S_{s,t}$ [volume]
- Tributary inflow $T_{s,t}$ [volume/season]
- Reservoir inflow $Q_{s,t}$ [volume/season]
- Reservoir release $D_{s,t}$ [volume/season]
- Import and export flow rates $I_{s,t}$, $E_{s,t}$ [volume/season]
- Irrigated land $L_{s,t}$ [area]
- Hydropower output $P_{s,t}$ [energy]

Some proposed facilities may not be built (i.e. optimum capacities are 0).

Screening Problem Formulation

For screening purposes use **amortized objective function**

All hydrologic inputs and decision variables represent long-term average hydrologic conditions for each season during a **typical year**

All time-dependent variables repeat every year

:

- **Benefits** are obtained every season, depend on time-dependent states (export flow, hydropower energy, cultivated land)
- **Operating costs** are incurred every season, depend on facility capacities
- **Capital costs** are incurred only at initial time, depend on facility capacities

$$\underset{\text{Project designs}}{\textit{Maximize}} \sum_{s} \sum_{f} \left[\left(\sum_{t} \underbrace{B^{f}_{s,t}}_{\text{Benefit}} - \underbrace{O^{f}_{s,t}}_{\text{Operating cost}} \right) - d(r,T)\underbrace{K^{f}_{s}}_{\text{Capital cost}} \right]$$

$$d(r,T) = \frac{r(1+r)^{T}}{(1+r)^{T} - 1}$$ Discount factor r = interest rate, T = planning period (yrs)

Subject to following constraint categories:

1. Capacity
2. Flow (water balance)
3. Irrigation
4. Hydropower

Example: Rio Colorado Basin, Argentina

Illustrate screening model with case study based on plan developed for the Rio Colorado river basin in Argentina (see figures below).

Case study documented in Major D.C. and R.L. Lenton, *Applied Water Resource Systems Planning*, Prentice Hall, 1979.

Base plan designed to maximize national income

3 seasons define a 'typical' year (t = 1, 2, 3).

Sites are located at each reservoir, river export, or low-head (no reservoir) hydropower facility as indicated on proposed project map (below).

Seasonal Benefits:

For Rio Colorado each benefit is assumed **linearly proportional** to an associated state variable

States are **constrained by capacities**.

Each capacity C_s^f (a decision variable) is constrained by **maximum capacity** $C_s^{f,max}$ (a specified input).

Benefit, state, and capacity > 0 only if associated facility integer variable $y^f_{s,t} = 1$:

$$\text{Export :} \qquad B^{exp}_{s,t} = \begin{cases} \sim E_{s,t} \le C_s^{exp} \le C_s^{exp,max}\, y_s^{exp} & \text{Non-reservoir export} \\ \sim E_{s,t} \le C_s^{exp} \le C_s^{exp,max}\, y_s^{res} & \text{Reservoir export} \\ \sim L_{s,t} \le C_s^{land} \le C_s^{land,max}\, y_s^{exp} & \text{Non-reservoir irrigated land} \\ \sim L_{s,t} \le C_s^{land} \le C_s^{land,max}\, y_s^{res} & \text{Reservoir irrigated land} \end{cases}$$

integer variable $y_s^{res} = \begin{cases} 0 = \text{ reservoir not built} \\ 1 = \text{ reservoir built} \end{cases}$

Hydropower: $B_{s,t}^{hydro} \sim \begin{cases} P_{s,t} \le C_s^{hydro} \le C_s^{hydro,max} y_s^{res} & \text{Reservoir hydropower} \\ P_{s,t} \le C_s^{hydro} \le C_s^{hydro,max} y_s^{hydro} & \text{Low-head hydropower} \end{cases}$

Conditionality constraint: Reservoir-related export, hydropower, and irrigation facilities cannot be built unless reservoir is built ($y_{s,t}^{res} = 1$).

Capital costs:
For Rio Colorado variable costs are assumed linearly proportional to capacity

Reservoir: $K_s^{res} = \gamma_{s,\,fixed}^{res} y_s^{res} + \gamma_{s,var}^{res} C_s^{res}$

$\gamma_{s,\,fixed}^{res}$ = fixed capital cost [$]

$\gamma_{s,\,fixed}^{res}$ = variable capital cost [$/unit capacity] ~ C_s^{res}

If $y_s = 1$ (so benefit > 0) fixed costs are incurred.
Capital costs for export and import channels, hydropower, and irrigated land facilities are defined in the same way.

Operating Costs:

$O_{s,t}^{res} = \gamma_{s,t}^{res} K_s^{res}$ [$/season] $\gamma_{s,t}^{res}$ = fraction of capital cost required for operation/maintenance each season

Capacity Constraints
Reservoir storage:

$S_{s,t} \le C_s^{res}$ $C_s^{res} \le C_s^{res,max} y_s^{res}$ [volume]

Flows in channels from/to reservoir or river:

$E_{s,t} \le C_s^{exp}$ $C_s^{exp} \le C_s^{exp,max} y_s^{res}$ or $C_s^{exp} \le C_s^{exp,max} y_s^{exp}$ [volume/season]

$I_{s,t} \le C_s^{imp}$ $C_s^{imp} \le C_s^{imp,max} y_s^{res}$ or $C_s^{imp} \le C_s^{imp,max} y_s^{exp}$ [volume/season]

Land irrigated from reservoir or river diversions

$L_{s,t} \le C_s^{land}$ $C_s^{land} \le C_s^{land,max} y_s^{res}$ or $C_s^{land} \le C_s^{land,max} y_s^{exp}$ [area]

Hydropower

$P_{s,t} \le \Delta t C_s^{hydro}$ [energy]

$C_s^{hydro} \le C_s^{hydro,max} y_s^{res}$ or $C_s^{hydro} \le C_s^{hydro,max} y_s^{hydro}$ [power]

$\Delta t = 1$ [season]

Flow constraints
Flows in each of the 3 seasons assumed to repeat every year

$Q_{s,t} = F_{s,t}^{*} + I_{s,t}$ Reservoir inflow

$T_{s+1,t}^{*} = I_{s,t} + T_{s+1,t}$ Tributary Import

$$S_{s,t+1} = S_{s,t} + \Delta t[Q_{s,t} - E_{s,t} - D_{s,t} - e_{s,t}(S_{s,t})] \quad \text{Reservoir water balance}$$

$$S_{s,1} = S_{s,4} \quad \text{Cyclical storage}$$

$$F_{s+1,t} = D_{s,t} + I_{s+1,t} + T_{s+1,t} \quad \text{Outflow to next site}$$

All states are **non-negative**

Evaporation-storage function $e_{s,t}(S_{s,t})$ is an input derived from topography.

Irrigation Constraints

Different amounts of land may be cultivated each season.

Water required to cultivate land area $L_{s,t}$

$$E_{s,t} = \tau_{s,t} L_{s,t} \quad , \quad \tau_{s,t} = \text{irrigation water requirement [depth/(season area)]}$$

Downstream return flow:

$$I_{s+1,t} = (1 - \rho_{s,t}) E_{s,t} \quad , \quad \rho_{s,t} = \text{consumptive use coefficient [unitless]}$$

Hydropower Constraints

Energy produced depends on release (reservoir) or stream flow (low head) and head:

$$P_{s,t} = \varepsilon_s D_{s,t} H_{s,t}(S_{s,t}) \quad , \quad \varepsilon_s = \text{efficiency [unitless]}$$

Head-storage function $H_{s,t}(S_{s,t})$ is an input derived from topography.

Results of Rio Colorado Study

Screening model produces following results:

1. Configuration of plan (facilities built with their capacities):
   $y_s^{res}, C_s^{res}, \quad y_s^{exp}, C_s^{exp} \quad y_s^{imp}, C_s^{imp} \quad C_s^{land} \quad y_s^{hydro}, C_s^{hydro}$

2. Seasonal values of states:
   $Q_{s,t} \quad S_{s,t} \quad e_{s,t}(S_{s,t}) \quad D_{s,t} \quad I_{s,t} \quad E_{s,t} \quad L_{s,t} \quad P_{s,t} \quad H_{s,t}(S_{s,t})$

3. Benefits and costs for each facility and for overall plan:

The base run, which maximizes national income, produced following plan:

Reservoirs constructed:

- 3 of 3 reservoirs in the upper (Mendoza) portion of basin
- 0 of 2 reservoirs in central portion
- 1 of 3 reservoirs (Case de Piedra) in lower portion

Irrigation areas constructed:

- 10 of 17 possible areas built in all 3 portions of the basin

Hydropower plants constructed:

- 2 of 13 possible plants constructed in upper portion, on diversion aqueducts

Interbasin transfers (exports) constructed:

- 2 of 2 exports (upper portion) and 1 of 2 imports (central portion)

Other cases using different objectives, putting priority on regional income, irrigation income, etc, give different configurations, see Major and Lenton (1979).

The following figures were taken from Major, David C, and R.L. Lenton. *Applied Water Resource Systems Planning.* Upper Saddle River, NJ: Prentice Hall, 1979. ISBN: 0130433640.

Map of Rio Colorado Basin
Altitude Profile Along Rio Colorado River
Facilities in Rio Colorado Lower Basin
Schematic of Proposed Rio Colorado Basin Plan
Reservoir Cost-Capacity Curves
Reservoir Volume-Depth Curves
Reservoir Area-Depth Curves

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