Renewable Energy & Hydroelectric Works

8^{th} semester, School of Civil Engineering

Hydroelectric reservoirs: technology and operation

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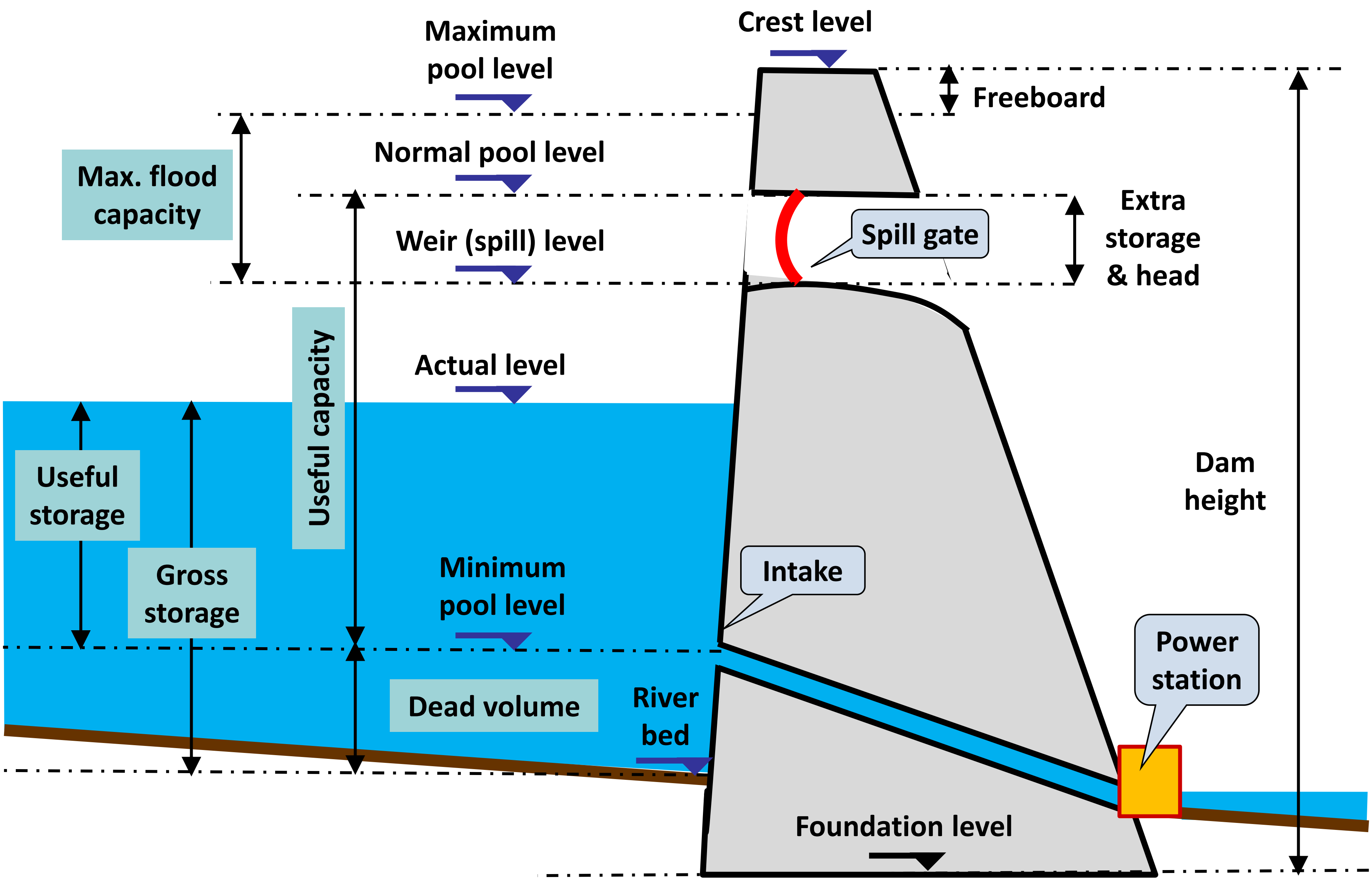
Schematic layout of hydroelectric reservoir

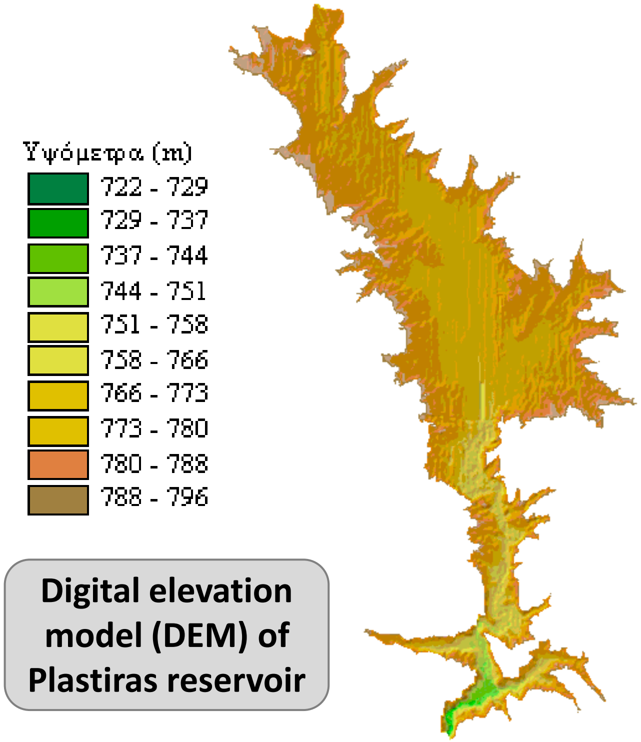


Characteristic elevations & storage components

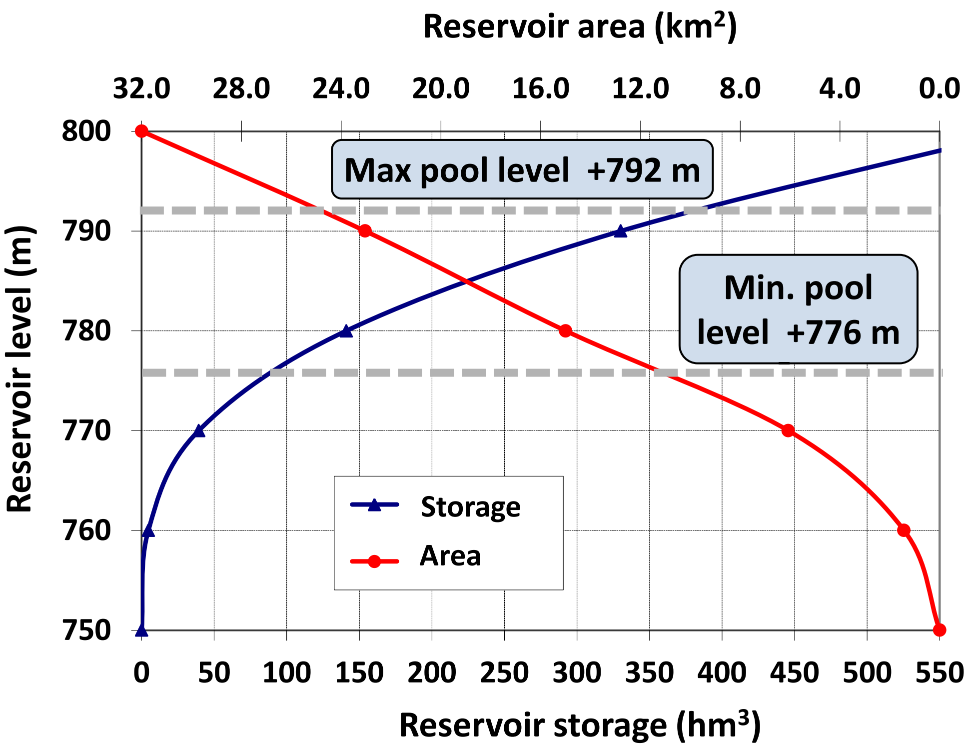
- **Normal pool level**: Maximum elevation to which the water surface will rise during normal operating conditions; the corresponding storage is referred to as **total capacity**.
- **Minimum pool level**: Lowest elevation to which water is drawn from a reservoir under normal operating conditions.
- **Maximum pool level**: Maximum elevation to which the water surface is expected to rise during the design flood of the spillway.
- **Dead storage**: Volume of water held below the minimum pool level, which cannot be used for any purpose under normal condition. It depends on:
    - the volume of sediment that is expected to be deposited into the reservoir during its design life;
    - the elevation of the lowest outlet of the dam;
    - the minimum head required for efficient functioning of the turbines.
- **Useful storage**: Volume of water stored between the normal pool level and the minimum pool level, i.e. difference between the actual storage and the dead volume; also referred to as **active storage**, as water can be used for various purposes.
- **Useful capacity**: Total capacity after subtracting the dead storage.
- **Surcharge or flood storage**: Uncontrolled volume of water stored between the normal and the maximum pool level; it exists only during floods and cannot be retained for later use (exception: regulation through effective **spillway gate control**).

Storage-elevation & area-elevation curves

- Graphs illustrating the change of reservoir storage, s, and impoundment area, a, against the water level, z.
- The relationships $s = f_1(z)$ and $a = f_2(z)$ are extracted on the basis of data sets (z_i, a_i) that either estimated by measuring the associated areas on a topographic map or are calculated automatically (and with high accuracy) by using the digital elevation model of the area of interest.



Digital elevation model (DEM) of Plastiras reservoir



- The two curves can also be expressed analytically, as power functions of z, i.e.:

$$s = \kappa\,(z - z_0)^{\lambda}$$

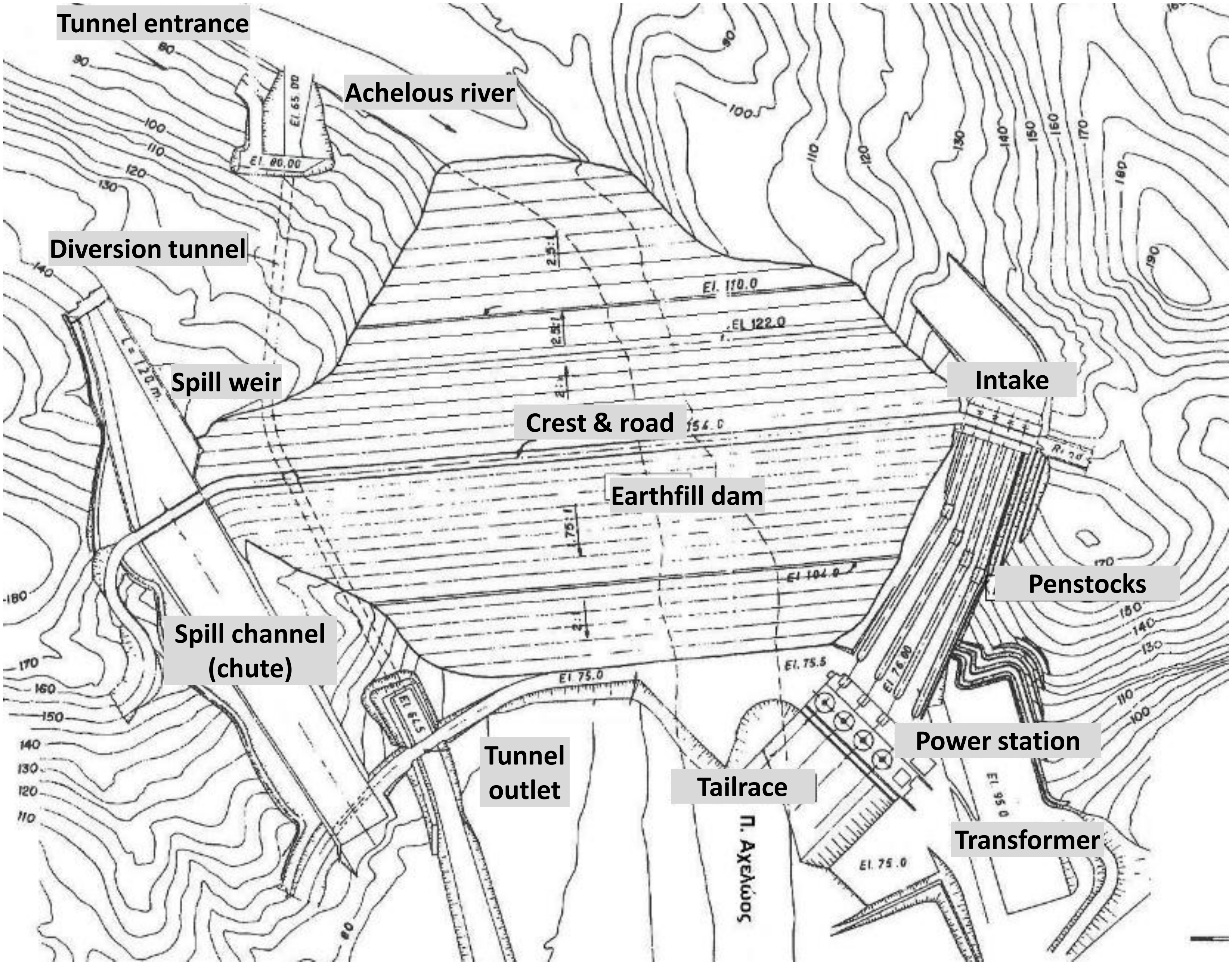
$$s = \kappa\,(z/z_0 - 1)^{\lambda}$$

where κ and λ are parameters that are estimated through regression, and z_0 is a characteristic low level, e.g. the dead volume level or the foundation level.

Major hydraulic structures

- **Dam**: Barrier constructed across a river, thus forming an artificial lake (reservoir) to hold back water and raise its level. Generally, they are classified into two groups:
    - *Embankment dams*, constructed from natural material excavated or obtained nearby (further classified into earthfill and rockfill);
    - *Gravity dams*, either from conventional vibrated concrete (CVC) or concrete mixed with earth materials, e.g. roller compacted concrete (RCC) or hardfill.
- **Ancillary hydraulic structures**:
    - *Bottom outlet*, which allows emptying the reservoir in case of emergency;
    - *Intakes* and *penstocks*, controlling the water releases through the reservoir;
    - *Spillway system*, typically consisting of a controlling weir, a channel (chute) and a stilling basin, to safely pass overflows downstream when the reservoir is full;
    - *Spillway gates*, to regulate floods flows and further increase both the storage capacity and the available head (mainly applicable to large hydroelectric works);
    - *Power station*, located at the end of the penstock, to host the electromechanical equipment (turbines, generators, transformers);
    - *Internal drainage* works, collecting seepage within the body of the dam;
- **Auxiliary structures (used during the construction phase)**:
    - *Cofferdams* (the upstream one is often incorporated into the main dam);
    - *Diversion system* (tunnel or channel), to bypass the river flows during construction;

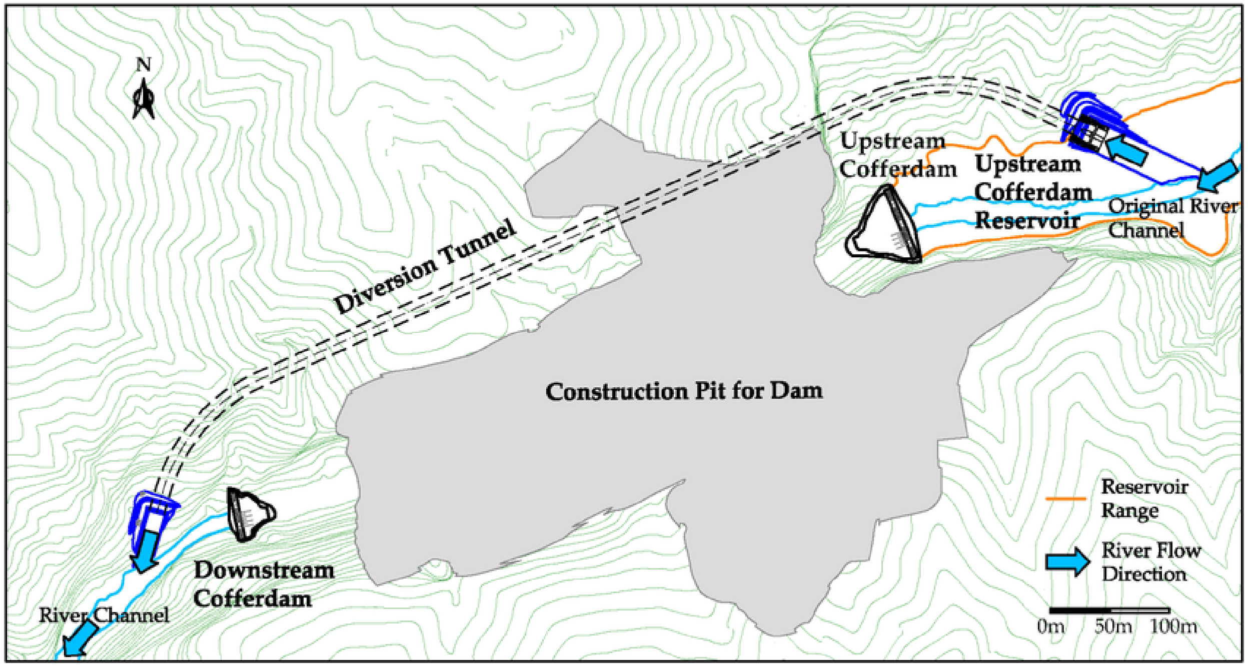
Layout of hydroelectric system: Kastraki, Achelous



Layout of hydroelectric system: Kastraki, Achelous

River diversion during dam construction

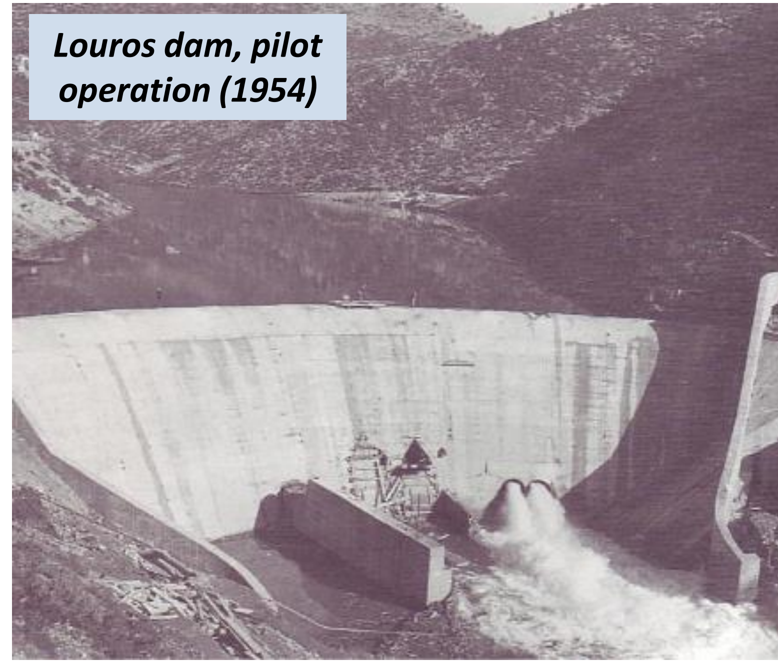
- The period of construction may exceed ten years, thus the upstream cofferdam and the diversion tunnel are designed to retain floods of return periods 20-50 years.
- Usually, another (smaller) cofferdam is built downstream of the main dam site to prevent water flowing back into the construction area.
- After the end of construction, two closure actions are employed to allow **first impounding**, i.e. a temporary closure of the entrance by using gates, and a permanent closing, by implanting a concrete plug inside the tunnel.



Entrance & outlet of diversion tunnel during construction of Hilarion dam

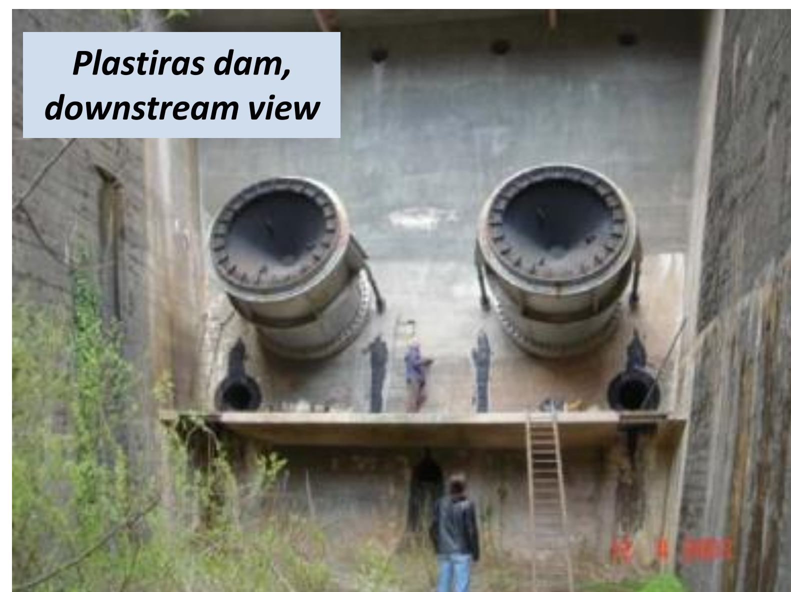
Bottom outlet

- Bottom outlets mainly are safety works, to ensure conveyance of water downstream to lower the level of the reservoir or even to empty the reservoir, in case of **emergency**.
- Their inlets are constructed close to the foundation; part of the diversion tunnel can be incorporated into the bottom outlet.
- Modern bottom outlets are also designed to provide **ecological flow** to the downstream river, as well as to discharge **sediments**, thus increasing the economic life of the dam.



Louros dam, pilot operation (1954)

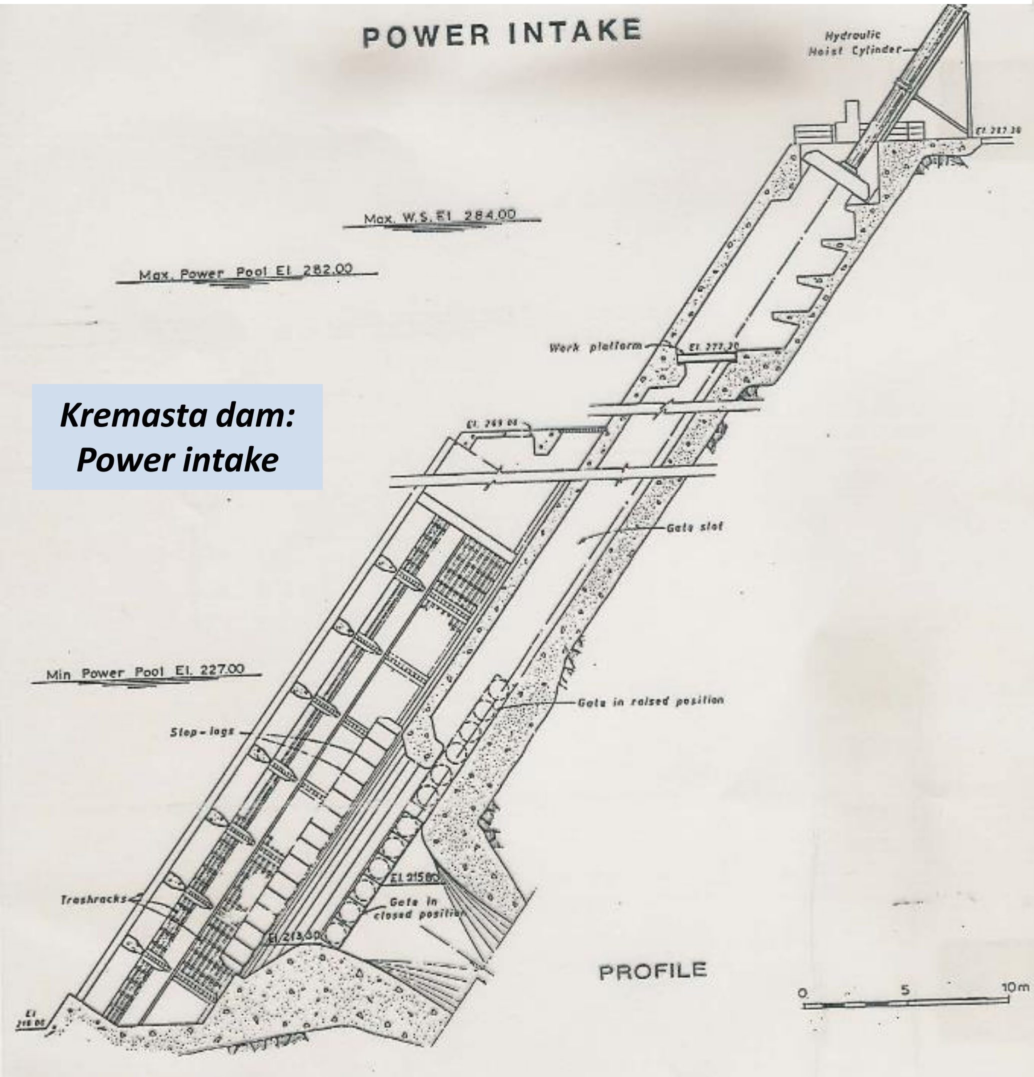
Cerro del Águila Dam, Peru (2015)



Plastiras dam, downstream view

Intakes and associated works

- Usually inclined or vertical structures that are submerged, equipped with gates, trash racks, bulkheads and stoplogs.



Kremasta dam: Power intake

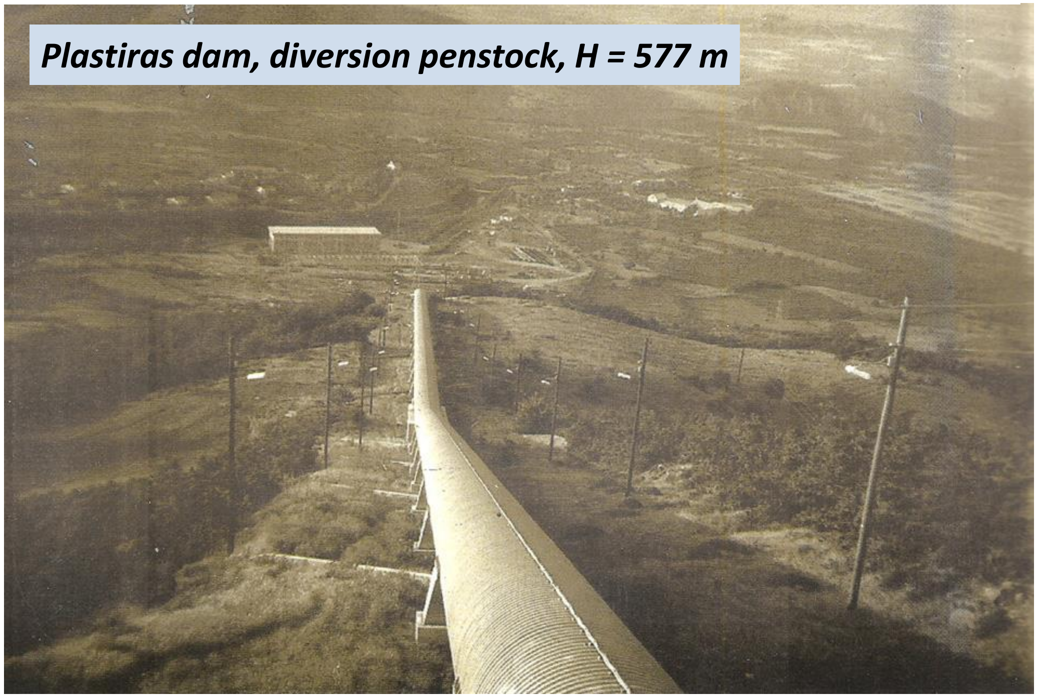
Stratos dam: inclined intakes under construction

Kastraki dam: trash racks and gates

Penstocks and associated works

- For large hydroelectric systems, the **number of penstocks** typically equals the number of turbines (expensive design); otherwise a single penstock of larger diameter is applied that splits at the power house (increase of local losses).
- General design recommendations:
  - Total hydraulic losses should not exceed 5% of gross head;
  - Velocity should not exceed 6 m/s
- Major design issue: water hammer (surge tank or pool, in case of large pipes and large heads)

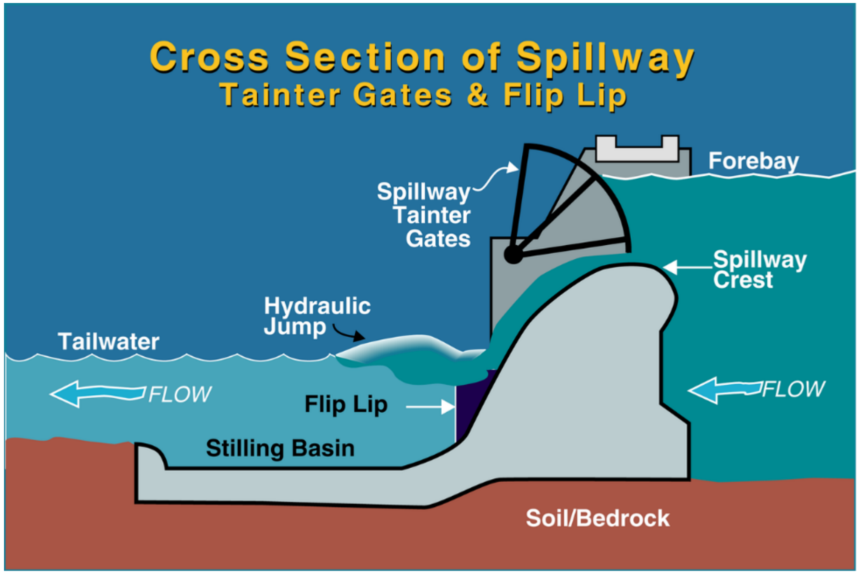
Kastraki dam: four exposed (surface) penstocks, H = 76 m



Plastiras dam, diversion penstock, H = 577 m

Spillways

- Objective: safe removal of the overflowed floodwater and its safe transfer and disposal to the downstream river. Main components are:
    - Approach channel;
    - Control structure (weir);
    - Discharge channel (chute);
    - Terminal structure (stilling basin);



- During a flood event, the inflow hydrograph is **routed** through the reservoir and the spillway system, thus the outflow hydrograph arriving downstream is attenuated. The return period of the **design flood** may exceed 5 000 to 10 000 years.
- **Controlled spillways**: The flow is regulated through mechanical structures or gates. This design allows nearly the full height of the dam to be used for water storage, and flood waters can be released as required by opening one or more gates.
- **Uncontrolled spillways**: When the water rises above the crest, it begins to be released from the reservoir. The outflow rate is controlled only by the depth of water above the reservoir's spillway. The volume above the crest can only be used for the temporary storage of floodwater; it cannot be accounted for as useful storage, because it is normally empty.

Remarks: In hydropower reservoirs, in order to minimize water losses due to spill, when the water level reaches or exceeds the weir elevation, the turbines are forced to operate in their maximum capacity, thus producing surplus energy (also referred to as **secondary energy**).

Spillways of large hydroelectric reservoirs in Greece

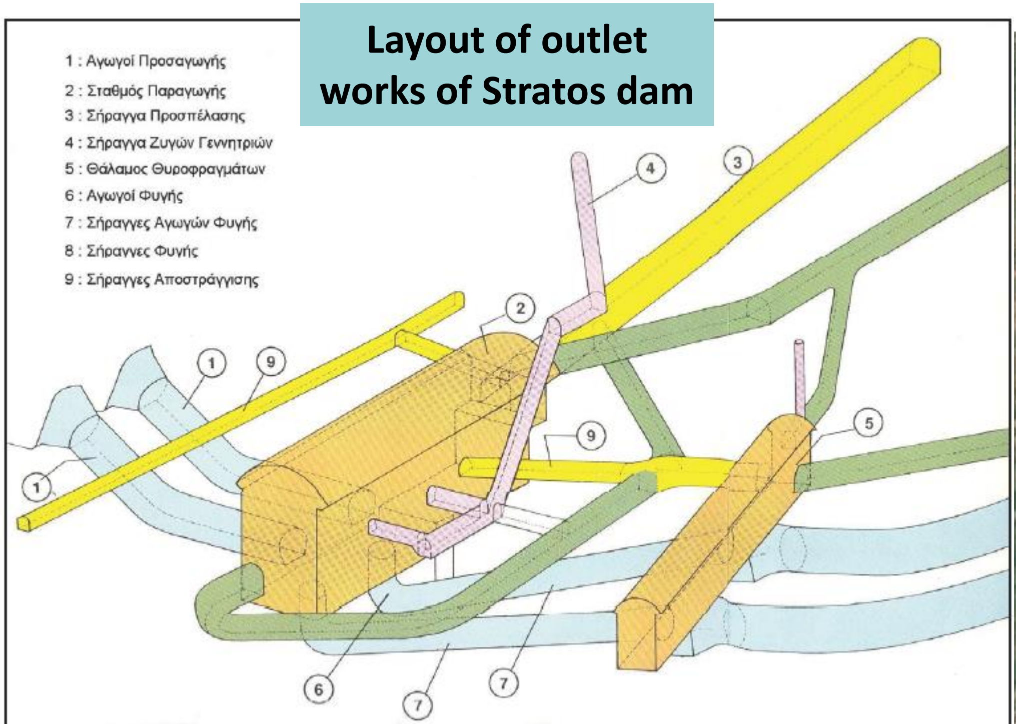
Gated spillway, Kremasta dam

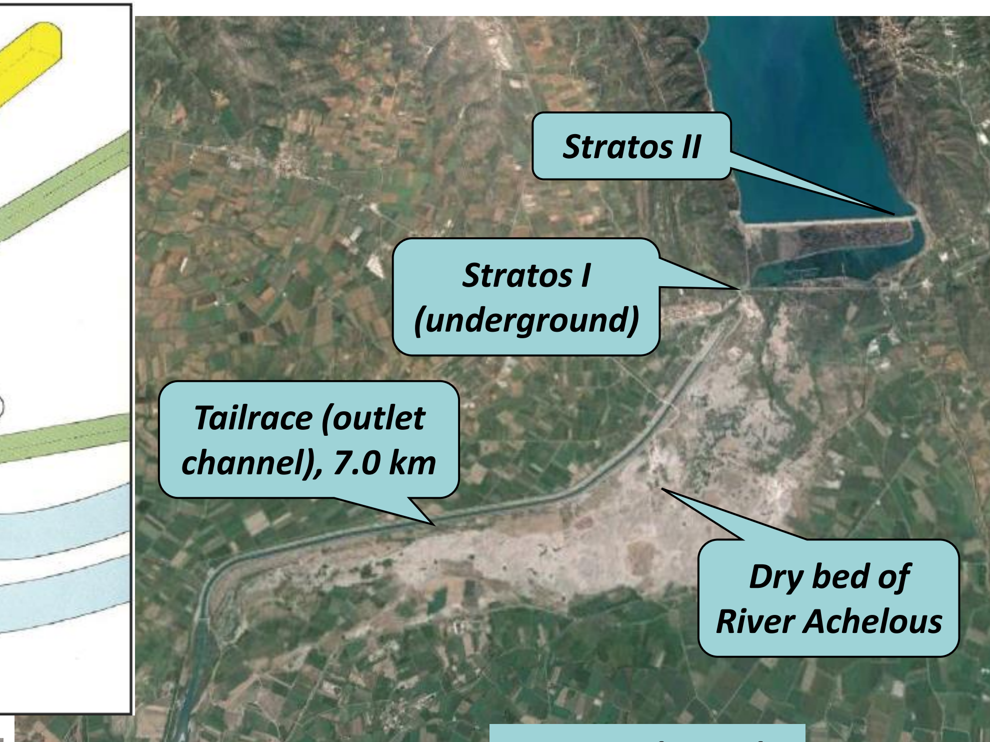
Side-channel spillway, Kastraki dam

Overturning gates, Kastraki

Pilot operation of Platanovrisi spillway

Outlet works: draft tubes & tailraces



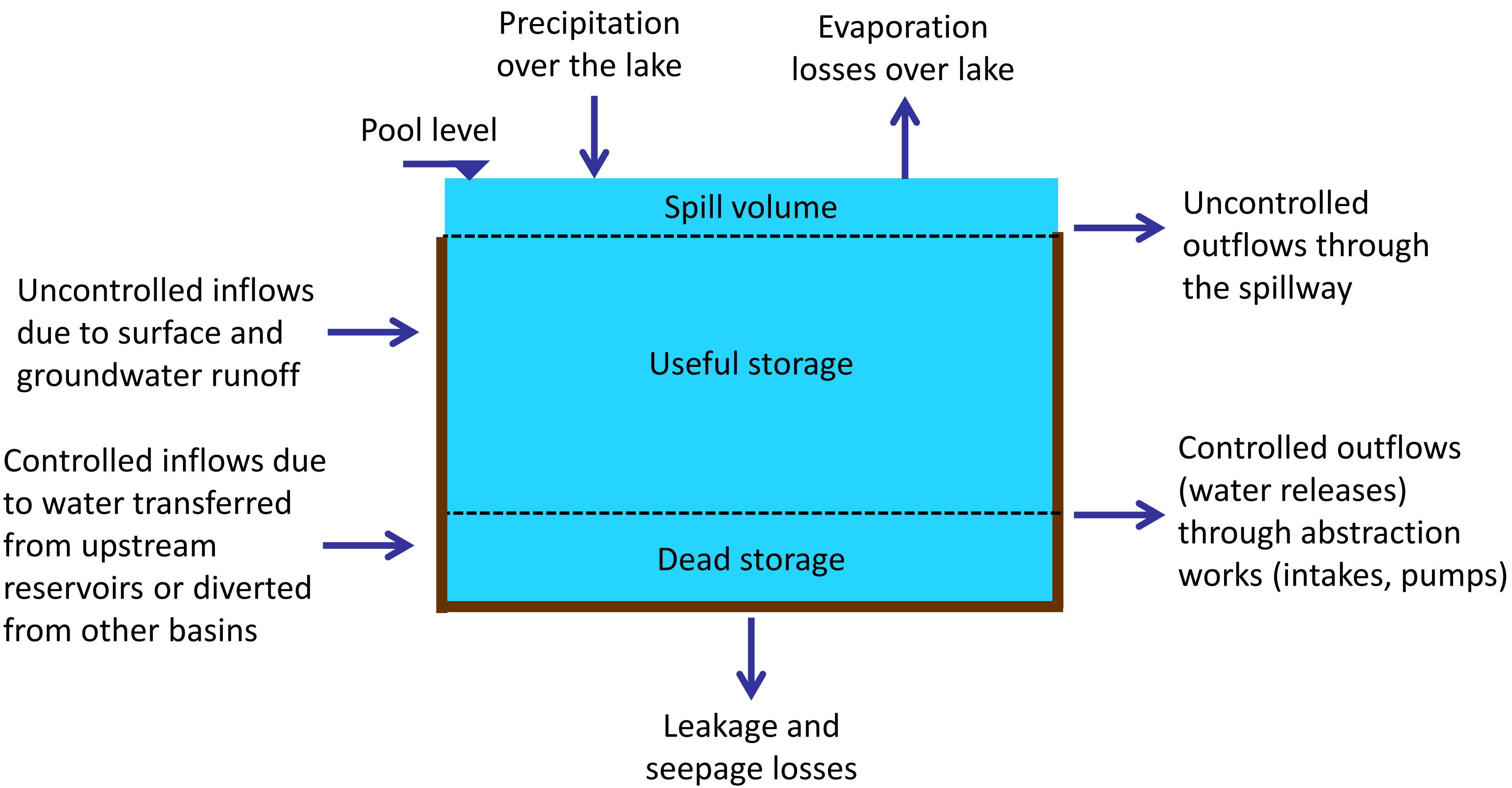


Reservoir dynamics: Water balance equation

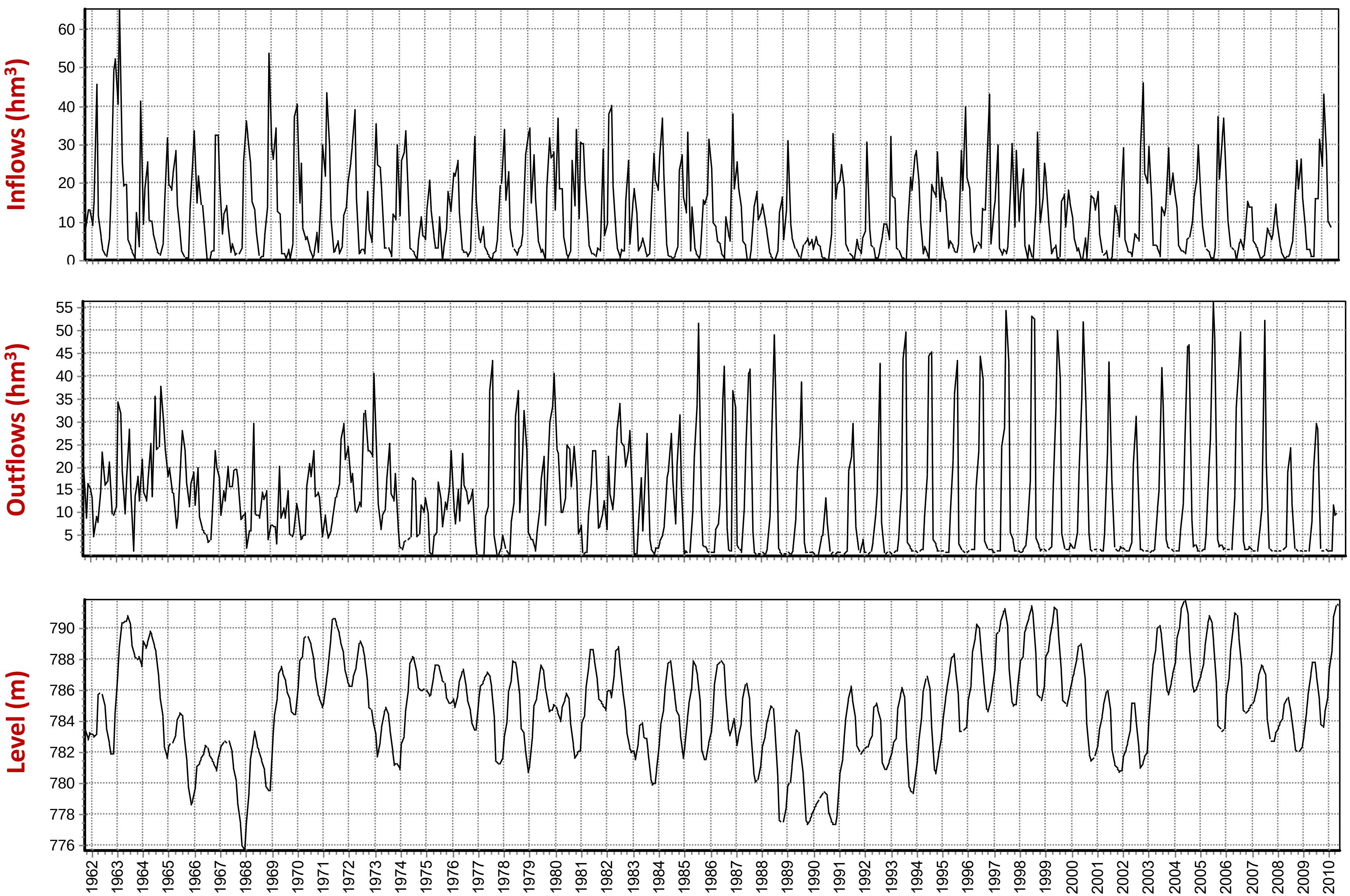
- Continuous formulation, considering all inflow and outflow variables as instantaneous:

$$ds/dt = \text{inflows} - \text{outflows}$$

- Discrete formulation, considering the storage difference and the accumulated inflows and outflows during a specific time interval (t, $t + \Delta t$).



Plastiras reservoir: monthly water balance components



Hydroelectric reservoir simulation: model inputs

- Simulation horizon (number of time steps): n
- Elevation data:
  - Minimum poll level, z_{min}
  - Maximum poll level, z_{max}
  - Bottom level (river bed, datum), z_0
  - Power station level (penstock outlet), z_κ
- Characteristic formulas (κ, λ, α, β, ψ: constants):
  - Storage vs. elevation:

$$s = \kappa\,(z - z_0)^\lambda$$

  - Discharge vs. head:

$$u = \alpha\,(z - z_\kappa)^\beta$$

  - Energy production vs. water release & head:

$$e = \psi\, r\,(z - z_\kappa)$$

where e: energy; r: release; $z - z_\kappa$: head; $\psi := \rho g \eta \leq 9810\ \mathrm{N/m^3} = 0.2725\ \mathrm{GWh/hm^4}$

- Inflow time series, i_t ($t = 1 \ldots n$)
- Target energy production, e^* (constant, seasonally constant or varying)
- Initial storage, s_0 (for relatively large n, its impact is negligible)

Simulation: Simplified, step-by-step representation of the operation of a **complex dynamic system**.

In the context of reservoir systems, simulation is employed to estimate the **unknown outflows** (i.e., releases to fulfill downstream water and energy demands, uncontrolled losses due to spill), for given technical characteristics, given inflows and demands, and given initial storage.

Based on simulation outcomes, we can evaluate the system **performance** against a set of criteria.

General formulation of reservoir simulation model

- The reservoir dynamics is described via the water balance equation in discrete time form:

$$s_{t+1} = s_t + i_t - r_t - w_t$$

  where s_t is the storage at time step t, i_t are the accumulated net inflows within time interval $[t, t + 1]$, i.e. runoff produced over the upstream basin and precipitation falling over the reservoir surface minus water losses due to evaporation and leakage, r_t are the controlled water releases through the intakes, and w_t are overflows through the spillway.

- For a given storage at the beginning of simulation, s_0, a given sequence of inflows (either projected or synthetically generated), and given demand d_t, the water balance can be explicitly solved to provide the unknown quantities s_{t+1}, r_t and w_t, at each time step.
- In particular, for a specific demand, d_t, the actual release will be the minimum between the available water and the desirable release to meet this demand, i.e.:

$$r_t = \min\,(s_t + i_t - s_{\min}, u_t, d_t)$$

  where $s_{\min}$ is the reservoir storage at the minimum operation level, i.e. up to the intake, and u_t is the maximum allowable abstraction due to flow capacity constraints.

- If the remaining storage, after implementing releases, exceeds the reservoir capacity, $s_{\max}$, the surplus quantity is considered water loss due to spill, i.e.

$$w_t = \max\,(0, s_t + i_t - r_t - s_{\max})$$

Remarks: The above configuration implements an explicit simulation scheme, where all individual components (processes) of the water balance equation are carried out sequentially.

Adjustment of simulation model for hydroelectric systems

- In the case of hydroelectric reservoirs, where a desirable energy production target is assigned, called **firm energy**, an equivalent water demand has to be estimated at each time step, on the basis of both the energy target, e^*, and the available net head.
- Actually, the net head is function of the unknown discharge and the varying reservoir level over the time interval. In order to provide an explicit simulation scheme, the varying level is approximated as constant and equal to the known reservoir level at the beginning of the time step, z_t, thus using the simplified formula:

$$d_t = e^* / \psi \, (z_t - z_\kappa)$$

- This approximation introduces some error in simulations, which requires adopting a quite **small time interval**, in order to ensure relatively small fluctuations of the reservoir level within a time step.
- Another key characteristic of hydroelectric reservoirs is the occasional generation of the so-called **secondary energy**, by passing surplus flow through the turbines in order to avoid or minimize spill losses, thus releasing more water than the one imposed by the associated firm energy target.
- The price of secondary energy is by definition lower than the firm one, since its production is unpredictable and not dictated by a systematic release policy. Actually, this resembles to energy produced by other renewables, including small hydroelectric works, where the lack of storage capacity forces the energy production to follow the pattern of randomly varying inflows instead that of the demand.

Evaluation of energy performance

- The evaluation of a hydroelectric reservoir is made on the basis of simulated energy, e_t, which allows estimating:
  - the probability of fulfilling the target energy (**reliability**), empirically computed as the percentage of time steps for which $e_t \geq e^*$
  - the energy production above target e^* (**surplus or secondary energy**)
  - the **energy deficit** with respect to target e^*
- A **power-duration curve** is obtained by sorting the simulated energy data in descending order and assigning an empirical exceedance probability to each energy value.
- If n is the size of simulated data (i.e. the length of simulation), the probability of exceeding the sorted value at position i is estimated by the **Weibull plotting position**

$$p_i = i / (n + 1)$$

- Using the power-duration curve we can estimate the **firm energy** provided by the reservoir, as the value ensured with a very high reliability level (typically, 95 to 99%).