Postgraduate program:
Environment and Development

Course: Energy and Environment

National Technical
University of Athens

Hydroelectric dams and reservoirs: Technology & operation

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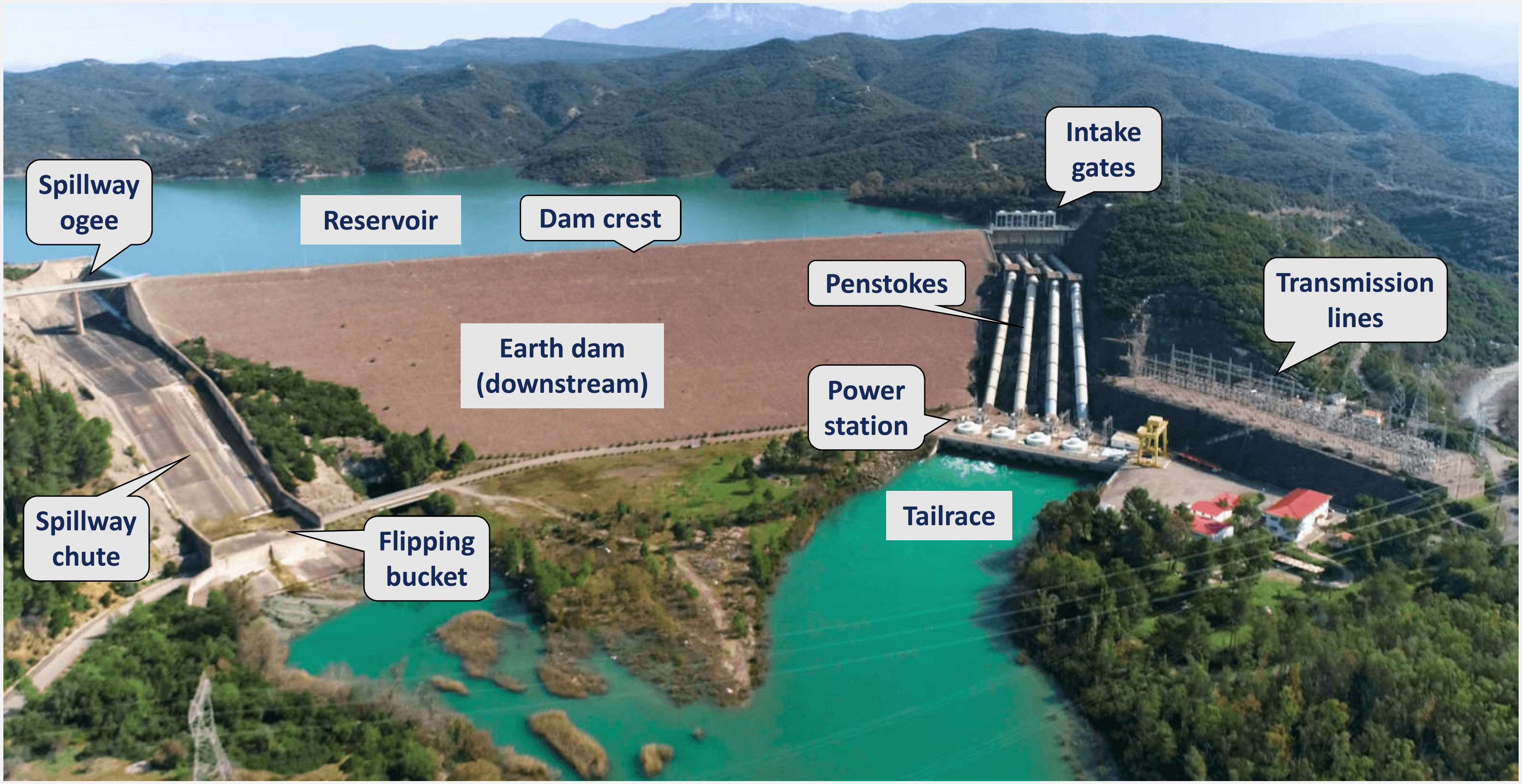
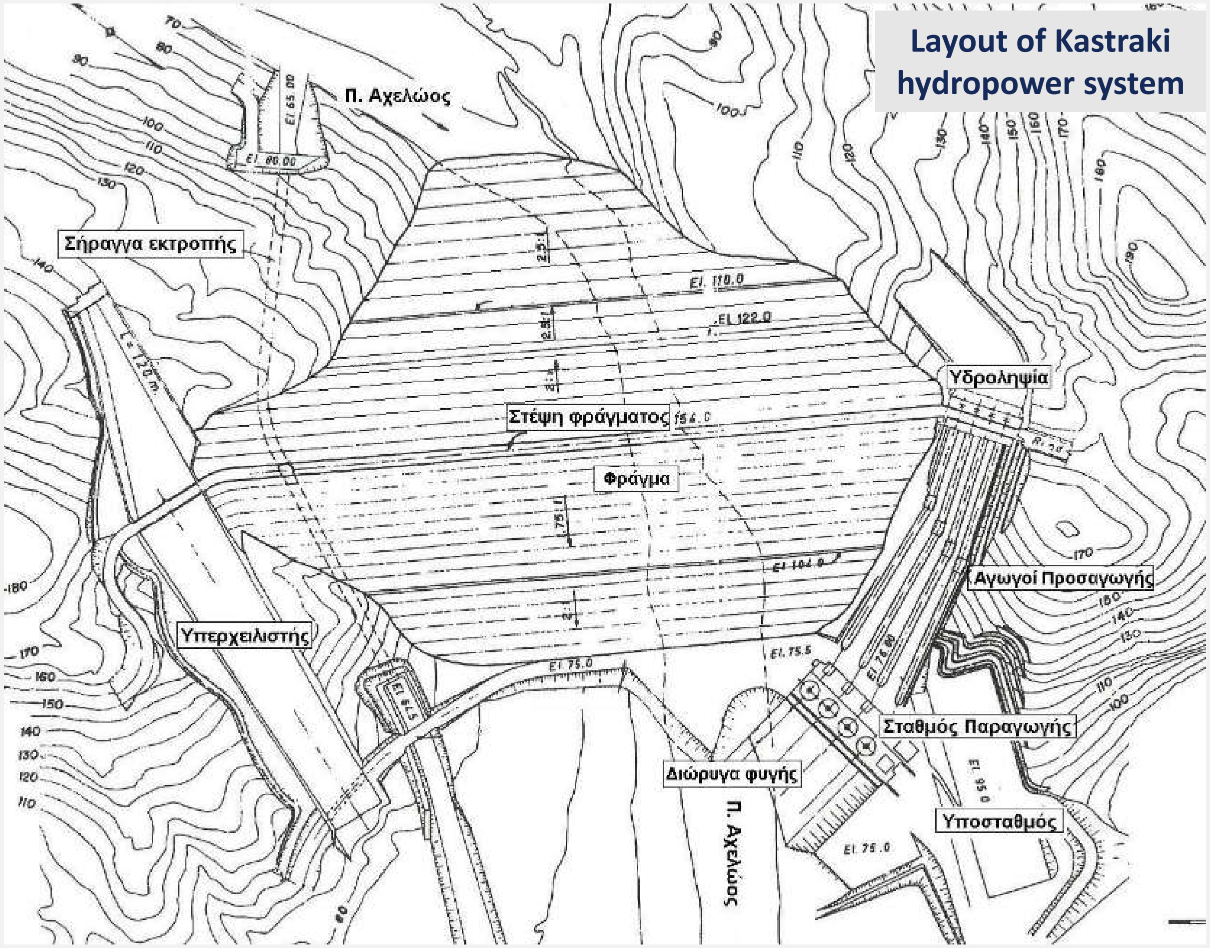
Overview of a typical hydroelectric reservoir (Kastraki, Achelous)



Components of hydroelectric systems: Dams and reservoirs

- **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, rockfill, etc.);
  - Gravity dams, either from conventional vibrated concrete (CVC) or concrete mixed with earth materials, e.g., roller compacted concrete (RCC) or hardfill.

Layout of Kastraki hydropower system

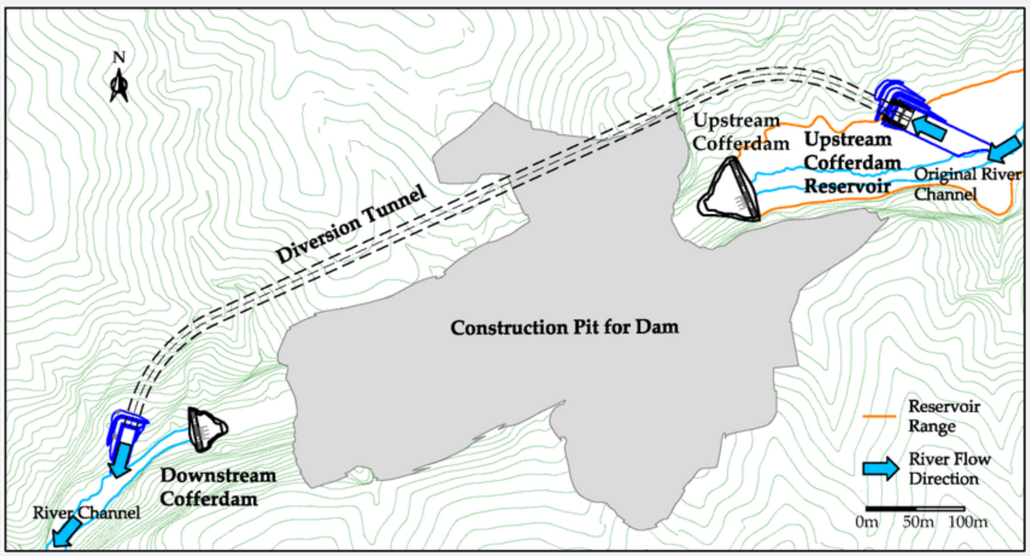


Components of hydroelectric systems: Ancillary structures

- **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 (usually underground), host the electromechanical equipment (turbines, generators, transformers);
- **Bottom outlet**, which allows emptying the reservoir in case of emergency (also used to pass the ecological flow to the downstream river and to flush sediments);
- **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;

River diversion during dam construction

- The period of construction may exceed ten years, and 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.
- 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 lug inside the tunnel.



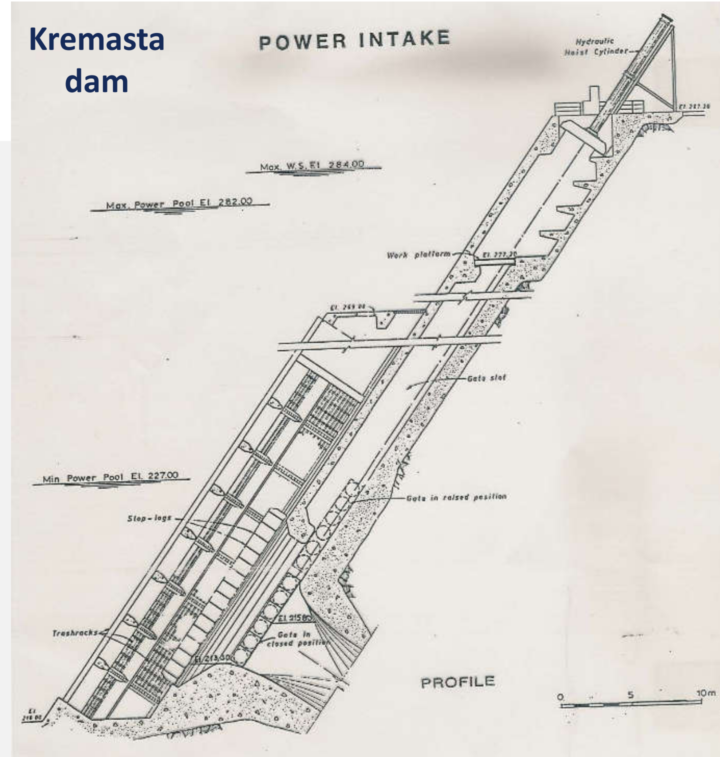
Diversion system of Mesochora dam

Hydropower intakes

- Typical configurations:
  - **Inclined intakes** on a sloping embankment, usually applied to high embankment dams, in seismic risk areas;
  - **Freestanding intake towers**, that can be also incorporated into the flood control outlet facilities of embankment dams;
  - **Face-of-dam intakes**, constructed as an integral part of the vertical upstream face of concrete dams.


Stratos dam


Kastraki dam: trash racks & gates

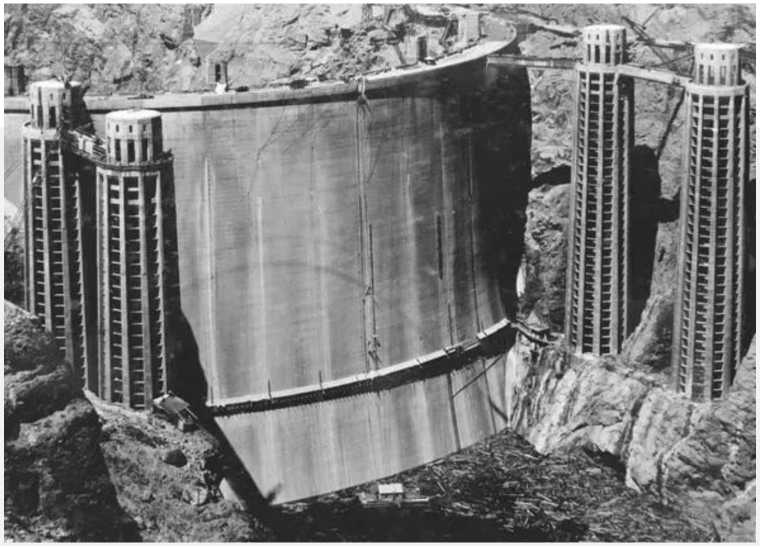


Kremasta dam

- All intake types are equipped with control gates (generally consisting of an emergency gate followed by a service gate), trash racks, bulkheads and stoplogs.

Free-standing tower intake structures

- Intake structures in the form of a tower, with **entry ports at various levels** to ensure **flow regulation** when there is a wide range of fluctuations of reservoir water level.
- Usually, they are more economical and easier to layout (by means of arrangement of conduits and openings, operating equipment, and access features) than inclined structures.

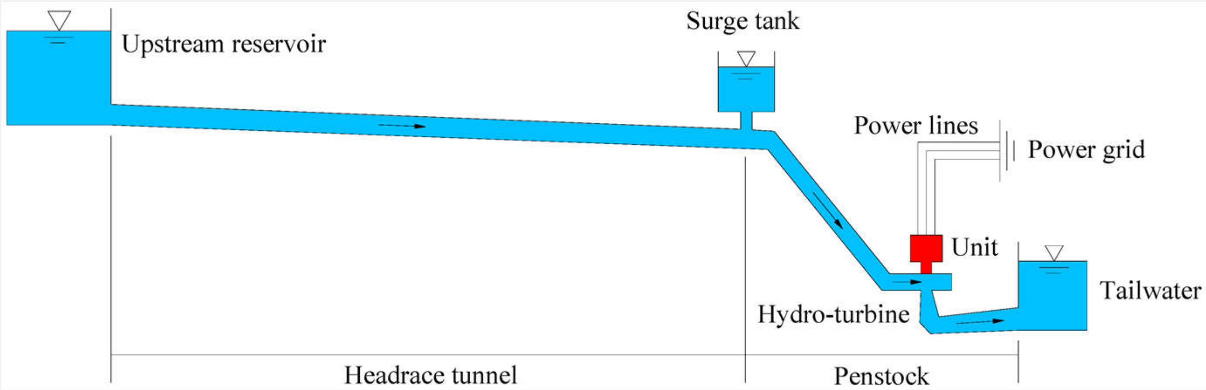


Plastriras dam

Hoover dam

Conveyance systems

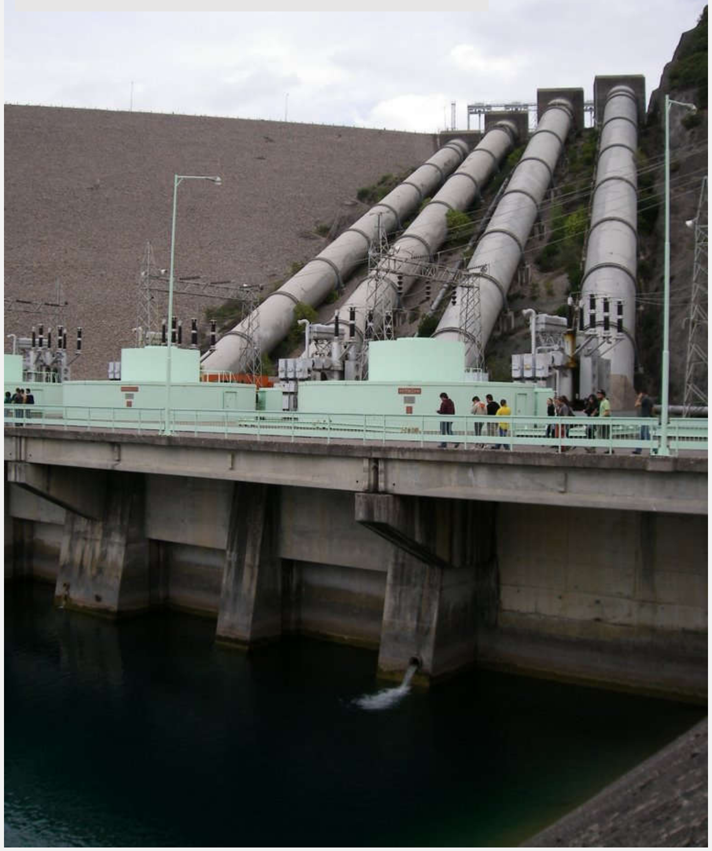
- For long distances, the conveyance system usually comprises two parts:
  - a **long low-pressure** tunnel or a headrace canal;
  - a **short high-pressure** pipeline (*penstock*) close to the turbine unit, separated by a surge chamber to absorb the water hammer pressure rises and covert them into mass oscillations.
- Major design issue: **water hammer**, created by sudden changes in power demands → formulation of a **surge chamber** or pool, in case of large pipes and large heads (upstream of the penstock).
- For large hydroelectric systems, the **number of penstocks** may equal the number of turbines (expensive design); alternatively, a single penstock of larger diameter is applied that splits at the power house (increase of local losses).
- General design recommendations (final layout specified after optimization):
  - Total hydraulic losses should not exceed 5% of gross head;
  - Velocity should not exceed 6.0 m/s



Penstocks (surface or underground)

- High-pressure pipelines designed to withstand stresses due to static and water hammer pressures
- Surface (exposed):
  - Located above the ground, supported by anchorages and rings
  - Expansion joints are necessary for longitudinal stresses
  - Economic solution for rocky terrains and large diameters
  - Easy to inspect faults and employ common maintenance
  - Direct exposure to environment and weather effects
- Underground:
  - Partially of fully buried (expensive, for large diameters)
  - Supported in the soil in a stretch of 1.0-1.5 m depth
  - Conservation of natural landscape
  - Protection from landslide and storms

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

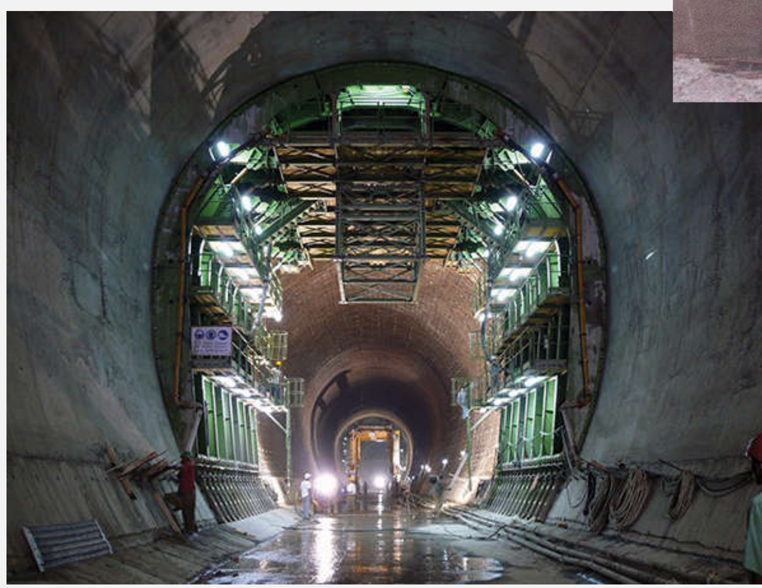


Construction details for exposed penstocks

Diversion penstock of Plastiras hydropower system: length 2985 m, diameter ranging from 2.60 to 3.50 m, elevation difference ~570 m

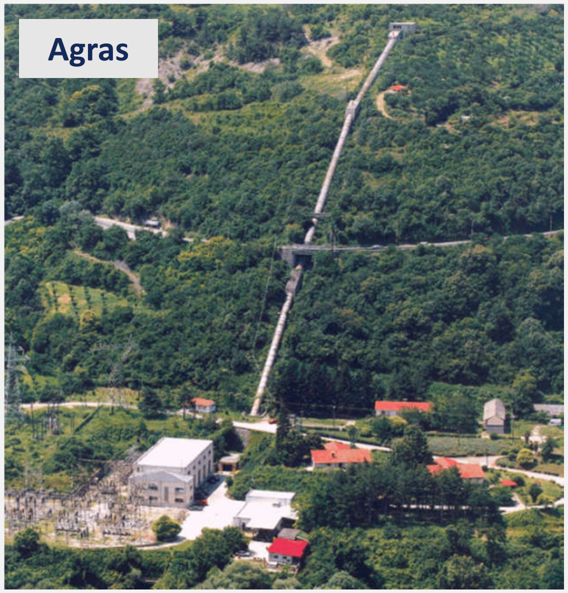
Hydropower tunnels

- Pressured tunnels, typically lined (by applying shotcrete-gunite, concrete, reinforced concrete, or steel)
- Exception: compact rocks → water and energy losses (roughness)
- Alternative layout: steel pipes embedded into tunnels
- Difficult construction in case of steep slopes

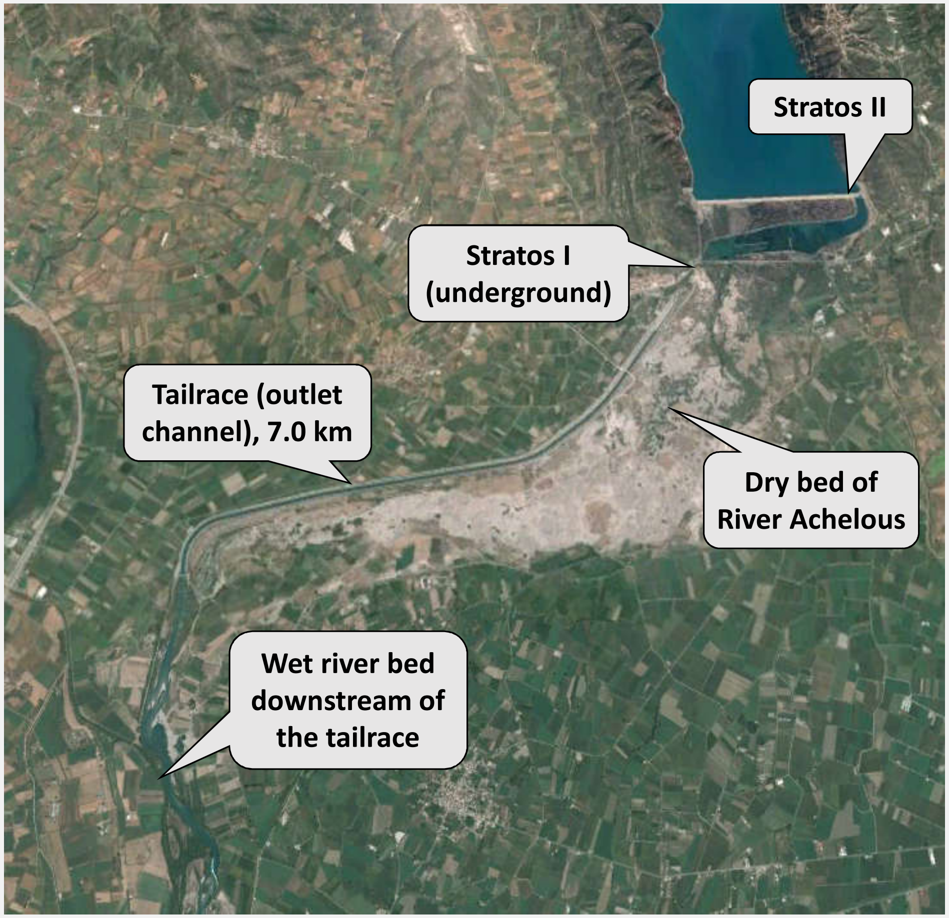


Power stations

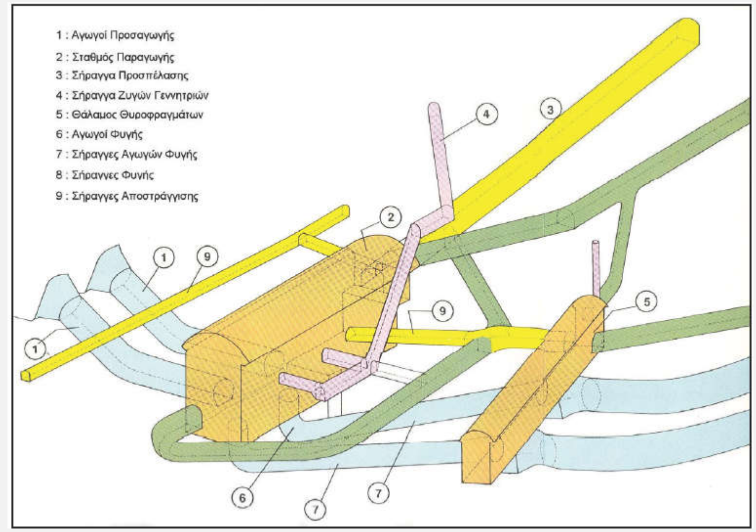
- Usually underground, located close to the dam foot
- Less usual configurations, ensuring larger heads (yet contrasted to longer conveyance distances):
  - Downstream of the dam (run-of-river schemes)
  - In a neighboring basin (diversion schemes)



Outlet structures: draft tubes & tailraces



Layout of outlet works of Stratos dam

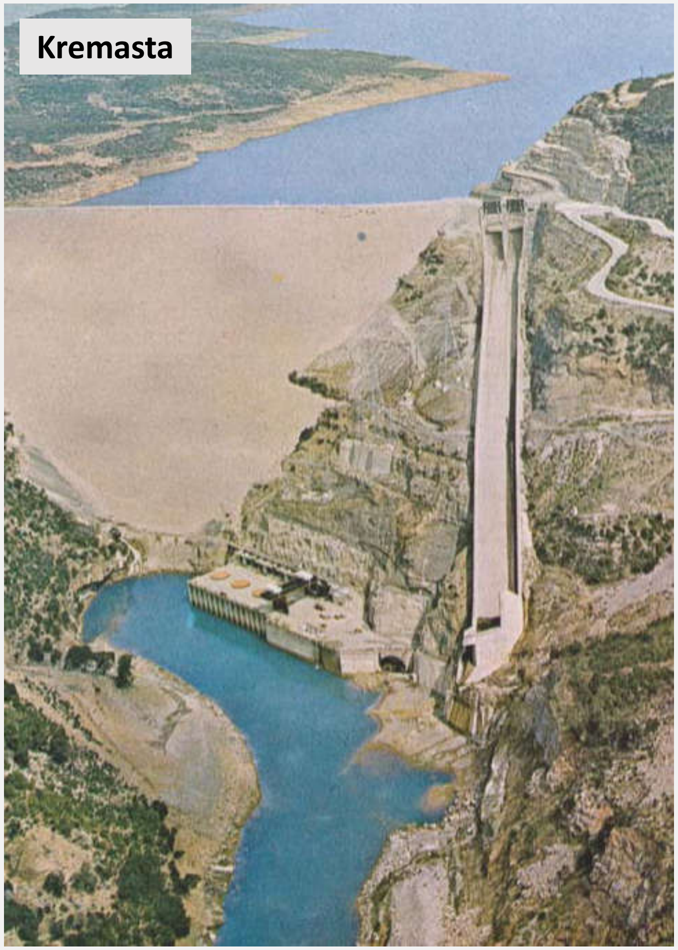


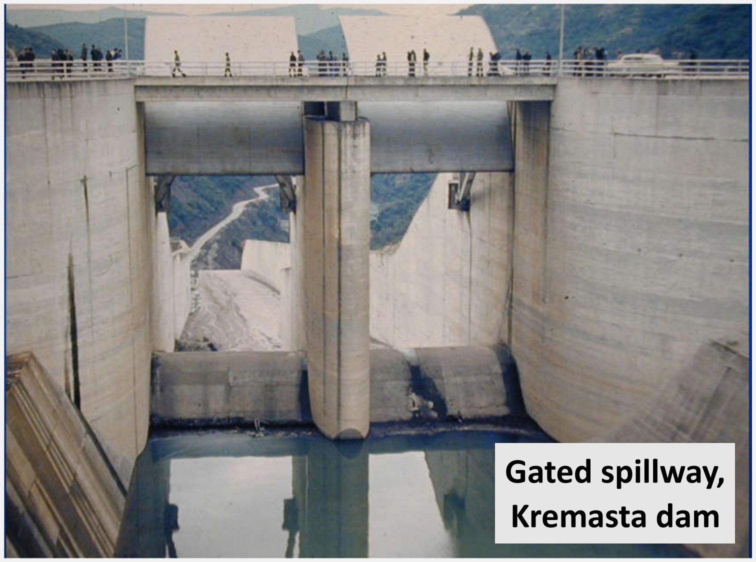
Spillway systems

Spillway system, Pourari dam

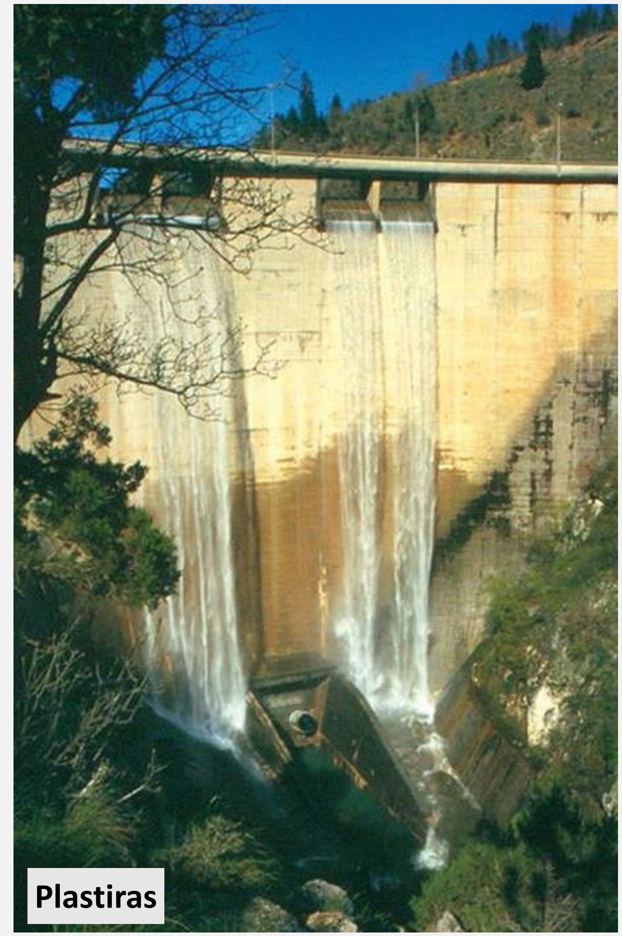
- **Objective**: Safe removal of the overflowed floodwater and its safe transfer and disposal to the downstream river. Main components are:
  - Approach channel
  - Control structure (weir, ogee)
  - Conveyance system (channel, chute, tunnel)
  - Terminal structure as energy dissipator (stilling basin)
- **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.

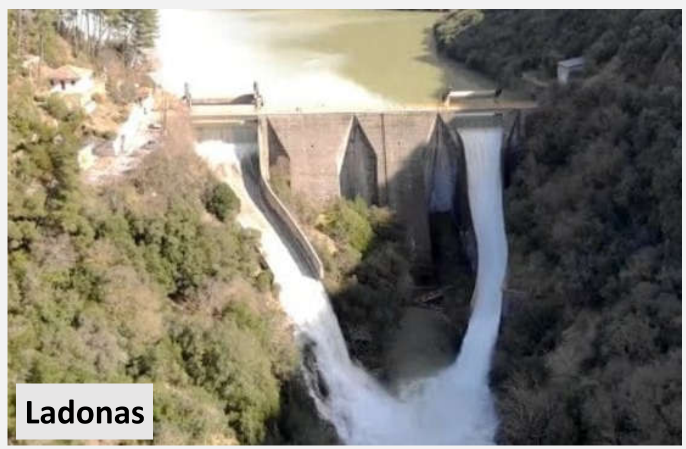
Typical layouts of spillway systems





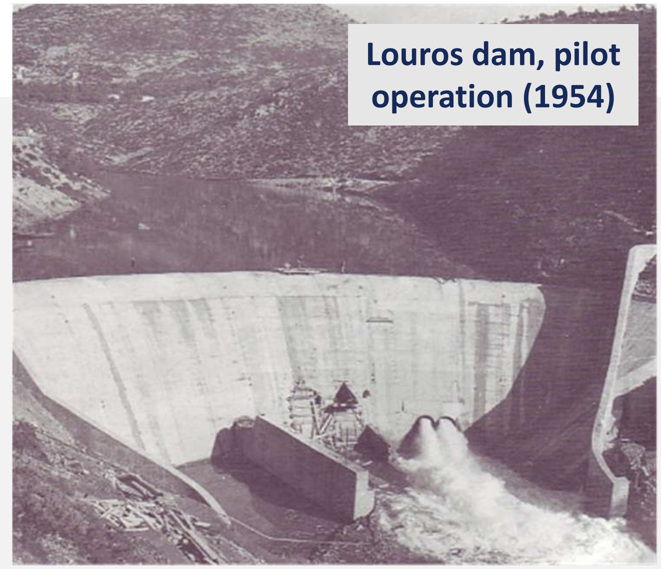
Spillways in operation





Bottom outlet

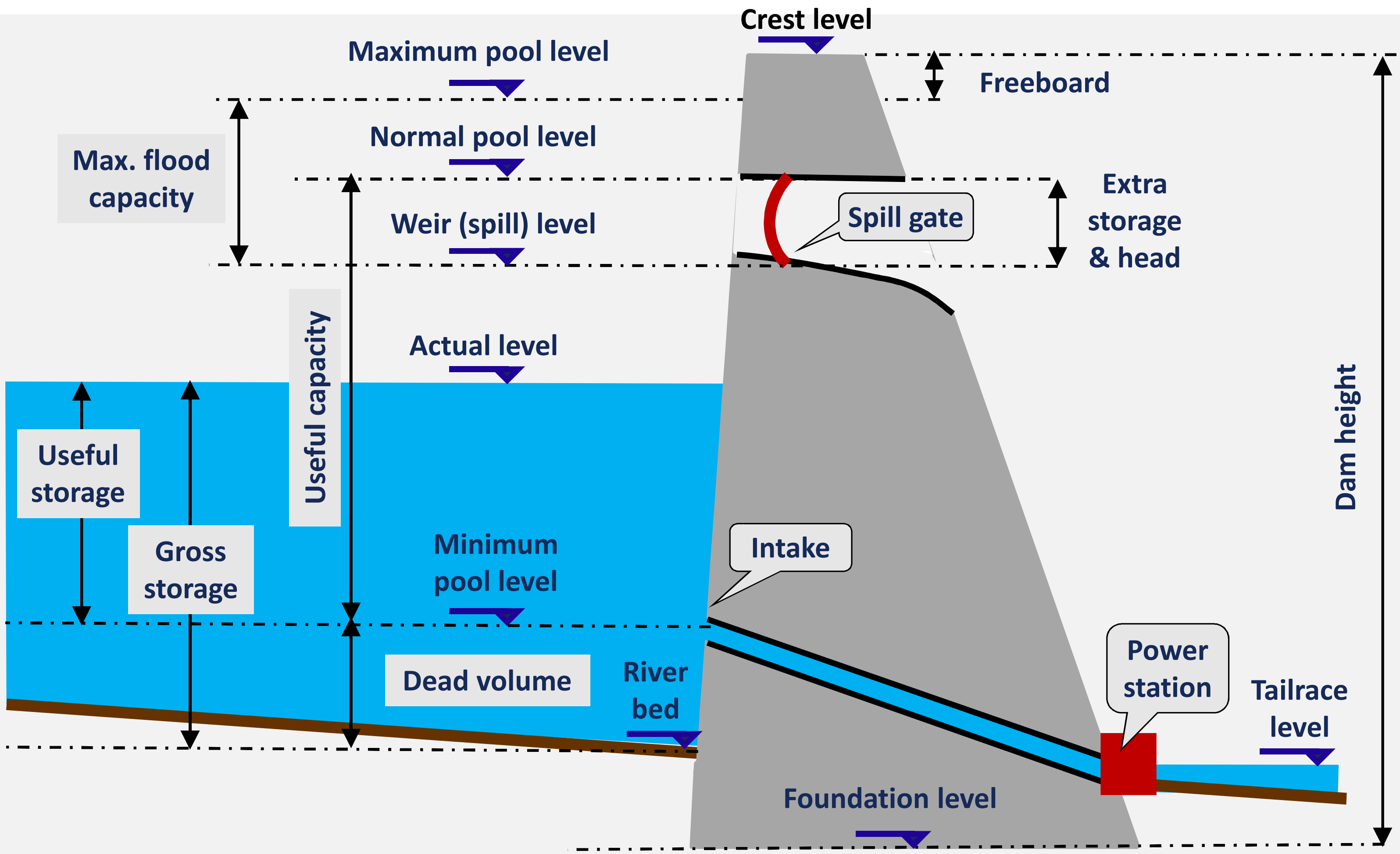
- Bottom outlets are **safety works**, to ensure conveyance of water downstream to lower the level of the reservoir or even to empty the reservoir, in case of emergency.
- Their inlets are constructed close to the foundation; part of the diversion tunnel can be incorporated into the bottom outlet.
-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


Louros dam, pilot operation (1954)


Plastiras dam


Cerro del Águila Dam, Peru (2015)

Hydroelectric reservoirs: schematic layout



Characteristic elevation quantities

- **Dam crest level:** Top of the dam
- **Dam height**: Elevation difference between the foundation and the dam crest.
- **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.
  - Uncontrolled spillways: normal pool level = **spillway crest**
  - Controlled spillways: normal pool level = **top level of gates**
  - Large hydroelectric reservoirs are typically equipped with gated spillways.
- **Minimum pool level**: Lowest elevation to which water is drawn from a reservoir, under normal operating conditions (i.e., water released to turbines for hydropower production).
- **Maximum pool level**: Maximum elevation to which the water surface is expected to rise during the design flood of the spillway.
- **Gross head**: Elevation difference between the actual pool level and the jet of the nozzle (impulse turbines) or the tailrace elevation (reaction turbines).

Characteristic storage quantities

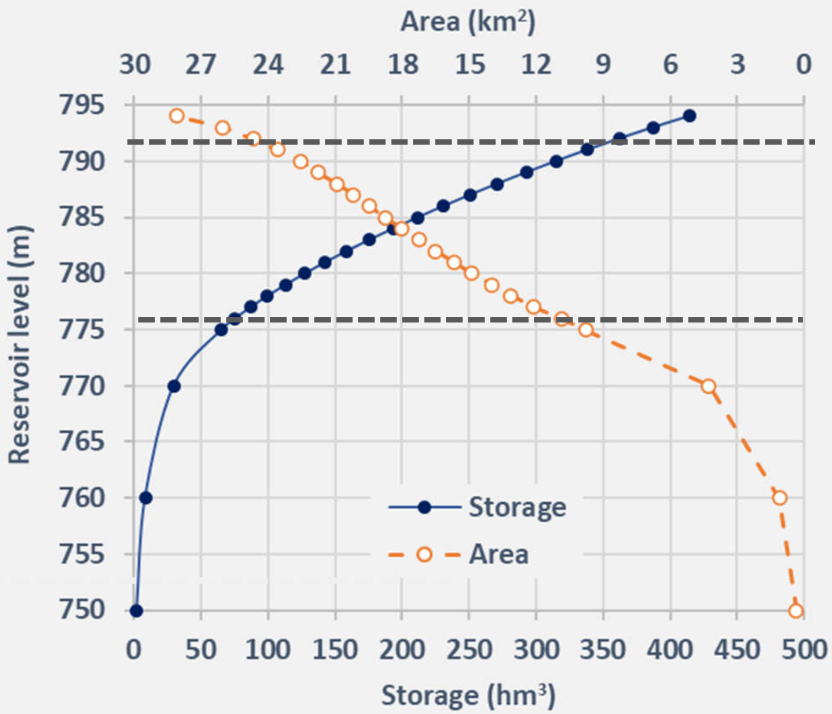
- **Dead storage**: Volume of water held below the minimum pool level, which cannot be used for any purpose under normal condition. It depends on:
  - the volume of sediment that is expected to be deposited into the reservoir during its design life;
  - the elevation of the lowest outlet of the dam;
  - 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 <u>active storage</u>, as water can be used for various purposes.
- **Total (or gross) storage**: sum of dead and useful storage
- **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 gross reservoir storage, s, and impoundment area, a, against the water level, z.
- Analytical formulas $s = f_1(z)$ and $a = f_2(z)$ can be extracted via regression, based on data sets (z_i, a_i).
- The level-area sets are either estimated by measuring the associated areas on a topographic map or are calculated automatically (with higher accuracy) on a GIS environment, by using a digital elevation model of the area of interest.
- Typically, the two functions are formalized as power-type expressions above a characteristic low elevation (datum) z_0, e.g., dead volume level or foundation level:

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

where κ, λ are scale and shape parameters, respectively.



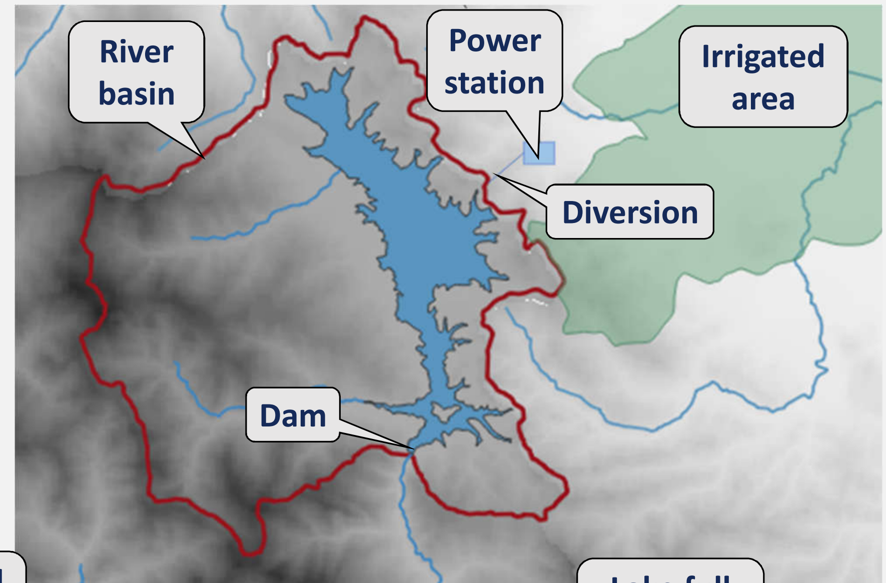
Storage-elevation-area curves for Plastiras reservoir. Minimum and maximum pool levels are +776 and +792 m, respectively, corresponding to a dead storage of 76 hm^3 and a total capacity of 362 hm^3 (useful capacity: 286 hm^3)

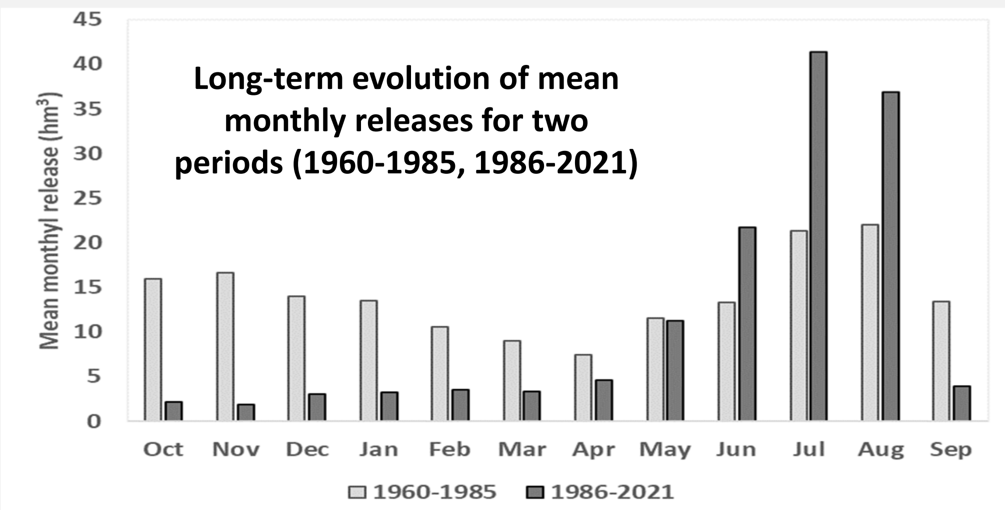
Overview of hydroelectric reservoir operation

- **Normal operation** (pool level lower than weir elevation or little higher, with closed spillway gates):
  - Generation of hydropower according to a day-ahead schedule, dictated by a combination of short and long-term management goals
  - "Traditional" approach, according to the role of the plant in the interconnected electricity system, usually imposing activation of turbines during peak demand hours (generation of **firm energy**)
  - Running policies mainly driven by energy market issues and constraints (combination with other renewables, regulation of electricity prices)
  - In case of multipurpose reservoirs, the generation of hydropower is also dictated by basin-scale water management objectives and constraints (e.g., irrigation during summer months)
- **Emergency operation for flood control** (pool level reaching or exceeding the weir elevation):
  - Continuous operation of turbines in their full capacity, to avoid (or minimize) unnecessary water losses due to spill (generation of surplus, also referred to as **secondary energy**)
  - Gradual (or full) opening of spillway gates, accounting for the arriving flood flows, the evolution of the reservoir level, the upstream hydrometerological conditions and the weather forecasts.

Example of hydroelectric reservoir management: Plastiras

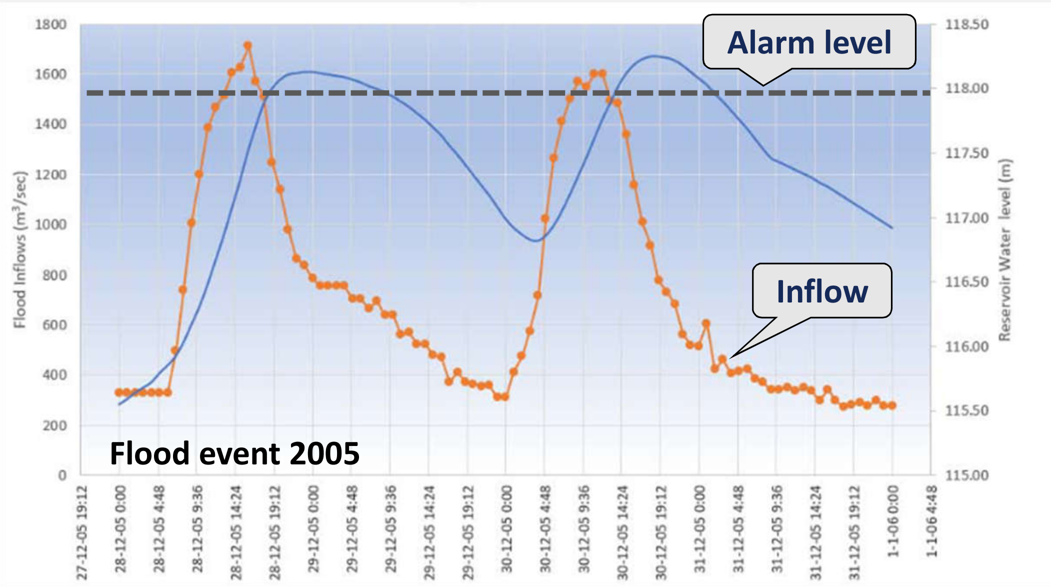
- Diversion dam (mean annual release 150 hm^3, mean annual energy production 200 GWh)
- Additional water uses: irrigation and water supply downstream of the power station (change of initial policy, to release most of water during summer)
- Additional constraints: touristic development around the lake, implying small fluctuations of poll level (aesthetic issue)

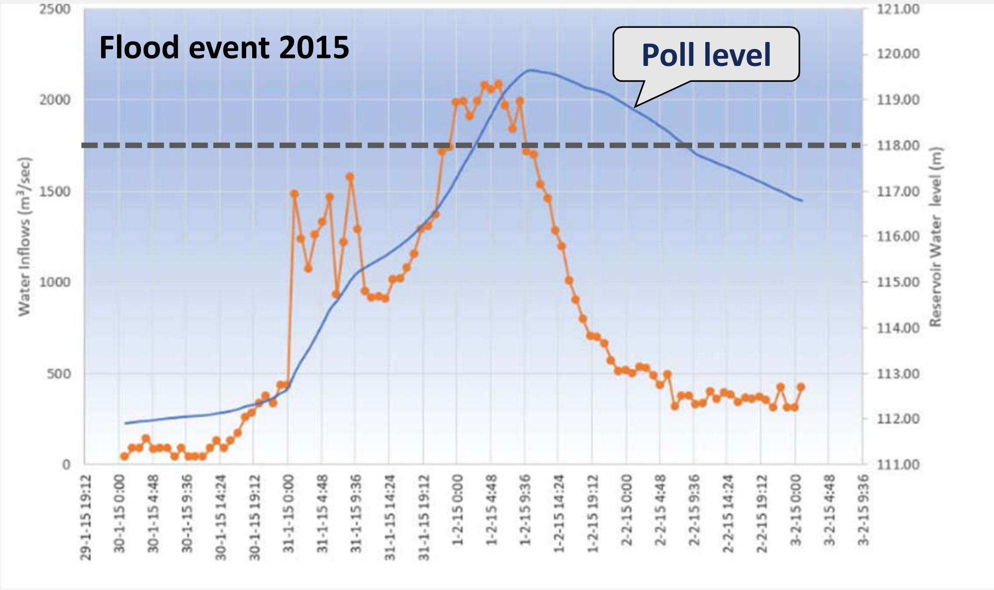




Example of spill management: Pournari hydroelectric reservoir

- Spillway system:
  - Crest level +107.5 m
  - 3 arched gates of 12.5×12.5 m (top level +120.0 m)
  - Dam crest +127.0 m (design flood +125.5 m)
  - Total discharge capacity 6100 m³/s
- Hydropower station
  - 3 Francis-type turbines of 3×100 MW
  - Total discharge capacity 500 m³/s
- Operation policy: alarm stage at +118.0 m, implying opening of the three gates





Simulation of reservoir operation

- Simulation is a generic approach for analyzing complex systems, based on a simplified step-by-step representation of their dynamics through a computer model that **mimics their actual operation**.
- Practical advantages:
  - understanding and assessing the system's behavior by evaluating the simulated responses (e.g., reservoir outflows) against alternative planning, design and management settings
  - providing empirical estimations of probabilistic quantities via sampling (e.g., reliability)
- Easily combined within **optimization models**, provided that the system dynamics is parameterized in terms of design/control variables to be optimized against one or multiple criteria, that are expressed in terms of an overall performance measure (objective function).
- Typical problems of simulation-optimization approaches in hydroelectricity:
  - Determination of the storage capacity of a standalone reservoir, to maximize the expected revenues from hydropower production with a specified reliability (**design problem**)
  - Determination of the optimal operation policy of an existing or planned reservoir (more generally, interconnected reservoirs as parts of broader hydrosystems; **management problem**)

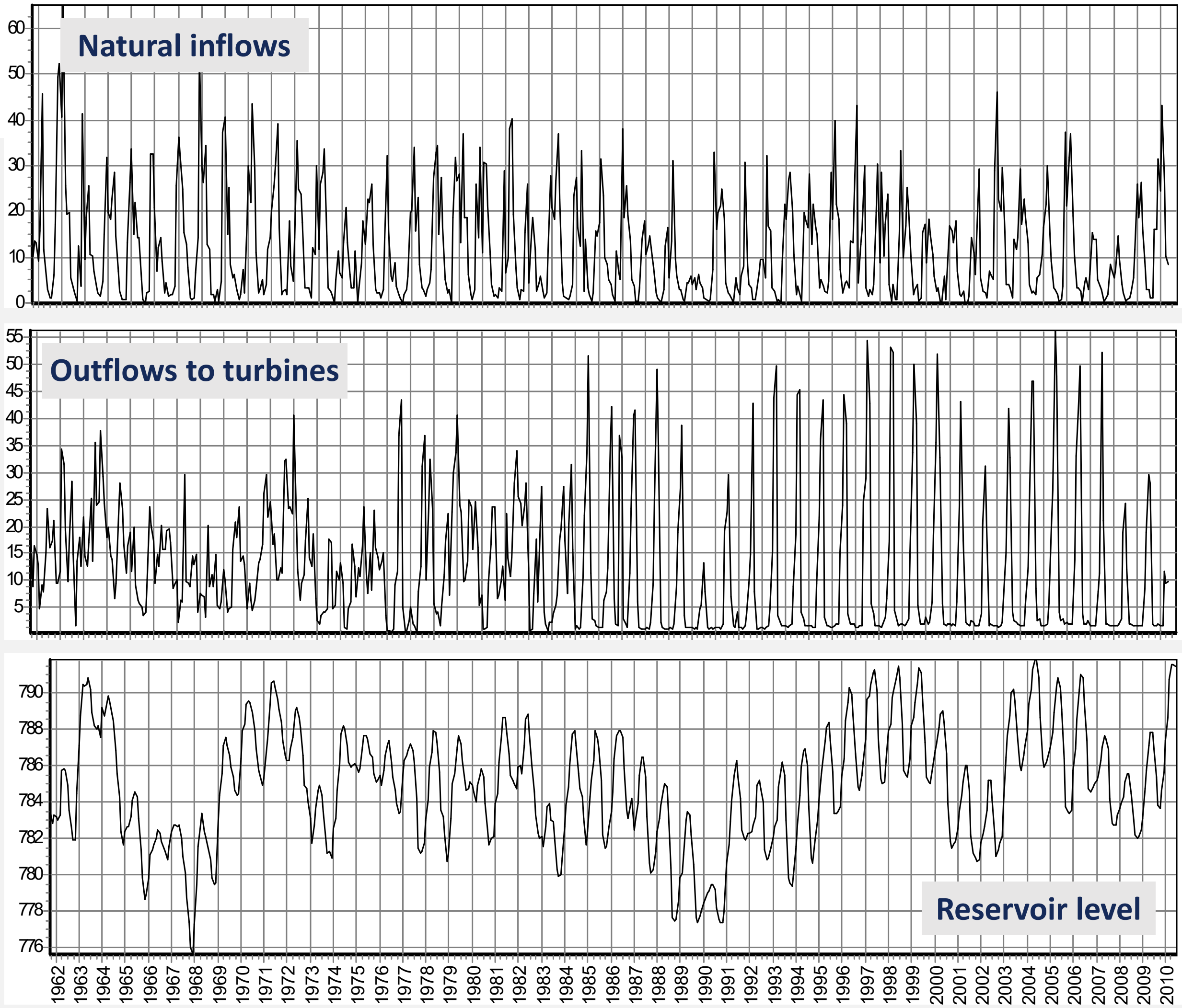
Reservoir dynamics

- Continuous formulation of mass balance equation:

$$ds/dt = i(t) - o(t)$$

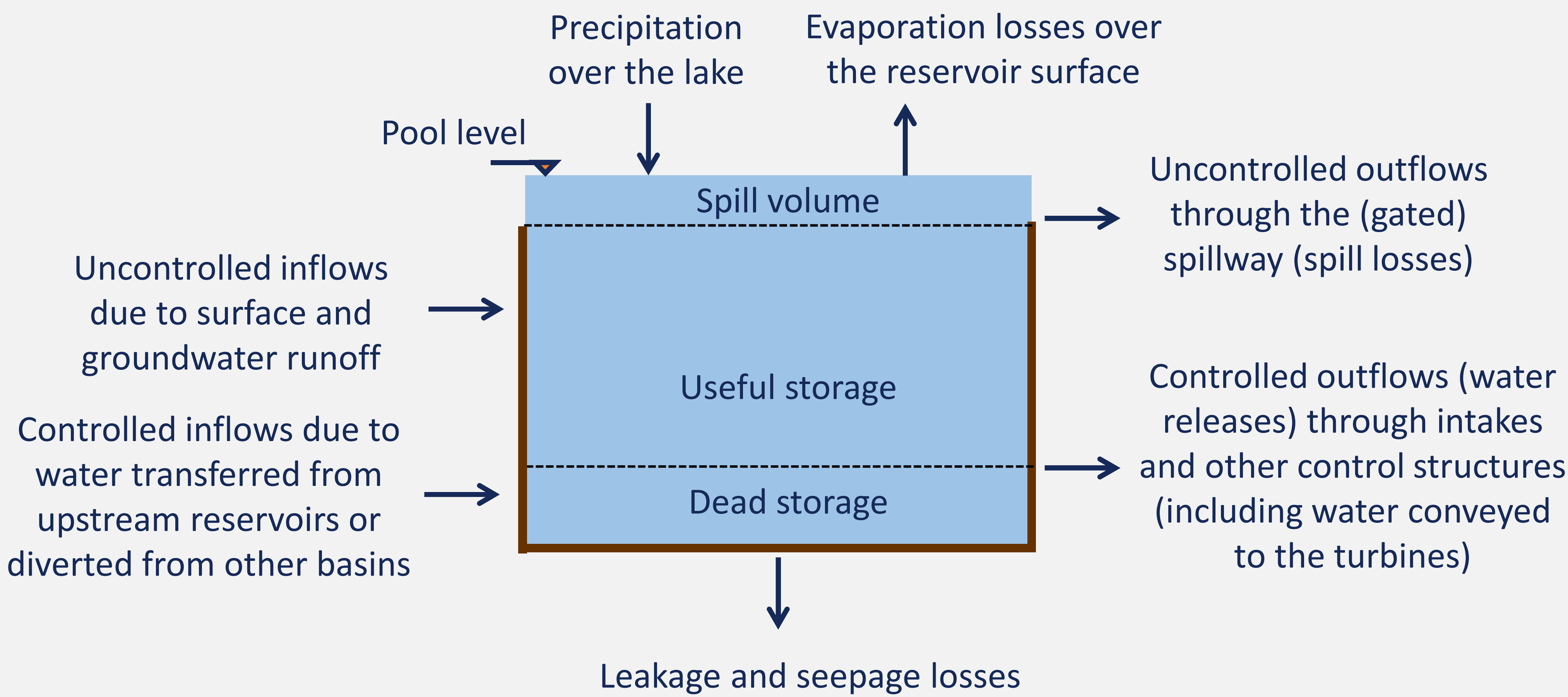
where ds/dt is the rate of storage change, $i(t)$ are the total inflows and $o(t)$ the total outflows.

- In a **simulation context**, the reservoir dynamics is expressed in discrete time, in terms of **time series of water balance components**, by considering the storage difference, Δs, and the accumulated inflows and outflows for a specific time interval $(t, t + \Delta t)$, typically daily or monthly.



Monthly inflow, outflow and reservoir level data for Plastiras reservoir (10/1961 – 12/ 2010)

Water balance components



Simulation of standalone hydroelectric reservoir: problem setup

- Single water use: target energy production, e^* (constant, seasonally constant or varying)
- Simulation horizon (number of time steps): n
- Initial storage s_0 at the beginning of simulation (for relatively large, n, its impact is negligible)
- Inflow time series, i_t ($t = 1 \dots n$) due to runoff produced over the upstream basin (projected or synthetically generated)
- Smaller-scale hydrological variables (rainfall, evaporation and leakage losses) that depend on reservoir level are omitted (or embedded within inflows, thus referred to as *net inflows*)
- Unknown variables: storage, s_t, water releases to power station, r_t, spill losses, w_t

- Elevation data:
  - Minimum poll level, z_{min}
  - Maximum poll level, z_{min}
  - Bottom level (datum), z_0
  - Power station level (penstock outlet), z_d
- Characteristic formulas (κ, λ, α, β, ψ: constants):
  - Storage, s, vs. elevation, z :
    $$s = \kappa\,(z - z_0)^\lambda$$
  - Discharge, u, vs. gross head, $h = z - z_d$:
    $$u = \alpha\,(z - z_d)^\beta$$
  - Energy production, e, vs. water release, r, and gross head, $z - z_d$:
    $$e = \psi\, r\,(z - z_d)$$

Simulation of standalone hydroelectric reservoir: model configuration

- For a given, s_0, the simulation problem can be **explicitly** solved to provide the unknown quantities s_{t+1}, r_t, and w_t, at each time step t, through a sequential (i.e., process-by-process) configuration of the water balance equation (i.e., by applying a specific order of water additions and subtractions, and updating the storage, each time a water quantity enters or leaves the reservoir).
- At the beginning of each time step t, the following actions are employed:
  - The active storage is set equal to the known value at the end of previous step, i.e., $s_t = s_{t-1}$.
  - The updated reservoir level z_t is computed, as function of s_t.
  - The updated conveyance capacity u_t (in volume terms) is computed, as function of z_t.
  - For the given target energy production, e_t^*, a target release is assigned, i.e.: $r_t^* = \frac{e_t^*}{\psi\,(z_t - z_\mathrm{d})}$

<u>Remark</u>: Actually, the net head is function of the unknown release and the varying reservoir level z_t over the time interval. Yet, under the explicit approach, z_t is approximated as constant and equal to the known level at the beginning of the time step. This introduces some error is simulations, which requires adopting a quite small time step, to ensure relatively small fluctuations of the reservoir level within each time interval.

Step-by-step computation of water balance components

- Adding of inflows to the actual storage, thus $s_t \to s_t + i_t$.
- Estimation of actual releases to fulfill the target energy, conditioned on the current water availability (i.e., useful storage, $s_t - s_{min}$), the conveyance capacity u_t, and the target release r_t^*:

$$r_{t,1} = \min(s_t - s_{min}, u_t, r_t^*) \text{ and } s_t \to s_t - r_{t,1}$$

- Provided that $s_t > s_{max}$, additional releases are employed by passing surplus flow through the turbines to avoid or minimize spill losses, which are subject to the remaining conveyance capacity:

$$r_{t,2} = \min\left[\max(s_t - s_{max}, 0), u_t - r_{t,1}\right] \text{ and } s_t \to s_t - r_{t,2}$$

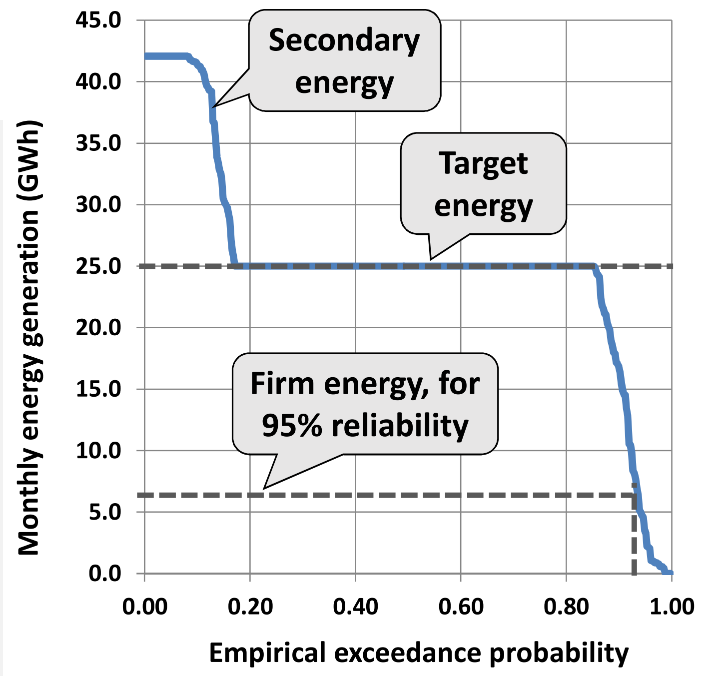
- If the remaining storage exceeds the reservoir capacity and since the remaining conveyance capacity is exhausted, the surplus quantity is considered as water loss due to spill:

$$w_t = \max(s_t - s_{max}, 0), \text{ and } s_t \to s_t - w_t$$

- The produced **energy** over the time interval is computed by setting the sum of releases, $r_{t,1} + r_{t,2}$, and after re-estimating the head (and specific energy, if the latter is not handled as constant) by considering the average reservoir level at the beginning and end of time step.

Evaluation of energy performance

- Based on simulated energy data e_t, the metrics to evaluate are:
  - the probability of fulfilling the target energy (**firm energy reliability**), empirically estimated as the percentage of time steps for which $e_t \geq e_t^*$
  - the energy production above target e_t^* (**secondary energy**)
  - the **energy deficit** with respect to target e_t^*
  - the **expected revenues**, by assigning different prices for firm and secondary energy, also penalizing deficits



- By plotting 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%).

Remark: The price of secondary energy should be set by definition lower than the firm one, given that its production is unpredictable and not dictated by a systematic release policy. In fact, this operation mode resembles to the energy produced by other renewables (solar, wind, small hydro), where the lack of storage capacity forces the energy production to follow the pattern of randomly varying “fuel” inflows instead that of the demand.