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HS5.2.3: Water resources policy and management – systems solutions in an uncertain world

Revisiting the storage-reliability-yield concept in hydroelectricity

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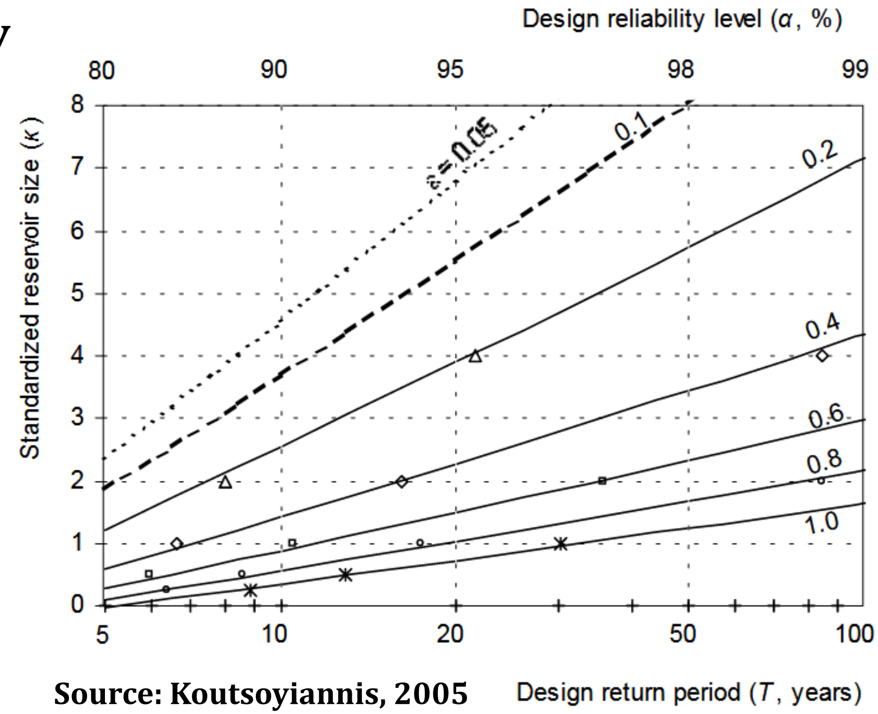
Efstratiadis, A., I. Tsoukalas, and D. Koutsoyiannis, Generalized storage-reliability-yield framework for hydroelectric reservoirs, *Hydrol. Sci. J.*, 66(4), 580–599, doi:10.1080/02626667.2021.1886299, 2021.

Storage-reliability-yield (SRY) in a nutshell

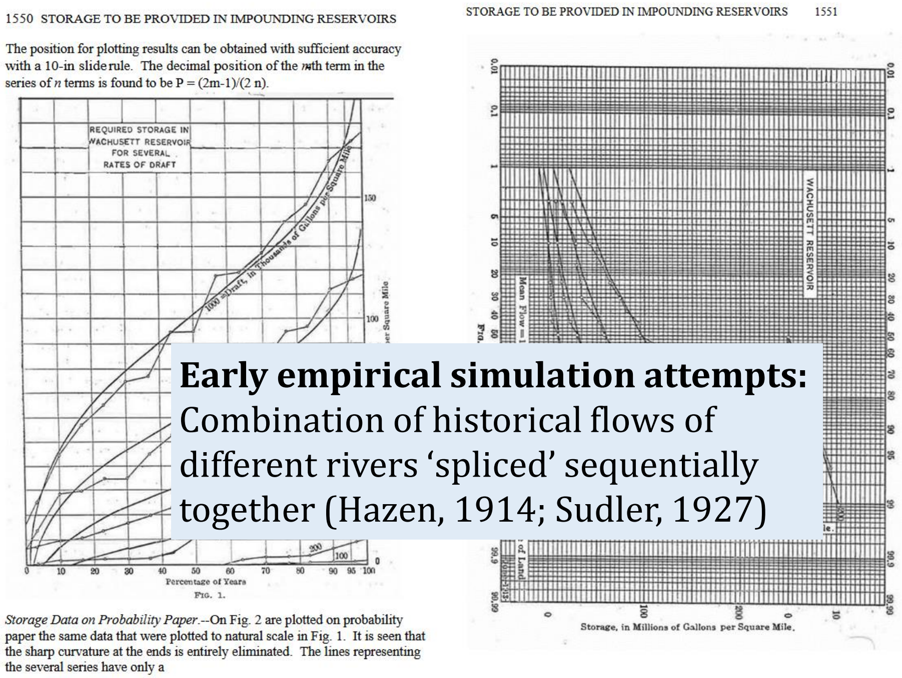
- Classical engineering tool for **preliminary reservoir sizing and performance assessment**, linking three key quantities:
  - active storage capacity;
  - water abstraction (yield or draft);
  - reliability;
- Outcome of detailed analyses, based on **simulations** with varying capacity, water demand targets, and inflow regimes.
- Often expressed by means of **summary statistical characteristics of inflows**.



Source: Koutsoyiannis, 2005

- Allows for recognizing the **major conflicts** of water resources systems:
  - minimization of investment costs (associated with reservoir capacity);
  - maximization of revenues (associated with yield);
  - minimization of deficits (associated with reliability).
- Embedding the concept of **reliability** within reservoir design has been a decisive step with respect to naïve deterministic approaches, following the mass curve method by Rippl (1883) and its improvements (e.g., sequent peak analysis).

Quick glance to history


1550 STORAGE TO BE PROVIDED IN IMPOUNDING RESERVOIRS

The position for plotting results can be obtained with sufficient accuracy with a 10-in slide rule. The decimal position of the *m*th term in the series of *n* terms is found to be P = (2m-1)/(2 n).

FIG. 1.

Storage Data on Probability Paper.--On Fig. 2 are plotted on probability paper the same data that were plotted to natural scale in Fig. 1. It is seen that the sharp curvature at the ends is entirely eliminated. The lines representing the several series have only a

STORAGE TO BE PROVIDED IN IMPOUNDING RESERVOIRS 1551

Early empirical simulation attempts: Combination of historical flows of different rivers 'spliced' sequentially together (Hazen, 1914; Sudler, 1927)

Journal of Hydrology, 47 (1980) 269—296
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

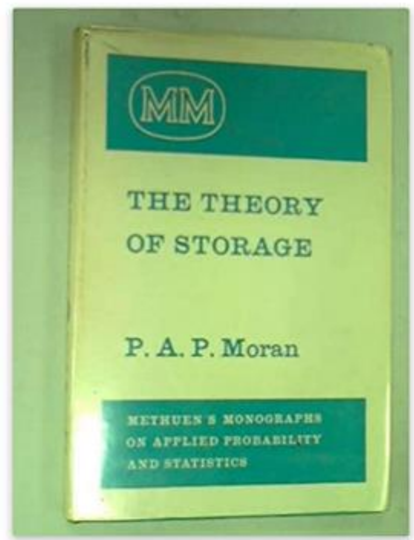
[3]

ON RESERVOIR RELIABILITY

G.G.S. PEGRAM

Department of Civil Engineering, University of Natal, Durban 4001 (South Africa)

(Received October 10, 1979; accepted for publication October 19, 1979)



Modern approaches: Reservoir sizing based on annual streamflow statistics (Moran, 1954, 1959; Gould, 1961), and establishment of SRY theory (Pegram, 1980); cf. review by Klemeš (1987)

The Soviet school: Theoretical studies concluding to practical rules for reservoir design, based on the SRY concept (Kritskiy & Menkel, 1935, 1940; Pleshkov 1939; Savarenskiy, 1940)

Journal of Hydrology

Generalized methods for runoff control computations based on mathematical statistics[1]

S.N. Kritskiy, M.F. Menkel

Translated by V. Klemeš from the Russian original "Obobshchennye priemy rascheta regulirovaniya stoka na osnove matematicheskoy statistiki", Gidrotekh. Stroit., 2: 19–24, 1940*

Received 29 March 1994; revision accepted 6 December 1994

Today's picture: Numerous theoretical, empirical and simulation-based approaches, practically only applicable to water supply reservoirs

Water supply vs. hydroelectric reservoirs

- **Water supply** is delivered to specific users/locations (e.g., metropolitan area);
- Water abstractions are dictated by the associated water demand;
- Reservoir geometry has limited influence to process descriptions (in preliminary studies, stage-depended processes, e.g. evaporation, can be omitted);
- Exploitation of excess water during flood events is not possible, thus any surplus storage must be released through the spillway;
- Environmental uses, by means of eco-flows, are conflicting with the water supply.

⇨ Simple simulation scheme, based on water balance calculations

- **Hydropower** is delivered to a large-scale interconnected electricity grid (e.g. national or peripheral area);
- Water abstractions are dictated by the **energy demand** and the available **head** (mainly depending on reservoir level);
- Reservoir geometry embedded in **head-discharge-energy transformations**;
- Overproduction of energy during floods is possible, by taking advantage of the generally large capacity of penstocks and turbines (surplus hydropower is called **secondary energy**, in contrast to the energy produced to fulfill the target value, generally called **firm energy**);
- Environmental flows can by released through the turbines, thus not being in conflict with hydropower uses.

⇨ Complex and site-specific simulations

Simulation model for hydroelectric reservoirs

- Model inputs:
  - Inflow data (typically resolved at the monthly or daily time scale);
  - Characteristic elevations (intake and spill level, power station elevation);
  - Reservoir geometry data (storage-elevation relationship);
  - Water conveyance data (discharge-elevation relationship);
  - Flow-energy transformation data (efficiency, function of discharge);
- Model controls: **power production target** (constant, for **steady-state simulation**)
- Simulation steps:
  - Update of elevation-depended quantities (reservoir storage, head, discharge capacity, efficiency);
  - Release of water through the turbines to fulfill the power production target (**normal operation, generation of firm energy**);
  - Release of additional water through the turbines up to the available discharge capacity to prohibit losses due to spill (**emergent operation, generation of surplus/secondary energy**);
  - Release of excess water through the spillway, if the conveyance capacity of the penstock is exhausted (**generation of maximum potential energy**).

Flow energy-transformations within simulation

- Hydroelectric energy generation formula:

$$e_t = \rho\, g\, \eta\, r_t (z_t - z_\mathrm{d} - h_\mathrm{L})$$

where ρ is the water density (1000 kg/m), g is the acceleration of gravity (9.81 m/s^2), η is the efficiency (function of elevation), r_t is the water release through the turbines, z_t is the reservoir level, z_d is the characteristic downstream elevation, which depends on the turbine type (thus the difference $z_t - z_\mathrm{d}$ is the **gross head**), and h_L are the hydraulic losses across the penstock (thus the difference $z_t - z_\mathrm{d} - h_\mathrm{L}$ is the **net head**).

- Equivalent expression, to facilitate computations:

$$e_t = \psi_t\, r_t (z_t - z_\mathrm{d})$$

- The quantity ψ_t is referred to as **specific energy**, defined as:

$$\psi_t = \rho\, g\, \eta\, (z_t - z_\mathrm{d} - h_\mathrm{L}) \,/\, (z_t - z_\mathrm{d})$$

- For an ideal system without hydraulic losses ($h_\mathrm{L} = 0$) and unit efficiency ($\eta = 1$) we get ψ = 0.002725 kWh/m^4.
- For a given energy production target, e^*, the target abstraction at each time step is:

$$y_t^* = \frac{e^*}{\psi_t\, (z_t - z_\mathrm{d})}$$

Embedding capacity factor in simulation

- The operation schedule of hydropower plants is associated with their role in the energy mix (**production of base or peak energy**).
- This operation is typically expressed in terms of **capacity factor**, defined as the ratio of the mean annual electrical energy output, E_a, to the maximum possible one, i.e. :

$$\mathrm{CF} = \frac{E_\mathrm{a}}{P\,T_\mathrm{Y}}$$

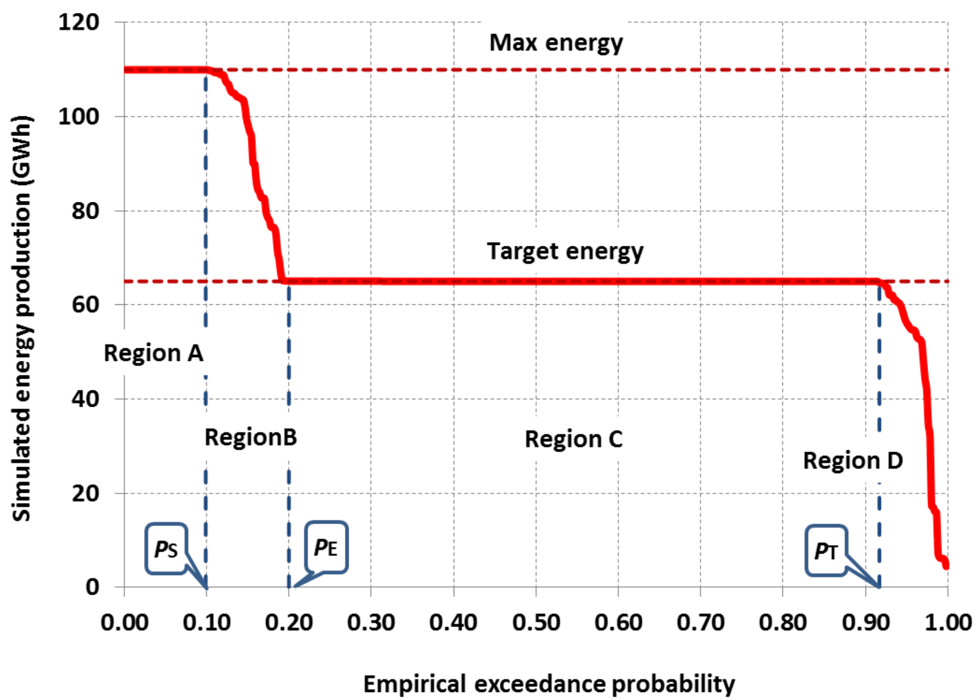
  where P is the total capacity of turbines and T_Y is the duration of one year (8760 h).
- Under the hypothesis of systematic operation of turbines in their full capacity, the ratio $T_\mathrm{a} = E_\mathrm{tot}/P$ denotes the **annual operational time of turbines**.
- In the design of large hydroelectric systems, the capacity factor, CF, and, equivalently, their annual time of operation, T_a, are specified *a priori*.
- For given CF, the conveyance capacity of penstocks is estimated by:

$$q_0 = \frac{V_\mathrm{a}}{T_\mathrm{year}\,\mathrm{CF}}$$

  where V_a is the expected annual water release for energy production, which equals the mean annual inflow, provided that **the outflows are practically fully regulated**.
- In the simulation context, the conveyance capacity q_0 is used as **constraint**, which is easily determined on the basis of inflow data and the desirable capacity factor.

Recognizing the operation regime of hydroelectric reservoirs through the energy-probability curve

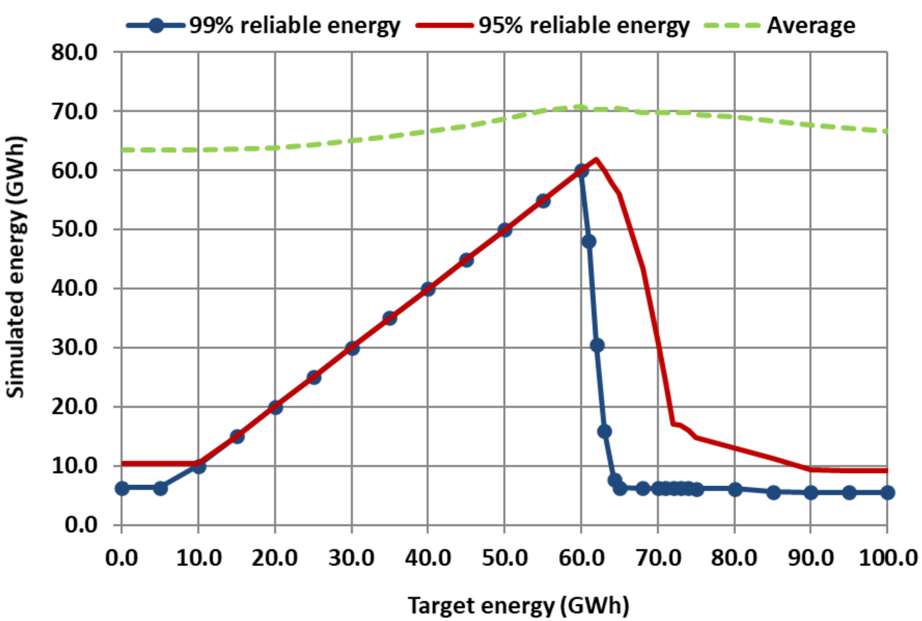
- **Region A**: The system produces the maximum potential energy by conveying surplus storage through the turbines, and at the same time the reservoir is spilling, since the conveyance capacity of turbines is exhausted (head and discharge are maximized).
- **Region B**: The system produces excess energy with respect to its target, by passing all surplus storage from the turbines, in order to eliminate spill losses.
- **Region C**: The system produces its target energy (normal operation).
- **Region D**: The system produces lower energy than the target, due to reduced storage/head.
- Key **probabilistic outputs** of simulation, shown in the EPC:
  - average energy production;
  - probability of spilling;
  - probability of excess energy;
  - probability of producing the target energy (= **reliability**).



Simulated EPC at Kremasta hydroelectric reservoir, Greece, using historical inflows from 1966 to 2008 (Efstratiadis et al., 2021)

Introducing the concept of reliable yield to hydropower production

- In conventional SRY analysis for water supply reservoirs, the reliable yield is defined as the **steady-state water demand that is fulfilled with a given reliability level**.
- Reliability is estimated **empirically**, by encountering the water deficits over the simulated time horizon; deficits are typically aggerated at the **annual time scale**.
- The **twofold operation** of hydroelectric reservoirs, i.e. normal and emergent, and the **higher price of firm over surplus energy** make essential to revise the concept of reliable yield, now defined as the power produced with a very high reliability, e.g. 99%, and estimated at **fine time scales**.

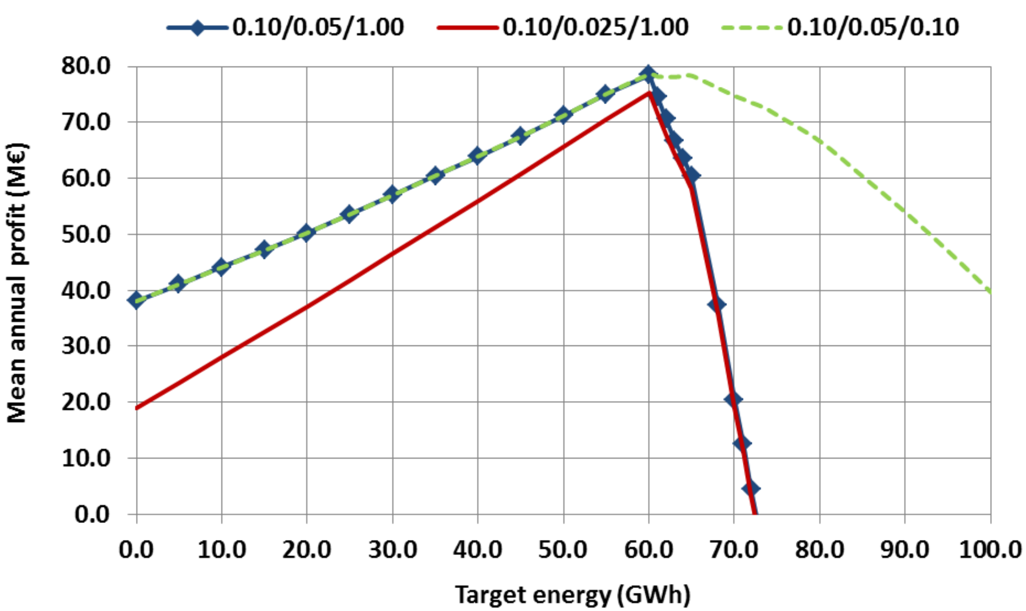


- The estimation of firm energy for a given reliability is subject to a global **optimization problem** with one control variable, i.e. the target energy.
- The firm energy equals the target until its maximum value is reached, then drops sharply, while for large target values converges to a minimum value.
- The **average energy** exhibits limited variability, and it is not recommended to be used as objective function.

Pseudo-economic function as performance metric for optimizing hydroelectric reservoirs

- The maximization of reliable energy may not be sufficient for fully assessing the performance of the system, without considering the **sharing between firm and surplus energy**, and the over- and under-production with respect to target.
- Pseudo-economic objective function, reflecting the **different market prices of reliable against secondary energy and against energy deficits**:

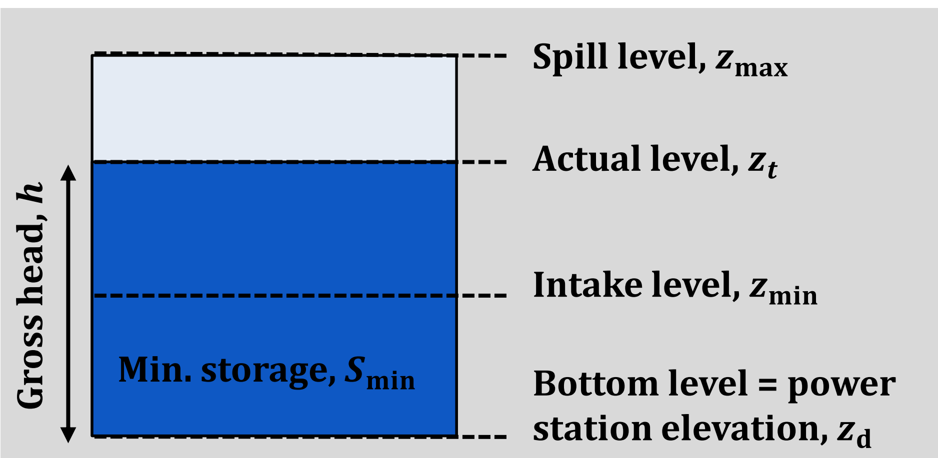
$$F(e^*) = \frac{1}{n} \sum_{t=1}^{n} [c_\mathrm{f} \min(e_t, e^*) + c_\mathrm{s} \max(0, e_t - e^*) - c_\mathrm{d} \max(0, e^* - e_t)]$$



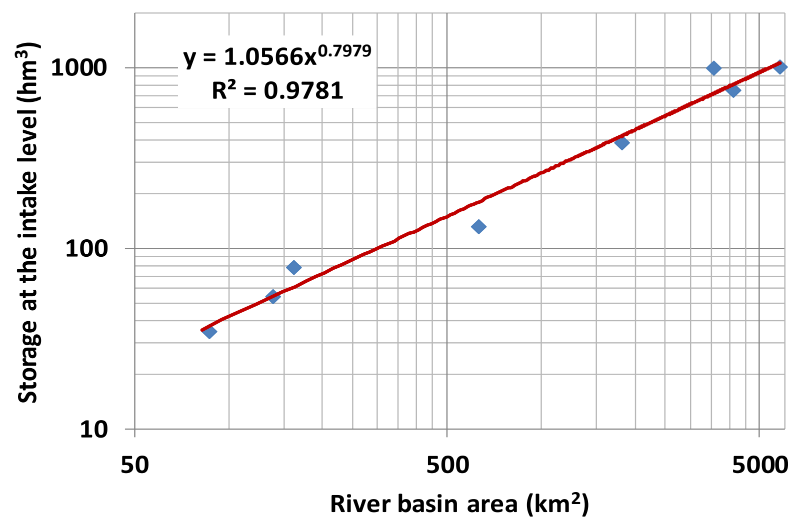
- Weighting coefficients:
  - c_f: unit profit for energy production up to the target;
  - c_s: unit profit for producing excess (secondary) energy;
  - c_d: unit penalty for deficits.
- Recommended values: $c_\mathrm{f} = 0.10$, $c_\mathrm{s} = 0.05$, $c_\mathrm{d} = 1.0$.
- The optimal value of target energy, e^*, is little sensitive against unit costs/profits.

Let's simplify: hydroelectric system configuration

- While in water supply the reliable yield is determined on the basis of a single input, i.e. the useful storage capacity, the hydroelectric yield is subject to more inputs:
  - minimum and maximum reservoir levels, z_{min} and z_{max};
  - downstream elevation, z_{d};
  - characteristic relationships, $S = f_1(z)$, $q = f_2(z)$ and $\psi = f_3(z)$.
- Assumptions:
  - The power station is located at the bottom of the dam.
  - The minimum storage (dead volume) is provided by the empirical relationship, $S_{\text{min}} = 1.06A^{0.80}$, where A is the upstream basin area (km^2).
  - The specific energy ψ is considered constant, equal to 0.00233 kWh/m^4.



Efstratiadis et al., Revisiting the storage-reliability-yield concept in hydroelectricity



Min. storage vs. upstream basin area, using data from eight hydroelectric reservoirs in Greece (Efstratiadis et al., 2021)

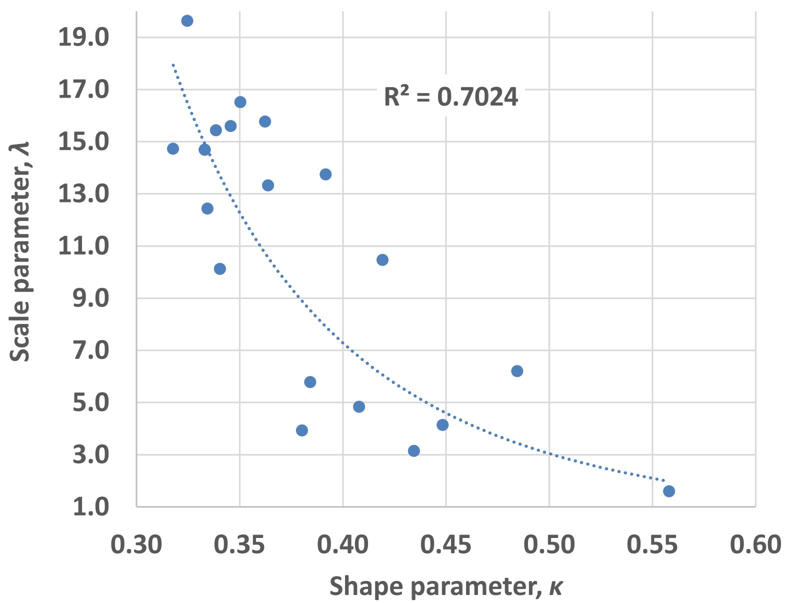
Let's simplify: storage-elevation function

- Typically expressed as a **power-type function**, i.e.:

$$h(S) = \lambda\, S^{\kappa}$$

where h is the water depth with respect to a characteristic elevation (generally, the ground elevation at the foot of the dam), while λ and κ are scale and shape parameters that are estimated through regression, using local bathymetric data.

- By fitting the power function to 20 large reservoirs in Greece (13 hydroelectric) we concluded that **the shape and scale parameters are highly correlated**.



Scatter plot of shape vs. scale parameters of power-type elevation-storage function, using data from 20 large reservoirs in Greece (Efstratiadis et al., 2021)

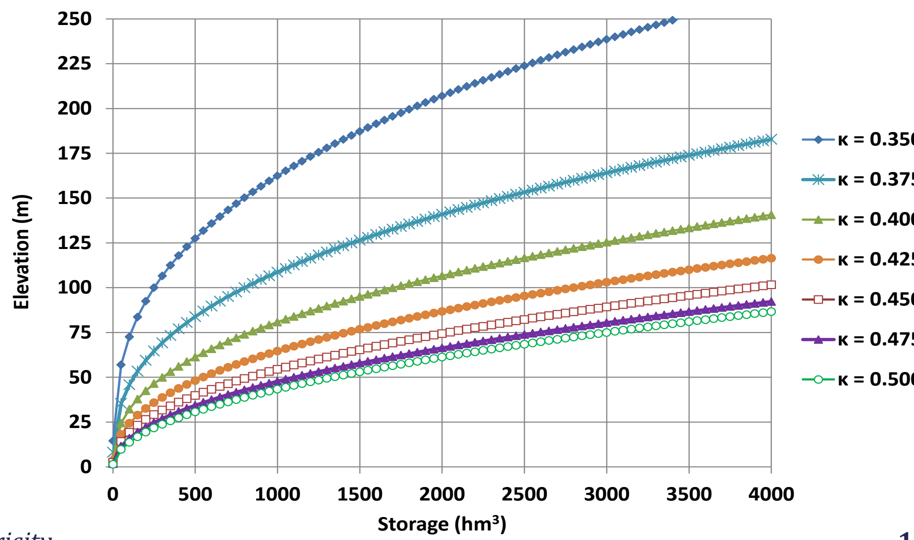
- After calibration, we obtained a **generic formula for the scale parameter**:

$$\lambda = 0.0386(\kappa - 0.25)^{-2.574}$$

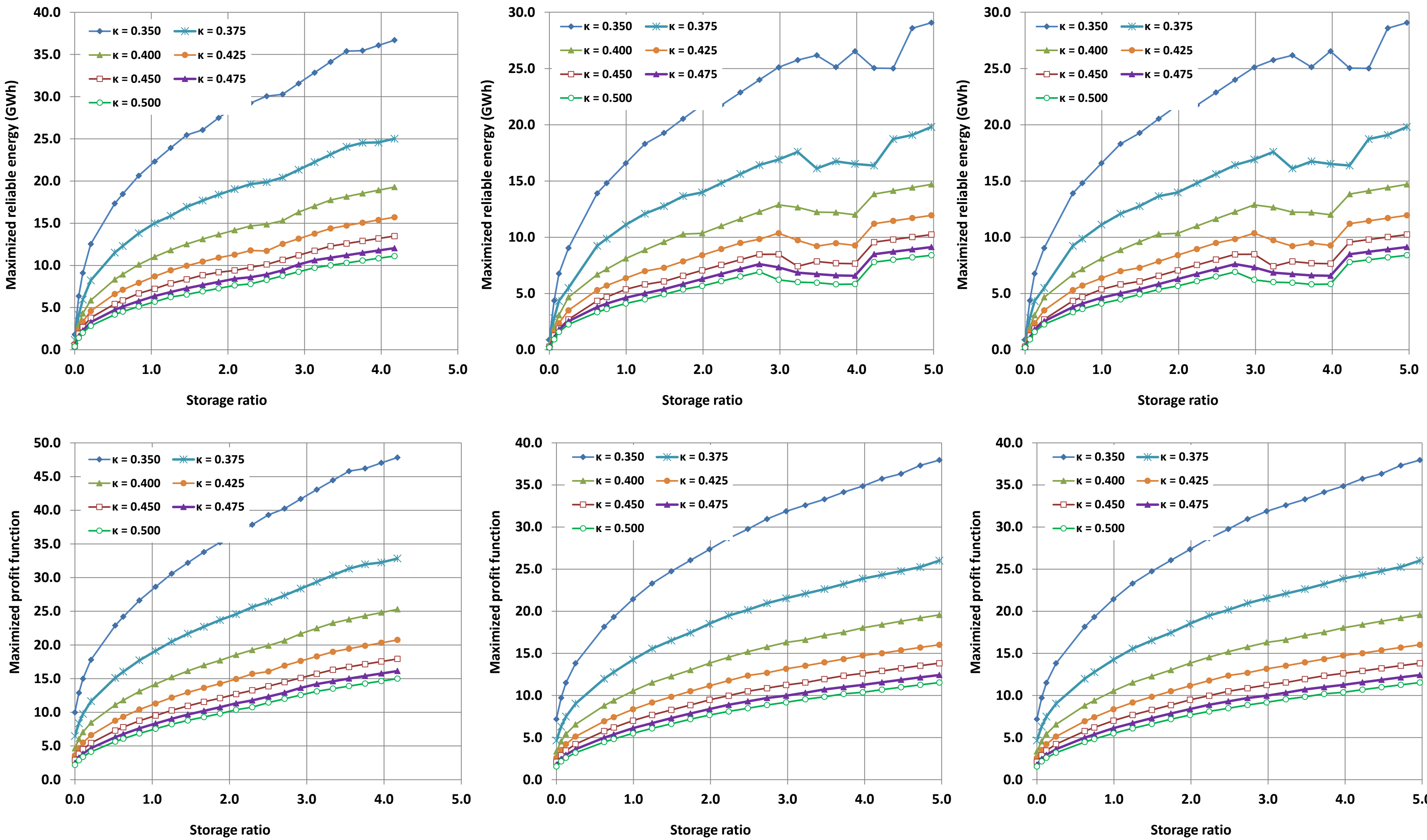
- The generic expression ensures very good fitting to the storage-elevation sample; in most cases, this is almost identical with the two-parameter expression.
- In this resect, **the reservoir geometry can be described through a sole local input**, representing the shape parameter of the power-type storage-elevation function.

Time for simulation: setting a proof-of-concept

- SRY analysis of numerous hypothetical reservoirs, by combining:
  - Three **synthetic inflow time series** of 5000 years length, generated through the anySim stochastic model (Tsoukalas *et al.*, 2020), which reproduce the probabilistic behavior and dependency pattern of historical data at three basins (Achelous, Evinos, Boeoticos Kephissos) with different hydroclimatic regime (mean annual runoff 965, 806 and 191 mm, respectively);
  - Two **operational modes**, representing the generation of base and peak energy, expressed in terms of capacity factors of 80% and 20%, respectively;
  - Seven **reservoir geometry** patterns, by employing the storage-elevation function with different shape parameter values (see graph).
- All basin areas are 1000 km^2 , thus all reservoirs have dead storage $S_{\min} = 266$ hm^3.
- Estimation of hydroelectric yield for numerous storage capacity values, by employing two alternative objective functions within the **stochastic simulation-optimization** problem:
  - 99% reliable energy, estimated on monthly basis;
  - pseudo-economic performance.

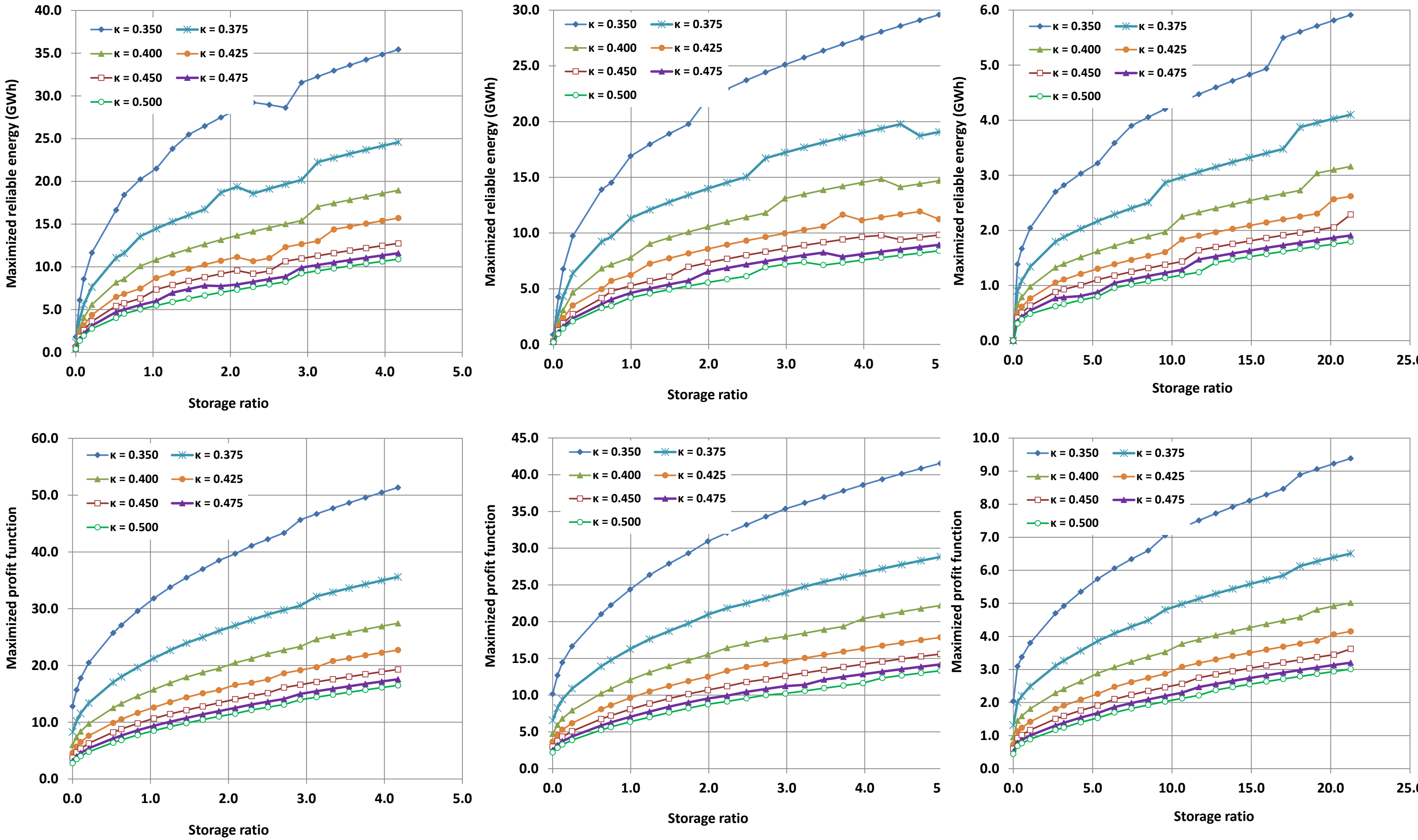


Results for base energy production (CF = 0.80)



Plots of maximized energy for monthly reliability level 99% (upper panels) and maximized profit (lower panels) as function of storage ratio (storage capacity/mean annual inflow) and the shape parameter, for capacity factor CF = 80% (from left to right: Achelous, Evinos, and Boeoticos Kephisos inflow data)

Results for peak energy production (CF = 0.20)



Plots of maximized energy for monthly reliability level 99% (upper panels) and maximized profit (lower panels) as function of storage ratio (storage capacity/mean annual inflow) and the shape parameter, for capacity factor CF = 20% (from left to right: Achelous, Evinos, and Boeoticos Kephisos inflow data)

Towards linking reliable energy with hydrology, reservoir geometry and reservoir capacity

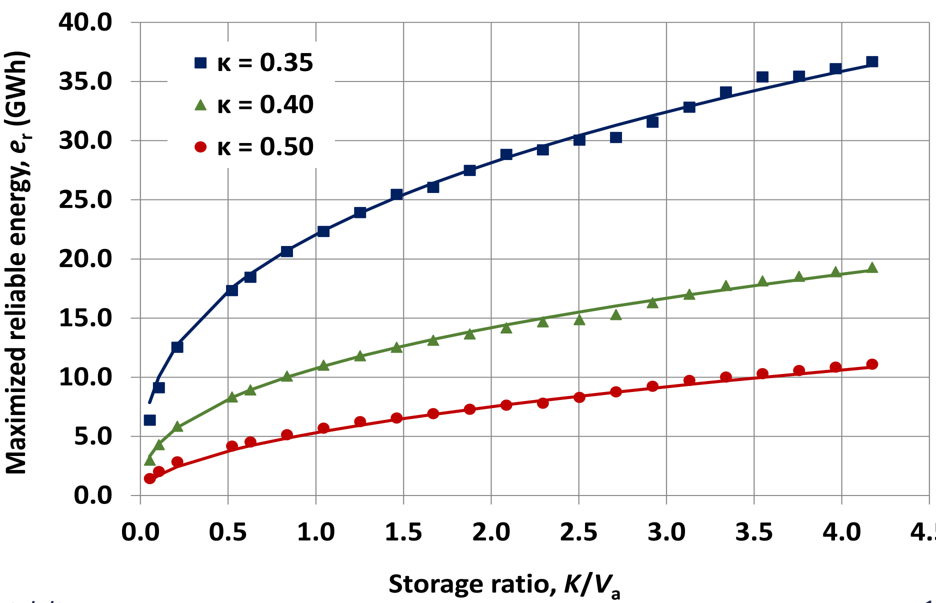
- The hydroelectric yield, either expressed by means of 99% reliable energy or in profit terms, can be approximated by a power-type function of storage ratio, K/V_a., where the mean annual inflow at the three sites of interest (965, 806 and 191 hm^3).
- After investigations, we obtained a generic formula for reliable energy, embedding the **storage ratio** and the **shape parameter** of the storage-elevation relationship:

$$e_\alpha = \frac{1}{\beta\kappa - \delta}\left(\frac{K}{V_a}\right)^\kappa$$

where β and δ are expected to be associated with the hydrological regime of the river basin upstream of the dam;

- The ratio δ/β, remains practically constant, i.e. 0.30 (to be confirmed whether is it a generic conclusion).

	β	δ
Achelous	0.955	0.289
Evinos	1.316	0.401
Boeoticos Kephisos	12.652	3.931



Key outcomes and concluding remarks

- Definition of **hydroelectric yield**, in terms of "firm energy", for clarity renamed here to "**reliable energy**".
- Configuration of the **stochastic simulation problem** with essential simplifications, including the expression of reservoir geometry through a **generic storage-elevation relationship** with a **single shape parameter**.
- Recognition of the system's performance through the **energy-probability curve**;
- Setup of optimization problem with a single control variable, i.e. the **target energy**, with respect to two alternative metrics used as **objective functions**, i.e. 99% reliable energy and mean annual profit (pseudo-economic function, reflecting the sharing between firm and excess energy production, as well as the energy deficits).
- Our simulation experiments showed that:
  - The maximized 99% reliable energy and the target energy are identical (except for very small storage capacity values).
  - Both metrics converge to the same target energy; however, **the mean annual profit is less prone to statistical uncertainties induced by the sample size**, in contrast to the reliable energy, which is an extreme probabilistic quantity.
  - For a given hydrological regime, the **reliable energy** is practically perfectly explained by the **storage ratio** (= reservoir capacity divided by the mean annual inflow) and the **shape parameter** describing the reservoir geometry.

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