Trade-offs in hydropower reservoir operation under the chain of uncertainty

EGU General Assembly 2024, Vienna, Austria, 14-19 April 2024; Session HS5.2.1: *Water resources policy and management - managing trade-offs at the nexus between water, food, energy and the environment*

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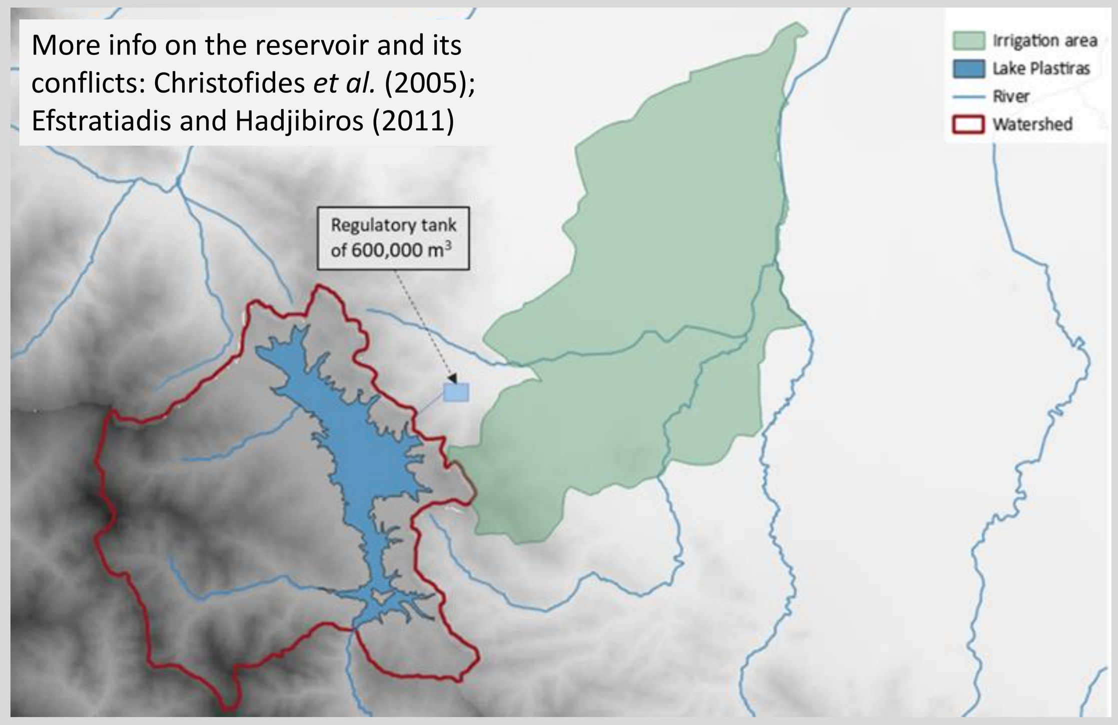
1. Abstract

The Water-Energy-Food-Ecosystem nexus is characterized by **synergies, complementarities and conflicts**, and thus its management is a demanding task. This becomes more challenging when **socioeconomic influences** are embedded. Key components of this nexus are multipurpose water reservoirs that provide drinking water, electricity, agricultural water for food production, and ecosystem services. These systems are driven by inherently uncertain processes, both hydroclimatic and human-induced (e.g., legal regulations, strategic management policies, real-time controls, and market rules), and thus their management should account for them. In this vein, this research proposes an **uncertainty-aware methodology for assessing the long-term performance of hydropower reservoirs**. Specifically, we investigate and describe in stochastic terms the main uncertain drivers i.e., **rainfall, water demands, and energy scheduling**, and eventually explore the cascade effects of the uncertainty chain. The modeling framework is stress-tested on a hydropower reservoir in Greece, Plastiras, which has been subject to **challenging socioeconomic conflicts during its entire 65-year history**. To estimate the water targets, we employ a statistical analysis of historical abstractions, concluding that the irrigation demand is strongly correlated with the reservoir level while it is negatively correlated with antecedent rainfall. For the estimation of the power plant's energy target, we adopt a **copula-based approach**, in which the desirable releases for energy production are dependent on day-ahead electricity prices. In particular, we adopt three policies, i.e., conservative, median, and energy-centric, that refer to 95%, 50%, and 5% quantiles of the copula. Finally, to account for the hydroclimatic and market process uncertainties, we are taking advantage of **stochastic models for the generation of synthetic rainfall and electricity price data**, respectively. Our findings indicate that the cascade effects of the **joint uncertainties** are crucial for all operation policies. Specifically, in terms of profitability the energy-centric and the median are similar, while from a water supply and irrigation reliability perspective, the uncertainty range of this policy is wider, thus making it unacceptable for some scenarios. Consequently, the conventional approach of ignoring uncertainty in policy selection may result in misleading perceptions for the operator, eventually guiding to sub-optimal reservoir management.

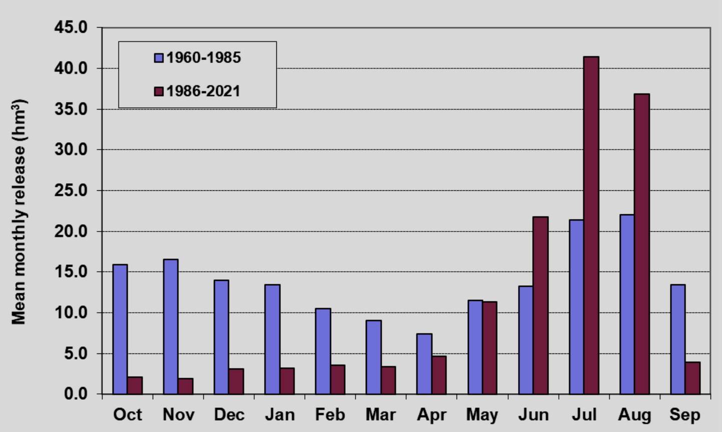
2. Case study: Plastiras multipurpose reservoir, Greece

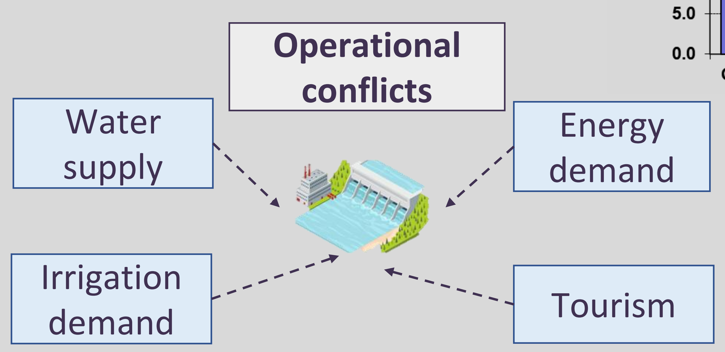
Reservoir information:
- Useful capacity: 286.3 hm³
- Drainage area: 161.3 km²
- Mean annual rainfall: 1609 mm
- Mean annual runoff: 155.9 hm³

Power plant characteristics:
- Installed capacity: 130 MW
- Mean annual energy production: 190 GWh
- Gross head: 577 m
- Capacity of penstock: 33.5 m³/s



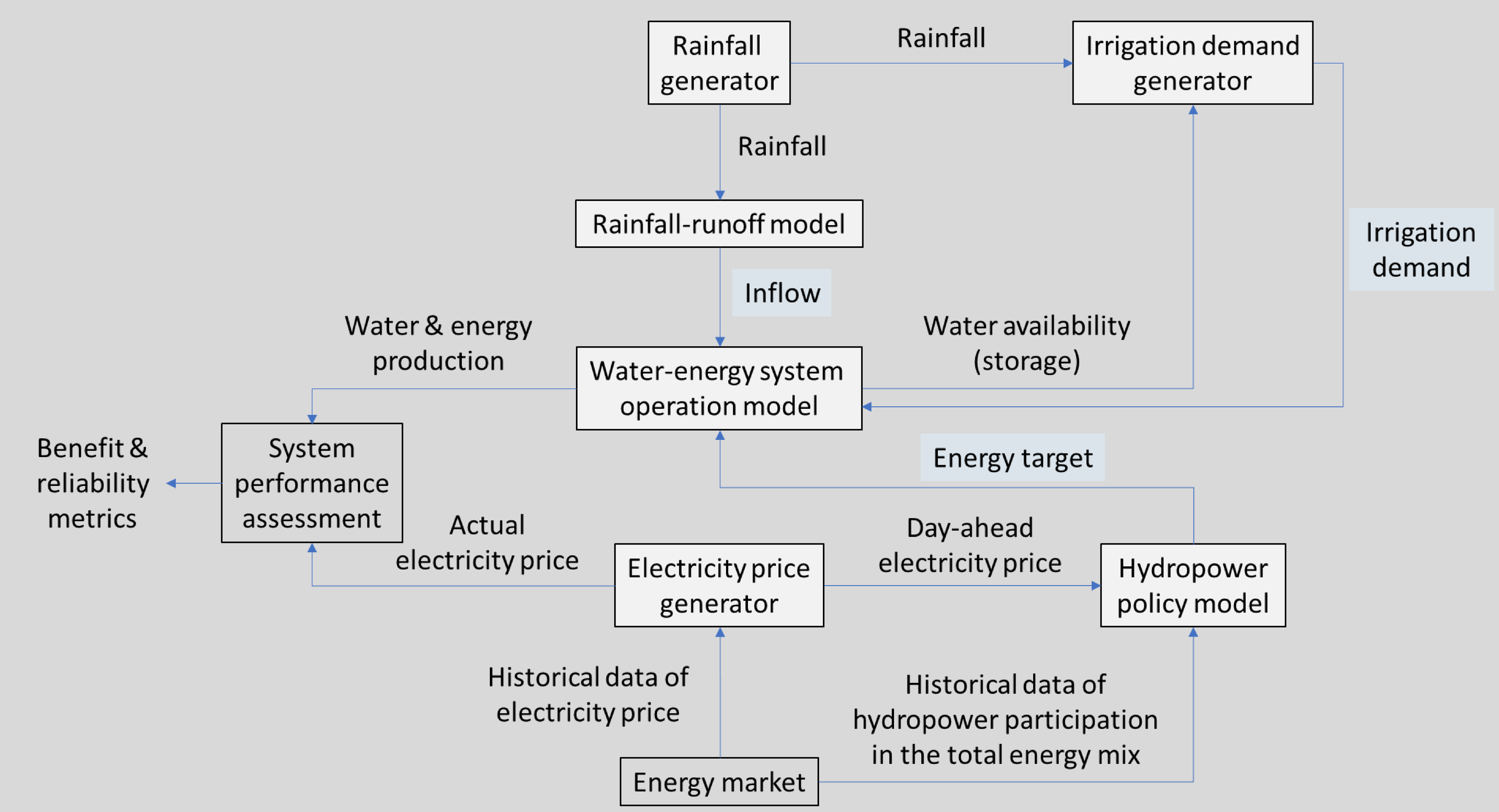
Historical evolution of reservoir uses
- As designed, in the end of the 1950s: hydropower production
- From 80's: Priority to irrigation and water supply of Thessaly plain
- From mid 90's: Touristic development around the lake





Water supply demand: 24 hm³
Irrigation demand: 110.3 hm³
Energy demand: *uncertain*

3. Schematic layout of models (light grey filled) and their interlinkages (blue lines)



4. Handling uncertainties – Optimization settings to optimize the water-energy system operation

Setting 1: Combination of historical inflows with m **ensembles of synthetic electricity prices** to account for the energy market uncertainty *per se*.

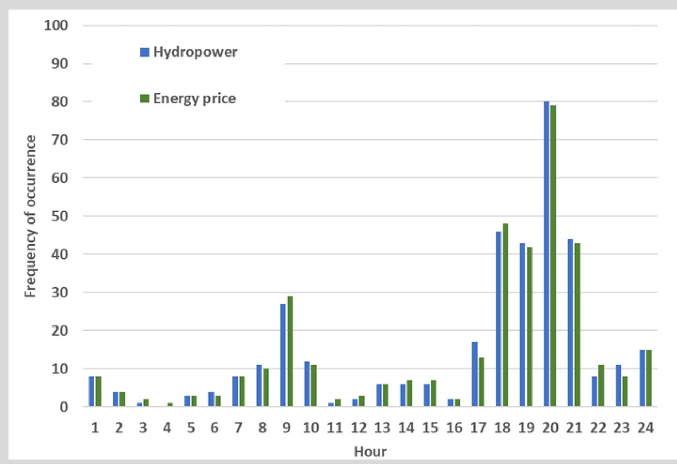
Setting 2: Rainfall-runoff model driven with historical precipitation data and m **equifinal parameter sets** to derive m ensembles of simulated inflows, next combined with m **ensembles of synthetic electricity prices** to account for both epistemic and energy market uncertainty.

Setting 3: Rainfall-runoff model driven with m **ensembles of precipitation data,** and parameters calibrated against historical inflows to derive m ensembles of simulated inflows, which are next combined with m **ensembles of synthetic electricity prices** to account for both the climatic and energy market uncertainty.

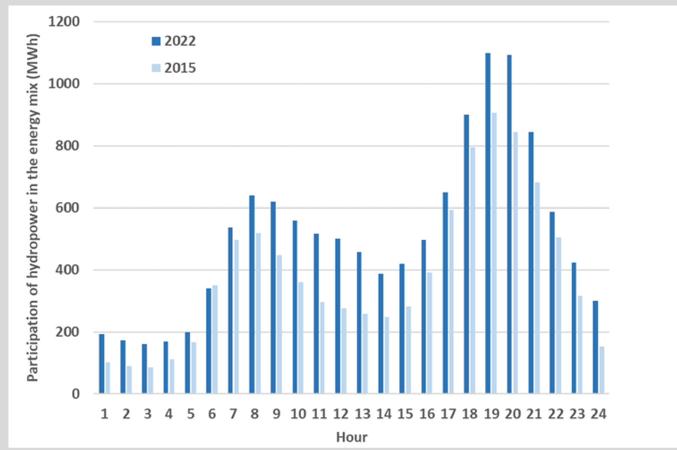
Setting 4: Rainfall-runoff model driven with m **ensembles of precipitation data** and m **equifinal parameter sets** to derive m ensembles of simulated inflows, next combined with m **ensembles of synthetic electricity prices**, to account for climatic, epistemic and energy market uncertainties.

Setting 5: Similar to setting 4, also **assigning dynamic irrigation demands**, thus accounting for climatic, epistemic, energy market and social uncertainties under a common context.

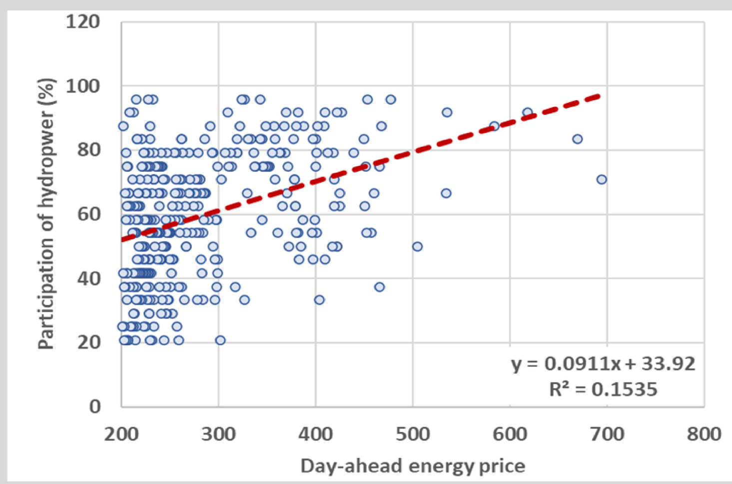
5. Estimation of highly uncertain daily energy target



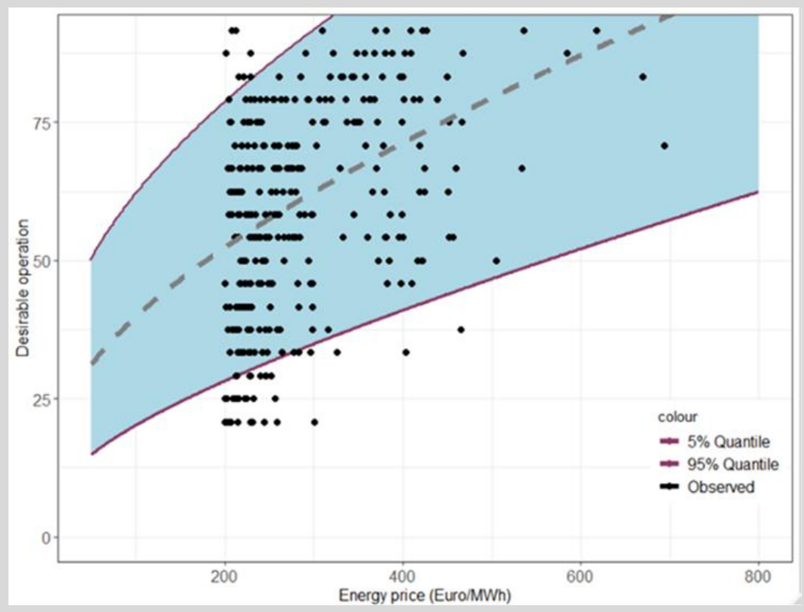
(1) Frequency of occurrence of maximum participation of hydropower generation in the mix and energy price for year 2021



(2) Participation of hydropower in the mix and the energy price for the years 2015 and 2022



(3) Correlation between day-ahead energy prices and the participation of hydropower plants in the energy mix

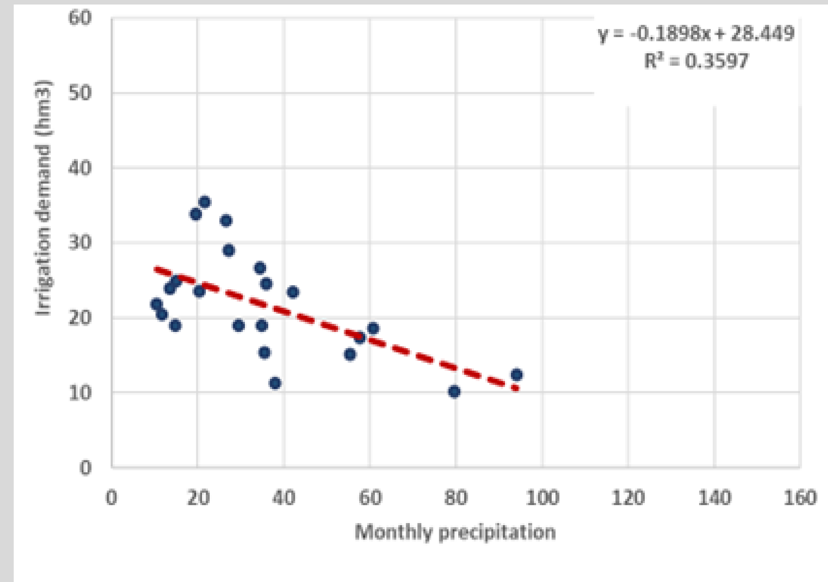


(4) To account the uncertainty in the operation of the hydropower plant, mainly induced by socioeconomic, we fit a copula formula, on the basis of which we select three quantiles, i.e., 95%, 50%, and 5% that represent the operation policy of the stakeholder.

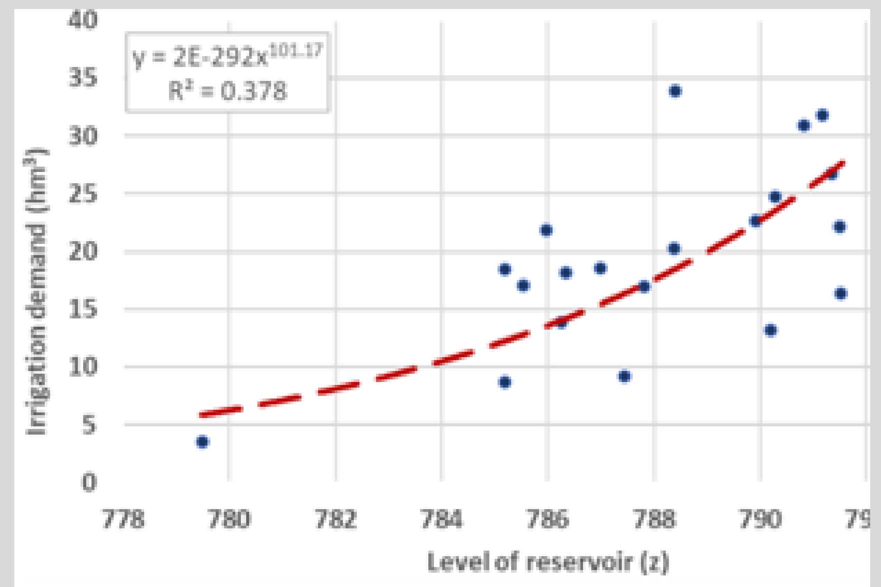
The three quantiles refer to the operational policies, i.e. conservative (95%), median (50%) and energy-centric (5%)

6. Estimation of irrigation demands

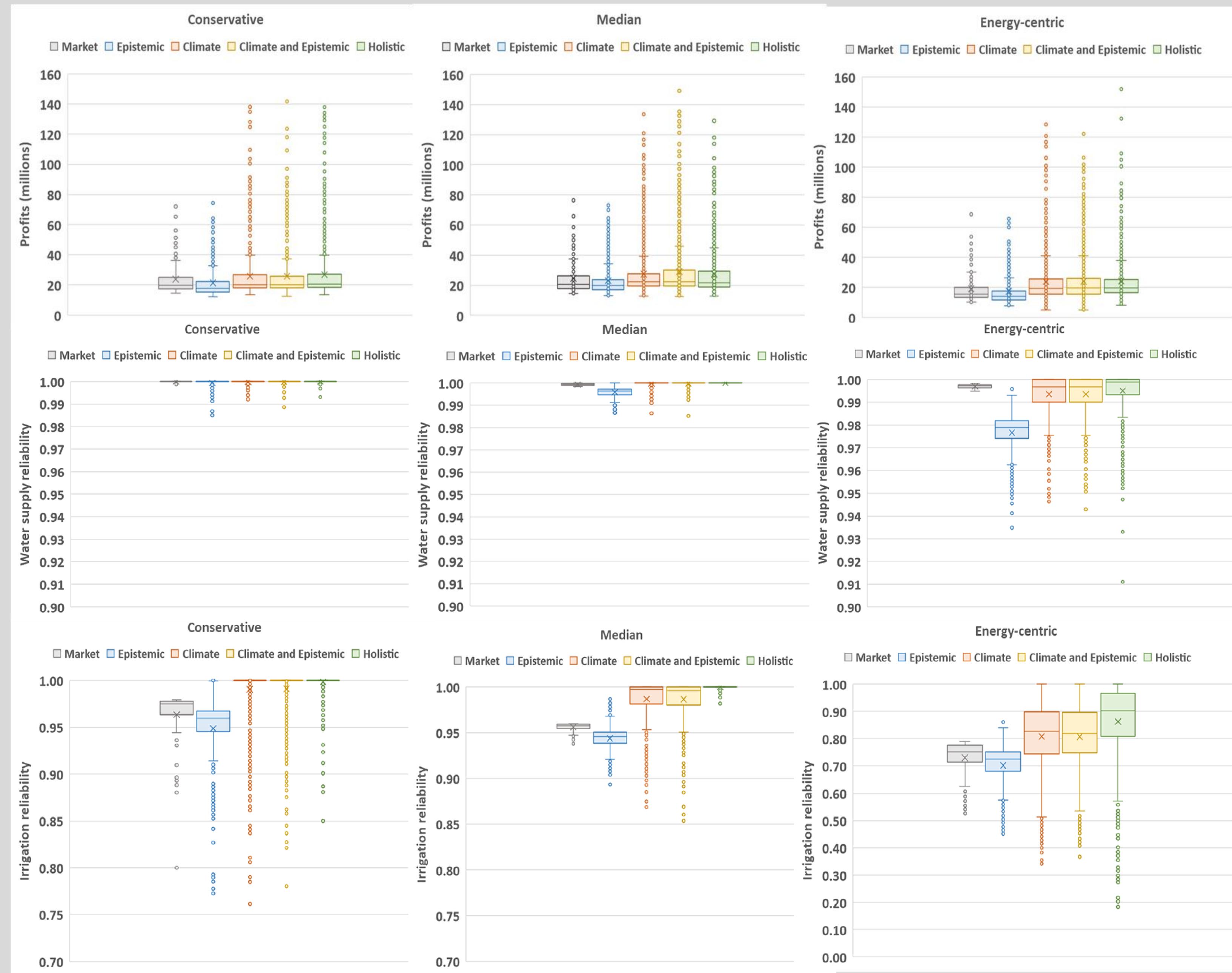
Irrigation demand (rational practice)



Irrigation demand (irrational practice)



7. Results



8. Conclusions

- Climatic and energy-market uncertainties are effectively represented through stochastic models, allowing for the generation of **synthetic rainfall and electricity prices**, as major drivers of hydropower systems.
- For the description of the **human-induced processes**, these are discriminated into **direct** and **indirect**, corresponding to the water demands and the operation policy, respectively.
  - For the direct component, i.e., the social response, a statistical analysis is employed to express **water demands as dependent random variables against rainfall and the reservoir state**.
  - For the indirect one, involving the operation policy of the hydropower, a copula-based tool is developed that estimates the **energy target related to day-ahead electricity prices and the operator's willingness**.
- The cascade effects of the joint uncertainties are crucial for all operation policies. The **median policy** ensures a good trade-off between total profits and reliability in fulfilling irrigation and water supply uses.

References

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