1. Abstract
We investigate the design of small hydropower plants under multiple sources of uncertainty and contrast it with the conventional deterministic practice that leads to a unique solution. In particular, we emphasize three sources of uncertainty, referring to: (a) the rainfall process (i.e., precipitation and evapotranspiration), and (c) the flow–energy conversion. The first is due to the nature (i.e., hydroclimatic), and is represented through stochastic approaches. The rainfall–runoff uncertainty arises from inherent structural uncertainty and poor parameter identifiability across the calibration procedure. In fact, hydrological model parameterizations using only historical data are often accurate in predicting catchment behavior over the long term, as they may not capture the full range of hydroclimatic conditions that the catchment may be subjected to. To address this issue, we use synthetic time series as drivers to parameterize the model and validate it against observed data. This approach preserves the observed data’s probabilistic properties and dependence structure while also providing a much wider range of hydroclimatic conditions for model training. In addition, a flexible approach is necessary for representing all the total model uncertainty. The final source of uncertainty is depicted by means of probabilistic efficiency curves. This Monte Carlo simulation framework is formalized as a modular procedure, the different sources of uncertainty and the full context are tested through the design of a small hydropower plant in Epirus, Western Greece.

2. Problem statement
The conventional design of SHPPs follows a fully deterministic procedure, thus all derived techno-economic quantities and associated decisions are solely based on local conditions and model limitations. The ignorance of uncertainty introduces significant risk, both from the engineering and the investor’s perspective. In order to tackle this issue, we establish a modular scheme to represent the following major sources of uncertainty:

- **Rainfall Process Uncertainty**
- **Hydrological Analysis of upstream catchments (collection of point rainfall and surface runoff, estimated by the NRCS SCS method)**
- **Turbine Optimization Uncertainty**
- **Optimization of turbine mixing for each proposed layout**
- **Cost of turbines (function of power capacity and head; cf. Aggidis et al. (2010), Koutsovitis & Koutsoyiannis (2008))**
- **Cost of energy production (CAPEX after 8 years length to select a subset of the synthetic rainfall record)**

3. The spark for delving into the uncertainty... As part of our undergraduate thesis work within the “Integrated Project in Hydraulic Engineering”, we implemented the conventional design of a run-of-river hydropower plant in Arachthos river basin, Epirus, NW Greece, comprising the following steps:

- **Development of a lumped concept small hydropower model and estimation of its parameters through calibration against observed runoff data, obtained by neighboring hydraulic natural stations**
- **Application of optimized parameters for the generation of historical daily inflow series in the proposed site, for a 20-year period**
- **Turbine selection and turbine sizing for each proposed layout, following the rationale by Sakki et al. (2022b)**
- **Assessment of turbine mixing for each proposed layout, following the rationale by Sakki et al. (2022b)**

4. Rainfall-runoff model and “mainstream” extraction of its parameters through calibration
- **The design procedure of the hydropower system is driven by daily streamflow time series, which is one in turn is derived from precipitation and potential evapotranspiration data.**
- **In the absence of hydrometric information at the site of interest (intake), the inflows are extracted through a deterministic river routing model that employs a typical bucket-type scheme, combining three interconnected tanks, as well as a small reservoir that emulates the propagation of the surface runoff (estimated by the NRCS-CN method) to the catchment’s outlet.**
- **The model contains four parameters that are derived via a conventional calibration algorithm, based on observed quality data quite different from the site of interest (Psaurou dam).**
- **The calibration ensures the model performance (NSE = 80%).**
- **The overall watershed is homogenous with respect to its physical characteristics, thus the optimized model parameters can be considered representative across the entire area.

5. Setup of rainfall-runoff model calibration under uncertainty
- **The model parameters are inherently uncertain, since they are inferred through calibration.**
- **We investigate two key sources of uncertainty within the calibration procedure, arising from the input data and the formulation of the objective function.**
- **In this vein, we employ 1000 independent calibration runs in a Monte Carlo context:**
  - We randomly select half of the observed streamflow data to feed the calibration, through a randomly varying window of 10-years length.
  - We formulate a multi-objective function comprising three metrics (Persistence Index, High Flow Index, Nash-Sutcliffe Efficiency, Penman (1939)) and assign random weights to them.
  - The outcome of the exercise has 4000 optimized model configurations, for which we provide a probability density function (PDF) of the parameters. The parameter uncertainty is easily visualized by means of empirical histograms.

6. Optimizing the turbine mix under uncertainty
- **For a given layout of the hydropower system (i.e., intake of intake and power station, delineation of conveyance system, and selection of penstock diameter), the most important design decision involves the selection of turbine capacity. Usually, two turbines of different power capacity are applied, such operating within a specific flow range, in order to ensure the maximum possible exploitation of the available hydropower potential (Sarantaopoulou et al., 2022).**
- **The challenge is to find an optimal design mix, which can be formalized as an optimization problem, where here this is configured in an optimization-aware context.**
- **Initially, we generate a synthetic rainfall time series of 2000 years length through the asymptotic package (Koutsovitis et al., 2020), thus reproducing the probabilistic and stochastic behavior of the observed data, as well as the Hurst-Kolmogorov dynamics, which is the footprint of the permanently changing, and thus uncertain, climate.**
- **We run the design optimization problem multiple times, by configuring equally probable scenarios, as follows:**
  - **We apply a randomly varying window of 20-years length to select a subset of the synthetic rainfall record.**
  - **We use this subset as input to the rainfall-runoff model, next running with randomly selected parameters, to provide stochastic streamflow data at the intake.**
  - **In line with the simulation of the SHPP op, we apply the turbine efficiency cure used by Sakki et al. (2022b)**


References


The presentation is available at: http://www.itia.ntua.gr/2272/